Explorations of the Rapid Automatized Naming (RAN) Task: What should the "A" in RAN stand for?

Evgueni Borokhovski

A Thesis

in

The Department

of

Psychology

Presented in Partial Fulfillment of the Requirements

for the Degree of Doctorate of Philosophy

at Concordia University

Montréal Québec, Canada

Library and
Archives Canada

Published Heritage
Branch

395 Wellington Street
Ottawa ON K1A 0N4
Canada

Bibliothèque et
Archives Canada

Direction du
Patrimoine de l'édition

395, rue Wellington
Ottawa ON K1A 0N4
Canada

Your file Votre référence
ISBN: 978-0-494-31121-9
Our file Notre référence
ISBN: 978-0-494-31121-9

NOTICE:
The author has granted a non-exclusive license allowing Library and Archives Canada to reproduce, publish, archive, preserve, conserve, communicate to the public by telecommunication or on the Internet, loan, distribute and sell theses worldwide, for commercial or non-commercial purposes, in microform, paper, electronic and/or any other formats.

The author retains copyright ownership and moral rights in this thesis. Neither the thesis nor substantial extracts from it may be printed or otherwise reproduced without the author's permission.

AVIS:
L'auteur a accordé une licence non exclusive permettant à la Bibliothèque et Archives Canada de reproduire, publier, archiver, sauvegarder, conserver, transmettre au public par télécommunication ou par l'Internet, prêter, distribuer et vendre des thèses partout dans le monde, à des fins commerciales ou autres, sur support microforme, papier, électronique et/ou autres formats.

L'auteur conserve la propriété du droit d'auteur et des droits moraux qui protège cette thèse. Ni la thèse ni des extraits substantiels de celle-ci ne doivent être imprimés ou autrement reproduits sans son autorisation.

In compliance with the Canadian Privacy Act some supporting forms may have been removed from this thesis.

While these forms may be included in the document page count, their removal does not represent any loss of content from the thesis.

Conformément à la loi canadienne sur la protection de la vie privée, quelques formulaires secondaires ont été enlevés de cette thèse.

Bien que ces formulaires aient inclus dans la pagination, il n'y aura aucun contenu manquant.

Canada

ABSTRACT

Explorations of the Rapid Automatized Naming (RAN) Task:
What should the "A" in RAN stand for?

Evgueni Borokhovski, Ph.D.
Concordia University, 2007

This research explored the cognitive nature of the RAN (Rapid Automatized Naming) task, a test widely used to assess reading development. It addressed automaticity- and attention-based processing and their relative contribution to RAN task performance to better understand why the RAN task has the predictive value for reading development.

Study 1 (N=68) utilized two different indices of automatic stimulus recognition and an index of attention control as predictors of naming speed on the four original versions of the RAN task. The study found little support for an automaticity-based account of RAN task performance, but did support an attention-based account. Symbolic and non-symbolic RAN subtasks differed in terms of the role played by automatic and attention-based factors, and in terms of their correlations with reading speed.

Study 2 (N=16) used ten modified versions of the RAN task that manipulated attention and memory demands. Naming speed was sensitive to attentional demands and to stimulus familiarity, but not to factors of long-term memory retrieval.

Study 3 (N=97) provided additional information on the roles played by automatic and attention-based processing in RAN task performance, using new measures of these constructs. Attention came out as explaining a large proportion of the variance in naming speed; skill in automatic stimulus detection and in lexical access efficiency did not. Working memory was strongly associated with RAN task performance.

Finally, a meta-analysis on a representative sample of research data (65 studies reporting 530 coefficients of correlation between RAN tasks performance and different measures of reading, N=8555) revealed the average point estimates were $r+ = .345$ and $r+ = .398$, for cross-sectional and longitudinal research designs respectively. The moderator analyses showed that reading skills more closely associated with RAN task performance required expertise with printed text and depend on applying rules and building and managing associations. These regularities are largely consistent with the results of the three experimental studies.

Overall, these indicated that attention-based factors rather than automaticity underlie naming speed as measured by the RAN tasks, and these mechanisms presumably link RAN to reading performance. Implications for further research and educational practices are discussed.

ACKNOWLEDGEMENTS

There is not a single achievement in education (from learning how to read and write to completing a doctoral degree) that can be attributed entirely to the efforts of the learner. There are always people around who motivate, encourage, guide, support, advise, believe in you, people whose everyday help, whether considerable or small, contributes to your success. My warmest words of acknowledgement and appreciation are to them.

First of all, I would like to express my deepest gratitude to Dr. Norman Segalowitz. While pursuing my doctoral degree at Concordia University, I was extremely fortunate to have him as my research supervisor, from whom I learned a great deal about cognitive psychology, second language learning and conducting research, and, no less importantly, about commitment, patience, creativity and about the primacy of human integrity over scholarly advances. Thanks a lot, Norman, for guiding my research, for mentoring me, and simply for your companionship during all these years.

I wish to express my love and gratitude to my wife Olga for her constant support and understanding. Olenka, I value very much your emotional involvement and your friendship. Thanks a lot for giving me encouragement and a good portion of various distractions, reminding me about the excitement of life outside academia, for sharing with me your inquiring and hopeful spirit. I love you very much.

There are two very special people I want to extend my gratitude to. My mother and my son who both still live in Russia, but who, I know for sure, think of me every day. Knowing it both invigorates and comforts me immensely. Thank you for believing in me, for your love and your kindness. I love you too.

I also would like to acknowledge my teachers and former classmates and colleagues in Russia who had no doubts in my abilities to earn an advanced degree from a North American university and did not hesitate to recommend me for this program at Concordia. Dear Dr. Tatiana V. Aleinikova, Dr. Irine P. Shkuratova, Dr. Irina Abakumova, and Dr. Carina Gaidar, I truly appreciate your vote of confidence.

I sincerely appreciate all help provided by the students (especially, Marlene Taube-Schiff, Irene O'Brien, and Talya Grumberg) and research assistants (Anne-Marie Linnen, Adam Christian, and others) in our lab through sharing their expertise, exchanging ideas, and through all stimulating discussions we have had. My special thanks go to Anna Sokolovskaya, Christina Tapler and Anna Peretiatkowicz for their assistance in some parts of my research. Also, important suggestions and thorough, constructive feedback was provided during all phases of this work by Dr. Guy Lacroix, a postdoctoral fellow at the lab and thesis committee member; his contributions were an enormous asset in progressing through this project. I am grateful, as well, to the committee members Dr. de Almeida and Dr. Von Grunau and to all the professors in the Psychology Department I learned a lot from.

I would also like to thank the leadership, the staff, and the research team of the Center for the Study of Learning and Performance (CSLP) for giving me the opportunity to gain invaluable experience in conducting systematic reviews while working as a research assistant on a variety of meta-analyses with Dr. Robert Bernard and Dr. Philip Abrami (not to mention the financial support generated through this work).

Finally, I would like to acknowledge the support that came for this research and my doctoral studies from the National Institutes of Health (Interagency Educational Research Initiative) (IERI) and the Fonds québécois de la recherche sur la société et la culture (FQRSC).

Here is just one more notion in conclusion.

The time I spent working on this project and everything that happened throughout it: studying, conducting research, and especially learning from and taking pleasure in communicating with all these people, – once again helped me realize a very simple, but essential rule.

Whatever you are busy with, no matter how important and meaningful it seems to be, do not take it too seriously, and try to be even less serious about yourself doing it. Enjoy, not endure it. Do not perceive difficulties, setbacks and time delays as obstacles, but rather as adventure and learning experience. Do not think of any moment in life as about preparation for further achievements or a better career, but simply live it to the best of your abilities. I honestly tried… The results are not for me to judge.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

CHAPTER 1: RESERCH OVERVIEW

General introduction

A diagnostic tool, especially one to be used in the area of cognitive development, primarily serves two goals: (1) to detect any unwelcome anomalies in development as soon as possible, and (2) to help people understand the sources of such anomalies so that one can design effective preventive measures and/or remedial interventions. Meeting these goals requires addressing particular sets of questions that necessarily arise as research on the test development and practical application progresses.

The first group of such questions deals with how and why an assessment test under consideration works. Depending on a researcher's point of view, concern in this category could involve issues of test validity, reliability, complexity, limitations, etc., or it could involve a concern to understand the cognitive processes responsible for test performance. At the core of the matter, however, lies a concern that is closely related to the ones raised earlier, namely, what are the cognitive mechanisms that underlie test performance that are critical to test outcomes and to their relationship to the expertise (competency) the test is designed to assess.

The second group of questions deals with the conditions under which test results will be most reliable and interpretable. It is almost never the case that the use of a psychological assessment tool is equally effective and informative across all conditions and samples. Even the most respected test with a long and fruitful history, standardized to account for specifics of gender, age, level of education, etc., often remains the subject of debate over its appropriateness for use in this or that context and over how to best interpret its outcomes. A highly illustrative example is the case of the theory of adaptive intelligence whose adherents have attempted to reshape our understanding of more the more commonly held concept of the intelligence quotient (IQ) (Sternberg, 1999, 2005). Another example is how efforts to develop a verbal means for assessing general intelligence evolved into the various tests of verbal intelligence (Naglieri, 1999, 2005). In both cases, we see there has been long debate over the use and interpretation of a well-known and well-accepted assessment tool (the IQ test).

In the area of reading development, the Rapid Automatized Naming (RAN) task (Denckla & Rudel, 1976b) is one of the most salient examples of how all these questions can together become the focus of debate surrounding a single cognitive assessment tool that has been in active use by psychologists and educators. This debate has endured for three decades, complicating (even undermining on occasion) understanding of the cognitive mechanisms underlying the RAN task and consequently the interpretation of what RAN task results actually mean.

As has been repeatedly pointed out (Savage, 2004; Stringer, Toplak, & Stanovich, 2004, among many others), the cognitive mechanisms underlying RAN task performance and its association with reading performance remain very much an enigma. There is no doubt RAN works as a strong predictor of reading outcomes in children of different ages (Wolf, Bowers, & Biddle, 2000). Even some recent meta-analyses that have turned out to be rather skeptical about the importance of RAN task results compared to other predictors of reading development nevertheless give RAN task credit for a moderate but significant correlation with reading outcomes (Hammill, 2004; Swanson, Trainin, Necoechea, & Hammill, 2003). But why is the RAN task successful (to the extent that it is)? Numerous hypotheses have been considered since the test first appeared (Denckla & Rudel, 1976a, 1976b), none of which, however, provide a satisfactory explanation of why there is an association between RAN performance and reading skill, present or future. Even authors who are heavily involved in theoretical and empirical analyses of RAN task phenomena, such as the authors of the "double-deficit" hypothesis (Wolf & Bowers, 1999), have expressed caution: "The arguments ... are highly speculative and represent work in progress... Considerable further work is needed before these relationships [naming speed – reading] will be sufficiently clarified" (Wolf et al., 2000, p. 396). Others who question some aspects of the "double-deficit" approach are nevertheless equally careful in describing the progress that has been made in understanding the cognitive mechanisms underlying RAN task performance. For example, "...there is a need for experimental work elucidating the nature of naming speed deficits..." (Savage, 2004, p. 301) and "...we wished to explore which cognitive domains are tapped by rapid naming tasks..." (Stringer, et al., 2004, p. 897). Such statements illustrate how far researchers find themselves from an unequivocal answer to the question of why RAN performance is associated with reading performance, even three decades after empirical exploration of the topic had been initiated.

Statement of the problem

The goal of the present work is to shed some light on the cognitive nature of RAN task performance and on the relationship between RAN and reading performance. In other words, this project is designed to explore the following questions:

(1) What are the cognitive mechanisms responsible for the connection between RAN task performance and reading abilities? (This is the "What makes it work?" question.)

(2) What are the conditions most favorable for a manifestation of a RAN – reading connection? (This is the "When does it work better?" question).

The first question is addressed in a series of experimental studies. These studies used normal adult readers. The reason for looking at this population, rather than at children or individuals with known reading difficulties, rests on the assumption that whatever the cognitive mechanisms involved in RAN performance, they are not uniquely specific for either early stages of cognitive development or for disadvantages in reading abilities. Though very few studies to date have dealt with adults who possessed normal reading abilities (e.g., Berninger, Abbott, Thomson, & Raskind, 2001; Chiappe, 1997; Howe, Arnell, Klein, Joanisse, & Tannock, 2006; and partially Wolff, Michel, & Ovrut, 1990), the documented research goes far beyond the populations of kindergarteners or elementary school students, casting doubt on the idea that RAN-reading relationships are purely developmental. Moreover, in adults, we might expect basic regularities linking naming and reading performance to be revealed even more clearly, because extensive practice in reading from childhood to adulthood will eliminate most of the more superficial aspects of RAN performance associated with underdeveloped cognitive skills in novice or impaired readers. Under such circumstances the use of an adult sample appears to be strategically beneficial, enabling an observation of what fully developed expertise in reading could reveal about the cognitive underpinnings of RAN task performance.

The second question is the focus of a systematic review of a representative sample of research evidence in a meta-analysis. This meta-analysis complements the experimental studies by examining the empirical evidence concerning the factors that contribute to the relationship between RAN performance and reading development, the extent of their contribution and the conditions under which they do so. The meta-analysis is conducted on a representative set of primary empirical studies that employed different versions of the RAN task and that reported correlations between RAN task performance and various measures of reading skill.

Research questions

Study 1 of this dissertation addresses the assumption, most prevalent in the literature especially within the framework of the double-deficit hypothesis, that the cognitive mechanism responsible for connecting RAN task performance to reading is automaticity-based. Study 1 addresses the following questions:

1. Do individual differences in the degree of automatic information processing underlie individual differences in RAN task performance, where "automatic" is operationalized either as ballistic processing or as rapid and stable (and consequently more efficient) processing?
2. Do individual differences in the degree of attention control operationalized in terms of shift costs underlie individual differences in RAN task performance?
3. Are automatic and attention-based aspects of RAN task performance equally or differentially linked to reading performance?

These questions are addressed in the context of individual differences in adult readers.

Study 2 is an extension of Study 1, reflecting preliminary findings from that study (namely that *attention*-based processing and not automaticity may play an essential role in RAN task performance). Study 2 addresses the following three questions by means of ten specially tailored versions of the RAN task:

1. How sensitive is RAN task performance to explicit manipulation of attention demands?
2. How important to RAN task performance is the "set size" factor, that is, the size of the potential "universe" or source set from which the actual target stimuli to be named are drawn from?
3. Does stimulus familiarity, as function of frequency in printed text, play any role RAN task performance and its link to reading rate?

Study 3 is built upon the outcomes of the first two studies and aims to further investigate the cognitive nature of the RAN task. In particular the study looks at the factors of attention, working memory and efficiency of lexical access. The study addresses the following research questions:

1. *Automaticity*: If automaticity of stimulus recognition is not associated with RAN task naming speed (as turns out to be the case), are other forms of automaticity operationalized in other ways (i.e., not as ballistic processing or efficient stimulus recognition), nevertheless related to RAN task performance?
2. *Attention*: Can particular aspects of attention be identified as being associated with successful RAN task performance?

3. *Other factors*: Are other factors, such as efficiency of lexical access and working memory capacity, capable of substantially adding to our understanding of the cognitive mechanisms of RAN task performance?

Finally a meta-analysis is reported. Among the methodological and substantive study features explaining variability in effect sizes, the meta-analysis considers the following aspects of the primary studies: research design (longitudinal or cross-sectional), participants' language, age and associated with it experience and proficiency in reading, version of the RAN task, and reading measures. These elements are crucial for a better understanding of what factors are responsible for the connection between RAN and reading performance and for the evidence of variability in that connection.

Before proceeding with the experiments and the meta-analysis, it will be useful to first put the issues into their larger context. This is accomplished in the brief literature review in the next chapter.

CHAPTER 2: REVIEW OF THE LITERATURE

Overview

Before addressing the major issues that the present study was designed to explore, it will be useful to first take a closer look at the RAN task itself. This look will consider different theoretical formulations that lie behind it and its association with reading, the history of research on it, and practical applications. This literature review will be presented in sections as indicated below.

- Defining developmental dyslexia – with emphasis on the cognitive roots of difficulties in reading acquisition;
- The double-deficit hypothesis – with a focus on the Phonological Awareness deficit and Naming Speed deficit as major cognitive factors in developmental dyslexia;
- RAN as a measure of naming speed – a brief summary of applied research using the RAN task;
- The cognitive nature of the RAN task – with a look at:
    - Controversial issues surrounding RAN;
    - Overlap between the task demands of the RAN task and reading itself;
    - Dependence/Independence of RAN task performance from phonological awareness;
    - Different types of stimuli used in the RAN task;
    - The role attention and automaticity-related factors may play in RAN task performance.

These topics are now taken up in turn.

Developmental dyslexia

Cognitive factors associated with success and failure in reading development have recently attracted more and more attention from psychologists, educators and health professionals. No doubt this is in large part due to the increasing importance of reading as a fundamental skill. In modern society, to become literate is nearly always the first step towards most of further achievements, whereas to be illiterate or weak in reading can often result in life-long professional barriers and social complications. Rare exceptions – stories of success despite persistent reading disadvantages (e.g., Morris, 2002) – only serve to emphasize the general necessity of literacy.

No wonder, then, that so many researchers study reading so closely in order to determine in a timely manner who is at risk for developing reading problems so that effective ways to help may be devised. There is a strong consensus that the road to skilled reading (in English and languages with similar writing systems) requires mastering of the alphabetic principle and that direct explicit approaches to teaching how to read appear to be among the most effective means for gaining this expertise (Rayner, Foorman, Perfetti, Pesetsky, & Seidenberg, 2001). Rayner et al., however, are cautious in what they say about the cognition behind reading skills. They ask whether particular cognitive prerequisites for successful reading acquisition can be identified, where anomalies, delays, or irregularities in the development of these prerequisites are responsible for underperformance in reading. This question remains largely unanswered, despite the overwhelming agreement on its utmost importance.

In this respect, so-called developmental dyslexia occupies a special place among reading impairments because no obvious reasons are readily available to account for the disorder. Researchers, educators and health practitioners all tend to agree that developmental dyslexia cannot be fully explained by either poor intellectual abilities, inappropriate education, inadequate socio-cultural opportunities or any detectable brain or perceptual deficiencies. For example, Critchley (1970) describes developmental dyslexia as follows: "… a disorder manifested in difficulty in learning to read despite conventional instruction, adequate intelligence and socio-cultural opportunity" (cited by Snowling, 2000, p. 15). This definition is similar to a vast collection of approaches to describing developmental dyslexia, including for instance, Bishop (1997), Kelly (1998), or the DSM-IV (Diagnostic and Statistical Manual of Mental Disorders, Fourth Edition, 1994). Such definitions not only distinguish developmental dyslexia from other forms of learning disabilities, where difficulties in reading do not occupy the central place, but they also emphasize that developmental dyslexia derives from problems in cognitive development not otherwise associated with any particular intellectual setback or social or educational deprivation.

In terms of the typical symptoms of developmental dyslexia – the so-called discrepancy criteria – one can imagine the following somewhat simplified working definition: Developmental dyslexia is a reading performance deficiency of at least 1.5 standard deviations below the age-matched norm on standardized reading measures that:

- is not accompanied by any intellectual impairment (that is, IQ is within one standard deviation of the age-matched norm on standardized tests of intelligence),

- is not due to deprivation in either proper reading instruction (through a recognized educational facility) or relevant exposure to spoken and written language through family and other social institutions and contacts; and
- is not explicable in terms of any obvious visual or auditory system trauma or dysfunction.

Developmental dyslexia, thus, implies presence of some kind of deficit in cognitive development – that is, whatever else is left capable of explaining it, must be rooted in some particular aspect(s) of the workings of human cognition. What could it be? The Double-deficit Hypothesis (Wolfe & Bowers, 1999) attempts to answer this question, and this is where the RAN task enters the picture.

The double-deficit hypothesis

Two major cognitive factors are commonly known to underlie successful reading and whose impairment results in developmental dyslexia of different degrees of severity.

The first factor is phonological awareness – an individual's ability to understand and efficiently handle the relationships existing between graphemes and phonemes as elements of written and spoken language respectively. Researchers typically define phonological awareness as a meta-cognitive skill that requires understanding of the sound structure of the spoken language. The existence of a phonological core deficit is now the most strongly supported theoretical account for developmental dyslexia (e.g., Morris et al., 1998, Rayner et al., 2001; Snowling, 2000; Stanovich, 2000, among many others). Consequently, phonological awareness is broadly recognized as the number one predictor for successful development of reading skills in children. This recognition is based upon a long line of psychological, linguistic and pedagogical research (Blachman, 1989; Bradley

& Bryant, 1983; Brady, & Shankweiler, 1991; Fawcett, 2001; Gallagher & Frederickson 1995; Havey, Story, & Buker, 2002; Heath & Hogben, 2004; Savage, Frederickson, Goodwin, Patni, Smith, & Tuersley, 2005a, 2005b; Stanovich, Cunningham, & Feeman, 1984). Experimental research has revealed again and again strong correlations between measures of phonological awareness and reading abilities (as for instance, in many of the works cited above) and this works in favor of the core phonological deficit hypothesis not only in children, but also in reading impaired adults (e.g., Bone, Cirino, Morris, & Morris, 2002). Pedagogical interventions especially designed to provide training in phonological skills appear to be quite successful in improving reading outcomes (e.g., Fleming, 1999; Wilson & Frederickson, 1995), as well. There are also data from languages other than English demonstrating similar strong relationships between phonological awareness and reading performance. For example, these relationships were observed in Chinese (Lu, 2004; Xiangzhi, Shuying, & Xiaolin, 2004), in Dutch (de Jong & van der Leij, 1999), though the effect of phonological awareness on reading tended to disappear after grade 1, and in German (Landerl, 2003), though the high grapheme-phoneme consistency of German orthography helps children to overcome phonology-based reading deficiencies more easily. It has also been shown in bilinguals (e.g., by Lafrance & Gottardo, 2005 in French/English bilinguals; by Veii & Everatt, 2005 in Herero (Namibian)/English bilinguals; and by van der Leij & Morfidi, 2006 in Dutch/English bilinguals).

An important discussion in the literature is about whether phonological awareness should be perceived as a single invariant construct or as a complex cognitive competency, in which one should distinguish at least between detection and production factors measured by different tasks (e.g., Savage, Blair, & Rvashiew, 2006). While this issue is beyond the scope of the present review, it is worth noting that what really matters is that researchers have little doubt about the existence of a strong association between phonological awareness and reading ability. For example, Castles and Coltheart (2003) acknowledge the strength of the association, even as they argue that the research to date has failed to convincingly demonstrate any apparent causality in these relationships. They argue that there is a possibility that preexisting literacy may have an influence on phonological awareness, and they came up with suggestions for a line of research potentially capable of establishing a cause-effect link from phonological awareness to successful reading acquisition.

A somewhat different question, however, is whether the cognitive foundations of difficulties in reading are perhaps limited to the core phonological deficit alone. Wolf and Bowers, the authors of the so-called double-deficit hypothesis (1999), give an unequivocally negative answer. They propose the second factor – naming speed – as making another major contribution to skilled reading that is relatively independent from phonological awareness. Naming speed, typically measured by the Rapid Automatized Naming (RAN) task, is the ability for speeded naming of large sequences of simple stimuli aloud. According to the double-deficit hypothesis, the most severe cases of developmental dyslexia occur when both phonological awareness and naming speed are impaired at the same time.

In brief, the key attributes of the double-deficit hypothesis are:

- the existence of a cognitive deficit that is different from the core phonological deficit – a naming speed deficit – that is directly responsible for difficulties in reading development (how exactly and to what extent naming speed is responsible for these difficulties is a different question, partially addressed by this work);

- the relative independence of the naming speed deficit from the phonological awareness deficit (implying a substantial difference between the two in their underlying mechanisms);
- a greater negative effect on reading outcomes when both deficits are combined in the same person.

This section provides a brief summary of the research evidence on the last point – the increasingly negative impact on reading resulting from the double-deficit. Other issues will be briefly considered in separate sections of the literature review below and in a meta-analysis that follows. These other issues include those related to operationally defining the naming speed deficit, to controversies surrounding the use of different versions of the RAN task, as well as the differential cognitive nature and predictive power of symbolic and non-symbolic RAN sub-tasks with respect to different aspects of reading performance under different testing conditions (research design, participants' age, language, reading abilities and experience, etc.).

The immediate question of concern is whether a core phonological awareness deficit combined with a naming speed deficit causes greater reading-related problems than either alone. Empirical research findings tend to support this idea. Lovett, Steinbach, and Frijters (2000) documented the most severe cases of developmental dyslexia in those of their participants who were classified as having both deficits in question. According to Manis, Doi, and Bhadha (2000), clearly noticeable difficulties on a wide range of reading tasks were observed in a subgroup of second graders diagnosed with the double deficit, but not in groups with only a single deficit. In a subsequent study of 251 Spanish-speaking young learners of English (kindergarten – grade 2), Manis, Lindsey, and Bailey (2004) demonstrated that both factors (phonological awareness and naming speed) underlying reading disabilities in monolingual children (e.g., phonological awareness and RAN) may be equally important for understanding difficulties in learning to read in a *second* language. Among other studies reporting findings generally in support of the double-deficit hypothesis were Berninger et al. (1995), Berninger, Abbott, Thomson, and Raskind (2001), Biddle (1996), Krug (1996), Meyer, Wood, Hart, and Felton (1998), Neuhaus and Swank (2002), and Petterson (2001) – see Wolf et al. (2000) for a review.

To summarize, the major idea here is that two deficits, even if each alone does not cause serious problems with reading per se, can together create a severe overload of the reading-related cognition system, which is difficult to compensate for. Even though this logically attractive idea has been backed up by an extensive body of empirical evidence, one might consider some alternative explanations. For example, Schatschneider, Carlson, Francis, Foorman, and Fletcher (2002) examined a sample of 362 first and second graders with different subtypes of developmental dyslexia. They argued that severity of reading problems in the double-deficit subgroup could be actually explained in terms of a statistical artifact. Results of their study, indeed, demonstrated that when measures of phonological awareness and naming speed are positively correlated (which is almost always the case – even if this correlation is not significant) participants identified as belonging in a double-deficit subgroup inevitably represent worse performers on either measure alone and consequently, poorer reading outcomes. Schatschneider et al. (2002)

suggested employing a pair-matched design to potentially overcome this particular shortcoming in further research.

Nevertheless, possible reservations aside, many researchers acknowledge that measures of naming speed and measures of phonological awareness, independent or not, are among the strongest correlates of reading achievements, especially in the early grades. Kirby and Parrila (1999) go further and add the factor of single letter recognition to the list of most frequent significant predictors of reading outcomes. Badian (1997) observed the worst reading performance in 90 six to ten-year-olds diagnosed with both deficits, or even three, if one also counts a deficit in orthographic skills. McBride-Chang and Manis (1996) observed an analogous pattern of results supporting the double-deficit hypothesis in Chinese readers of approximately the same age range. McBride-Chang, Shu, Zhou, Wat, and Wagner (2003) later on also emphasized the importance of so-called morphological awareness for successful acquisition of reading in Chinese. In Japanese, both factors combined proved to be the best predictors of oral reading fluency in first graders (Kobayashi, 2001).

The importance of phonological awareness and naming was also demonstrated in studies designed to evaluate the effectiveness of different instructional interventions in reading. For example, Harn (2000) reported that kindergarten students with the double-deficit were less responsive to any of three seven-month programs of special instructions in reading. Also, among the three, the most systematic program (the one that systematically addressed skills in each impaired domain and that used effective design principles) was also the most successful across the groups. Similarly, instructional interventions in reading that selectively targeted different aspects of reading difficulties tended to be unequally efficient in students representing different subtypes of developmental dyslexia (e.g., Lovett et al. 2004).

There have been other reports regarding the joint effect of both deficits in people with severely impaired reading. Nopola-Hemmi, Myllyluoma, Voutilainen, Leinonen, Kere, and Ahonen (2002) analyzed the neurological data of 24 dyslexics from a three-generation Finnish family. They established that in all of them the phonological awareness deficit was accompanied by a naming speed deficit, as well as by problems with short-term verbal memory. Cluster analysis of several subtypes of developmental dyslexia, undertaken by Fletcher et al. (1997), revealed that in four out of five such subtypes phonological awareness was the major common factor coinciding with either slower naming speed or somewhat impaired verbal short-term memory. In another piece of research, Tiu, Wadsworth, Olson, and DeFries (2004) investigated genetic and environmental factors in reading disabilities on a large sample of twins drawn from the Colorado Learning Disabilities Research Center database. They concluded that both phonological awareness and naming speed contributed to impairment in reading and both should therefore be included into any comprehensive model of developmental dyslexia, alongside a measure of IQ.

As impressive as it is, the evidence in favor of the double-deficit hypothesis is not unassailable. Some researchers have presented findings that contradict the double-deficit explanation. For example, Ackerman, Holloway, Youngdahl and Dykman (2001) did not find any markedly impaired reading performance in their sample of dyslexics with a double-deficit profile compared to subgroups with a single deficit. Moreover, all poor readers, in addition to having compromised phonological awareness and naming speed skill, also demonstrated problems with orthographic tasks, attention, arithmetic, and nearly all WISC-III (Wechsler Intelligence Scale for Children, the Third Edition – e. g., Watkins, Kush, & Glutting, 1997) subtasks. This led the authors to propose a "multiple causality theory" of developmental dyslexia as being more plausible than the double-deficit hypothesis. Other, less conclusive, studies have reported patterns of results that were not in complete accord with the regularities expected within the double-deficit framework. These results varied across different dyslexia subtypes depending on the particular skills addressed, assessment tools used, and so on (e.g., Pennington, Cardoso-Martins, Green, & Lefly, 2001; Sunseth & Bowers, 2002).

In summary, putting aside for now the issue of their interdependence, phonological awareness deficits and the naming speed deficits are broadly acknowledged to be among the major cognitive factors underlying developmental dyslexia. It is time now to consider naming speed more closely – that is, how it is operationalized and measured in applied research, and what findings are obtained under what circumstances.

Rapid Automatized Naming (RAN) task and reading

Naming speed is empirically measured by performance on the Rapid Automatized Naming (RAN) task. Like phonological awareness, naming speed also has rather a rich research history. Originally proposed by Geschwind (1965) and then tested by Denckla (1972), the idea is that cognitive factors involved in attaching a verbal label to an abstract visual category (in that case – basic colors) might well predict future reading performance. This idea eventually resulted in the design of the original version of the RAN task (Denckla & Rudel, 1976b). This test has now become the prototype for many subsequent versions broadly used as naming speed assessment tools in research fields of cognitive development, education and educational psychology and has been included in some standard screening procedures for early diagnoses of reading disorders (e. g., Fawcett & Nicolson, 1994a; Mitchell, 2001; Nicolson & Fawcett, 1996).

The typical RAN task is composed of four sub-tasks in which participants are required to name aloud as quickly as possible a large sequence of either symbolic (letters, numbers) or non-symbolic (colors, pictures of common objects) stimuli presented in a 5 x 10 (five rows of ten characters per row) display, either on a white paper sheet or on a computer screen. Since the initial introduction of the RAN task, numerous studies have demonstrated a strong connection between people's performance on the different types, versions, and subtasks and their reading abilities. In brief – the faster RAN task performance, the more favorable prognosis for reading development.

During the past three decades, the connection between RAN task performance and reading has been empirically studied cross-sectionally, longitudinally, and in cross-language studies. Most accounts have provided strong evidence in support of the double-deficit hypothesis (see Denckla & Cutting, 1999; Wolf & Bowers, 1999; Wolf et al., 2000, for reviews). Cross-sectional studies have addressed the question how well RAN task performance distinguishes developmental dyslexia from other learning disabilities that are not reading-specific. Longitudinal studies have used RAN task performance in earlier stages of cognitive development as a predictor of reading outcomes later on in different age groups. Finally, cross-language studies have looked at the relationships between measures of RAN task performance and reading fluency in different languages.

Some of the most relevant and illustrative examples of cross-sectional and longitudinal studies involving RAN are the following. These all show that individuals with dyslexia, and poor readers in general, perform much worse on practically all RAN and RAN-like subtasks than do age-matched average readers and, importantly, even than people with non-reading-specific learning disabilities (e. g., Berninger et al., 1995; DeJong & Van der Leij, 2003; Denckla & Rudel, 1976a, 1976b; Etmanskie, 1999; Fawcett & Nicolson, 1994b; Felton, Naylor, & Wood, 1990). They also show that naming speed, as measured by different versions of the RAN task, is strongly associated with different aspects of reading skills across age groups and can be useful in predicting success of instructional intervention in reading (e. g., Aarnoutse, van Leeuwe, & Verhoeven, 2005; Cronin & Carver, 1998; Meyer et al., 1998; Scarborough, 1998b; Sprugevica, 2003; Sprugevica & Hoien, 2004; Uhry, 2002; Vellutino, Scanlon, & Sipay 1997; Wimmer, Mayringer, & Landerl, 2000).

In particular, Ackerman and Dykman (1993) tested a sample of 7–12 year-olds. They found that RAN task performance distinguished dyslexics from both slower learners and those diagnosed with Attention Deficit Disorder (ADD). According to Denckla (1972), dyslexic children are more than one standard deviation below kindergarten norm on naming colors. Similarly, Blachman (1984) found RAN performance to be predictive of first grade reading outcomes, and Badian (1993, 1994) showed that RAN performance on all subtests – colors, objects, digits and letters – correlates with later reading achievements. In addition, it is worth noting again that, according to double deficit hypothesis of Wolf and Bowers (1999), naming speed contributes to reading not only significantly, but also independently from phonological awareness. Several studies have examined the RAN task's predictive power when the factor of phonological awareness was first accounted for. Cornwall (1992) reported

RAN's unique share in variance of reading among other factors such as phonological awareness and verbal memory. Felton et al. (1990) conducted a study, in which RAN task performance proved to be one of best individual predictors of reading abilities, clearly differentiating impaired from normal readers. According to Bowers and Kennedy (1993), digit-naming speed makes contribution of a unique portion of variance in reading speed.

The list of examples goes on, although not all of the research unequivocally demonstrates that RAN task performance is uniquely linked to the development and manifestation of reading skills. Some such concerns will be considered briefly later on in this and following sections.

One interesting source of variation in the relationship between RAN task performance and reading skill is the language in which the tests are given. The more transparent the language grapheme-phoneme structure is (i.e., the more word pronunciation directly matches spelling), the more closely RAN task performance predicts reading. This kind of regularity has been observed and documented in several languages. These include studies of Finnish (e. g., Holopainen, Ahonen, & Lyytinen, 2002; Korhonen, 1995; Lepola, Poskiparta, Laakkonen, & Niemi, 2005), of Dutch (e. g., de Jong & Van der Leij, 2003; de Jong & Vrielink, 2004; Van den Bos, 1998; van den Bos, Zijlstra & van den Broeck, 2003, although Patel, Snowling & de Jong, 2004, reported no particular difference between English and Dutch in the relative predictive power of phonological awareness and naming speed measures), of German (e. g., Naslund & Schneider, 1991; Landerl, 2001, 2003; Mayringer & Wimmer, 2000; Wimmer, 1993; Wimmer et al., 2000, although Wimmer, Mayringer, and Landerl (1998) acknowledged the leading role of phonological awareness deficits in comparison with the naming speed deficits in reading impairments in German), and of Spanish (e. g., Clinton, 2001; Novoa, 1988, although Manis et al. 2004, suggested that in bilinguals, some cognitive factors, like phonological awareness, function across languages, even if others, like naming speed appear to be stronger reading correlates within a given individual language). There have also been studies of Russian, by Chandarina (2003), for example, who showed that whereas phonological awareness remained the strongest predictor of basic reading skills in English, naming speed played that role for Russian in Russian-English bilinguals in first and second graders.

As Wolf, O'Rourke, Gidney, Lovett, Cirino, and Morris (2002), have emphasized, the greater orthographic regularity in more transparent languages reduces the demand for phonological analysis. Almost echoing this remark, Landerl (2003) suggested that although a phonological awareness deficit still could be the core deficit in German poor readers, the high consistency of German orthography might just make it easier for learners to overcome the problem. To complete the picture, there is also the notion that phonological skills, especially in the more transparent languages, could be a function of literacy exposure developing as a result of experience in reading (Mann, & Wimmer, 2002). Under such circumstances, the cognitive factor of naming speed, as measured by RAN task performance, overtakes phonological awareness as a leading predictor of reading outcomes. This observation may also be important as an argument in favor of the relatively independent nature of naming speed within the set of cognitive factors contributing to successful reading acquisition.

However, some researchers have recently expressed caution when interpreting RAN-related findings. As noted earlier, one possible way to explain the high severity of dyslexia symptoms in people with a double-deficit is in terms of a statistical artifact (Schatschneider et al., 2002) that can mask the individual contribution of each factor to overall reading impairment. In addition, the central assumption of the double-deficit hypothesis, that naming speed is independent from the cognitive processes responsible for phonological awareness, has been repeatedly questioned in the literature. In several studies, phonological awareness and naming speed came out to be correlated significantly above chance or showed other signs of interdependence (e.g., Chin, 2001; Neuhaus, 2000; Neuhaus & Swank, 2002; Torgesen & Burgess, 1998; Wagner, Torgesen, & Rashotte, 1994). There is not complete agreement either on the RAN task's capacity to distinguish among particular forms of learning and reading disabilities (e.g., Waber, Wolf, Forbes, & Weiler, 2000, who found the RAN task to be capable of detecting learning disabilities in general, and not just reading-specific disabilities). There are also several studies whose results indicate the RAN task to be related not specifically to reading, but also to early competency in mathematics (e. g., Chiappe, 2005; Mazzocco & Thompson, 2005; Roditi, 1988).

Finally, not all longitudinal and special population studies have yielded equally conclusive evidence regarding the predictive power of the RAN task. For example, Bishop (2003) found a model combining measures of letter identification, phonological awareness, and naming speed to be the best of five tested in her study predictive models of early reading development, whereas Dyer, MacSweeny, Szczerbinski, Green, and Campbell (2003) reported no direct relationship between RAN task performance and a level of reading achievements. Holland, McIntosh, and Huffman (2004) emphasized the role of orthographic processing rather than either phonology or naming speed in explaining their participants' decoding skills. See also Torgesen, Wagner, Rashotte, Burgess, and Hecht (1997), James (1996), and Kirby, Martinussen, and Beggs (1996) for some other predictive or path-analysis models involving RAN. Yet, other studies appear to have design problems that prevent separating reading difficulties from other co-occurring developmental problems and pinpointing their sources, making it complicated to draw firm interpretations of findings (see Savage, 2004, for review).

Notwithstanding these controversies, research to date has rather convincingly demonstrated naming speed, as measured by performance on the RAN task, to be one of two major factors underlying development of reading. The overall impression from reviews of relevant research is that the empirical evidence predominantly supports the existence (well beyond chance) of association between RAN task performance and the measures of reading skills. The strength of this association, however, varies substantially across studies. Here are a few examples from studies mentioned in this section. Individual coefficients of correlation range from about virtually negligible (Bowers & Swanson, 1991 – $r = 0.02$ – between digit naming and a measure of decoding skills or Chandarina, 2003 – $r = 0.03$ – between letter naming and vocabulary knowledge) to extraordinary high (e.g., Deutsch, Dougherty, Bammer, Siok, Gabrieli, & Wandell, 2005 – $r = 0.87$ or Berninger et al., 2001 – $r = 0.71$ – both between letter naming and measures of single word reading efficiency). In other words, the RAN-to-reading correlation is heterogeneous and its degree presumably depends on many factors including, among others, particular measures of either naming speed or reading skills, participants' age, language and degree of proficiency/impairment in reading.

A meta-analysis (which is a part of the present project) was designed to explore, based on a much larger number of coefficients of correlations, the influence of those factors on the magnitude of association between RAN task performance and reading. Its methodology, scope and results are reported in Chapter 6.

There remain, however, many important questions about the cognitive nature of performance on the RAN task that underlies its association to reading skill acquisition.

Cognitive nature of RAN

Overlap between the task demands of the RAN task and reading

One of the most pressing issues is to understand how representative RAN performance is of cognitive mechanisms of reading. After all, if RAN is just a simplistic or reduced version of reading, its use in research risks being circular (reading predicts reading). The answer to the following question, then, is important from both theoretical and applied perspectives: Does RAN task performance predict reading development or does it simply reflect (follow) it? The first option implies that a better understanding of the major cognitive processes underlying performance of the RAN task – a search for answers to the *"what makes it work?"* question – would be useful for shedding light on reading itself. If however, RAN is merely an early version of reading, then a search for answers to the *"when does it work better?"* question, would be useful for learning about practical usage of the test.

One possible way to address this question about the relationship between RAN and reading is through a meta-analysis of empirical research that would consider whether the strength of the RAN-reading association increases with age (as a consequence of experience with exposure to printed text and practice in its processing) consistently across different studies. Such an attempt is made in the meta-analysis that follows, which also explores several other very important issues, such as: (1) To which aspects of reading (viewed as a complex skill involving variable levels of expertise – from individual character recognition and grapheme decoding to entire text comprehension) is RAN most closely linked? and (2) How successful a predictor of reading skills is RAN across a group of participants differing in their reading and learning abilities?

If RAN is nothing more than a “proto-reading” activity (reading without text, but with separate stimuli which do not require assembling into meaning-producing patterns), then it still may prove useful for reading acquisition prognosis in young children, whose exposure to actual reading tasks has not yet begun or is extremely limited. At the same time, if the goal in using RAN is to understand the cognitive nature of reading in a way that will lead to improved development through proper training and instruction, then the concern about the amount and specificity of overlap between the demand characteristics of RAN and reading becomes extremely important. Without a full understanding of what cognitive resources the RAN task calls upon, one cannot know what aspects of reading it addresses. Considering how fragmented and controversial current knowledge about RAN is, it becomes all the more important to study the RAN test itself and its relationship to reading.

Dependence/Independence of RAN task performance in relation to phonological awareness

Many researchers feel it necessary to emphasize how closely RAN approximates real reading. Consider, for example: "...naming speed (particularly serial naming speed) provides an early, simpler approximation of the reading process (see Blachman, 1984), with reading's similar combination of rapid, serial processing and integration of attentional, perceptual, contextual, lexical, and motoric sub-processes [...although the] demands in reading for high-level comprehension processes go far beyond those in naming speed" (Wolf et al., 2000, p. 393). Also Stringer, et al. (2004, p. 892) wrote that "...RAN is an apparent analogue of the reading process." Practically everyone interested in RAN agrees that each and every one of its sub-tasks has a lot in common with reading, which presumably makes RAN such a successful diagnostic tool. As for understanding *how* it works, it is no less important to realize and consider the differences between RAN and reading.

One possibly vital difference between RAN and reading may have to do with how the role of phonological processing in each is understood. RAN clearly involves accessing the phonological code. However, according to Wolf and Bowers (1999) in their presentation of the double-deficit hypothesis, the additional demand of rapid serial processing across all subcomponents present in RAN makes it clearly more than just a phonological task. From this perspective, if one accepts a phonology-based explanation for RAN task performance, then RAN cannot be equivalent to reading: at the very least, components responsible for integrating text into meaning seem to be underrepresented in such model. On the other hand, RAN may involve not only phonological processing but something else that goes quite far beyond phonological processing, something that adds a unique contribution to the prediction of reading outcomes. If so, this would bring the RAN task closer to reading. This, however, would still leave open the question of what those components are based upon.

The whole debate over RAN's dependence on or independence from phonological awareness is far from being resolved. Wolf and Bowers (1999) made this issue one of the focal points of their double-deficit hypothesis. They emphasized that a naming speed deficit (as measured by RAN performance) is different from a phonological awareness deficit, and that the simultaneous presence of both kinds of deficits leads to the most severe cases of developmental dyslexia. For them, the RAN task provides a measure of naming speed only, a position which many tend to agree with (e.g., Doi, 1996; Pennington et al. 2001; etc.). Others (e.g., Chin, 2001; Savage et al., 2005a, 2005b; Sidhu, 2001; Torgesen & Burgess, 1998; Wagner & Torgesen, 1987) continue to insist that RAN performance is largely based on phonological processes, and they present empirical evidence to argue against the double deficit approach. It is quite easy, however, to find studies that do not concern themselves much with the issue, but rather enlist the RAN task as a phonological assessment tool – either of coding or decoding (e.g., Buehler, 2001; Foy & Mann, 2003; Frederickson, Frith, & Reason, 1997; Manley, 1993), thus practically equating it with some kind of a measure of phonological processing (e.g., the Comprehensive Test of Phonological Processing (CTOPP) in Buehler, 2001 and Mitchell, 2001).

Another suggestion has recently appeared in the literature – that it is not phonological, but rather orthographic processing that is reflected in RAN task performance and that links it to reading. In particular, Conrad (2003) found that children performing more slowly on the RAN task also lacked orthographic knowledge and had problems with processing individual letters presented in sequences. In addition, the author also observed some improvement in naming speed of individual letters as a result of special training in letter identification, but only when accompanied by exercises in orthographic pattern recognition. Using data from 79 elementary school students to model by means of path-analysis the relationships among many variables associated with early literacy – variables such as processing speed, phonological awareness, articulation rate, memory span, RAN, orthographic knowledge, and word reading – Cutting and Denckla (2001) found that RAN and orthographic skills were strongly related, though indirectly through processing speed. A very similar pattern involving an indirect link from RAN to word decoding through phonological and orthographic factors was observed in another path-analysis by Holland et al. (2004). Golden (1997) reported that RAN, understood as a measure of speed of access to individual letter codes, was correlated with several subtests of a newly introduced battery of orthographic awareness measures. Hultquist (1996) simply named RAN as a measure of orthographic processing. Bowers and Wolf (1993) provided a similar explanation within the framework of the double-deficit hypothesis by suggesting that naming speed in symbolic RAN subtasks (letter naming) "…may reflect precise timing mechanisms necessary to the development of orthographic codes and to their integration with phonological codes…" (p. 69; see also Wolf et al., 2000).

Regardless of how much overlap may exist in the mechanisms responsible between naming speed, phonological awareness, and orthographic processing these factors would hardly constitute the complete set of cognitive competencies necessary and sufficient for successful reading acquisition. Each factor also has unique features that could enable it to be an independent predictor of reading ability. This is especially true for those RAN subtasks that use non-symbolic stimuli (colors, objects), where performance is even less explicable in terms of orthographic processing than it is in terms of phonological awareness.

Different types of stimuli used in the RAN task

The original version of the RAN test included four different sub-tasks – naming objects, colors, letters, and digits – all aimed toward the same goal of diagnosing reading problems. The initial hypothesis linking naming speed and development of reading skills was generated for color naming (Geschwind, 1965), and was first tested on symbolic and non-symbolic stimuli alike without a clear distinction being made between these two categories (Denckla, 1972; Denckla & Rudel, 1974, 1976a, 1976b). Over time, more and more researchers came to believe that only the symbolic or, "alphanumeric" RAN subtasks (i.e., letter and digit naming) possess true predictive power with respect to later reading outcomes (e. g., Johnson-Davis, 1993; Joy, 2003; Manis & Doi, 1995; van Daal & van der Leij, 1999;Young, 1993, and especially, more recently Savage & Frederickson, 2004; Stringer et al., 2004, among many others). It is noteworthy that van den Bos, Zijlstra, and van den Broeck (2003) simply called symbolic (alphanumeric) RAN subtasks "...superior predictors of word reading speed..." (p. 407). This historical development gives rise to the following question: Do different versions of the RAN task (e.g., symbolic, non-symbolic) have different predictive value for reading performance outcomes, and if so, why and what does it reveal about reading and about RAN tasks? As indicated above, results of recent studies suggest that symbolic and non-symbolic RAN tasks do differ.

Differences between symbolic and non-symbolic RAN subtasks appear to vary across different age groups. In older populations non-symbolic RAN is only weakly associated with reading outcomes, whereas symbolic RAN retains or even grows in predictive power with age of the readers (e. g., van den Bos et al. 2002; Wood & Felton, 1994). This was one of the findings of the present research as will be seen in Chapters 3-5 (results were reported in Borokhovski, Segalowitz, & Lacroix, 2004; 2005). In contrast, in younger children (in preschoolers, in particular) the association between non-symbolic RAN and reading is quite strong and well documented (e. g., Badian, 1994; Blachman, 1984; Fawcett & Nicolson, 1994b, Wolf, Bally, & Morris, 1986; Wolf, Pfeil, Lotz, & Biddle, 1994). It is especially true for children in which dyslexia symptoms coincide with Attention Deficit Hyperactivity Disorder – ADHD (e. g., Martinussen, Frijters, & Tannock, 1998; Rucklidge & Tannock, 2002; Tannock, Martinussen, & Frijters, 2000).

There are also indications that the different RAN subtasks yield *similar* patterns in adults with reading impairments (e. g., Hutchens, 1989; Ransby & Swanson, 2003; Schmidt, 2003; Walker, 2002). Taken together, this pattern of results is suggestive of a practice-dependence effect to explain the difference between symbolic and non-symbolic RAN subtasks, though not all the evidence fits such an explanation equally well. For example, there are also indications that with increasing age all of the RAN tasks become less strongly associated with reading ability. Some studies have either found very little or no support at all for a symbolic versus non-symbolic RAN-reading connection (e.g., Chiappe, Stanovich, & Siegel, 1997; Meyer et al. 1998, Vukovic, Wilson, & Nash, 2004), whereas others have reported equally strong symbolic and non-symbolic RAN-reading associations. For example, Howe, Arnell, Klein, Joanisse, and Tannock (2006) found such a pattern when they tested a standard and a computerized version of the RAN tasks on a representative sample of university students with no apparent reading difficulties. Similarly, Hutchens (1988) demonstrated that naming speed deficits as measured by different versions of RAN persisted in troubled college level readers. In other words, there is low consistency in observations of how symbolic and non-symbolic RAN subtypes relate to reading across age groups and test conditions. The same could be said about specific reading skills; it seems that different RAN tasks vary in terms of how strongly they are associated with reading.

A meta-analysis reported below will pay special attention to this issue. Here are just a few examples from some already mentioned sources. Badian (1993) found letter naming to be more strongly associated to word recognition and object naming – to reading comprehension. Van den Bos et al. (2003) emphasized the prominent role of letter and digit naming in predicting reading performance and word reading speed, in particular. Young and Bowers (1995) named both symbolic RAN subtypes as the best predictors of success in word identification tasks (both – speed and accuracy), which also seems to mediate their connection (if any) to reading comprehension (Spring & Davis, 1988; Wolf, 1991). According to Wolf and Obregon (1992), object naming is linked to comprehension more than other RAN subtasks, whereas in a study by Wolf et al. (2002) the correlation between letter naming and a word identification task was just marginally higher than between letter naming and a passage comprehension measure.

All of the above underlines the question regarding to what extent the mechanisms responsible for RAN performance overlap with those of reading, given that there is only a limited consistency between RAN and reading across the different subtypes of RAN tasks. Perhaps the different RAN subtasks, because they use different stimuli, differ in the underlying cognitive mechanisms they draw upon. Such a possibility is worth considering, though even if confirmed, would not necessarily mean there are no common cognitive foundations for naming speed phenomena across different RAN subtasks.

Two more points merit consideration regarding the relationship of RAN to reading. First, there are neurological data showing a great deal of resemblance in patterns of brain activation (areas and networks involved) in reading and during RAN task performance across its different subtasks using both symbolic and non-symbolic stimuli (e. g., Breznitz, 2005; Deutsch et al., 2005; Dougherty, Bammer, Siok, Gabrieli, & Wandell, 2005; McCrory, Mechelli, Frith, & Price, 2005; Witt, 2004). Results by Misra, Katzir, Wolf, Poldrack, and Russell (2004) indicate that in addition to activation in neural areas associated with eye movement control, as might be expected, performance on both object and letter naming also involved activation of structures typically implicated in attention and reading tasks, especially in the case of letter naming.

Second, in several cases when the RAN task was modified by, for example, presenting stimuli discretely, that is one-by-one in rapid succession, the character of the RAN-reading association also changed somewhat (e. g., Bowers & Swanson, 1991; Pennington et al., 2001; Wolf, 1986; and especially Wolff, Michel, & Ovrut, 1990). In Wolff et al. (1990), for instance, it was the number of errors in the rapid serial presentation version of RAN that was most closely related to reading, whereas in the standard (simultaneous matrix-like) presentation version the major correlate of reading was naming time, as usual. Swanson (1989) and Stanovich (1981) also reported that performance on the discrete RAN showed lesser potential of distinguishing between poor and good readers (see Denckla & Cutting, 1999 for a summary on the issue).

The role attention and automaticity-related factors may play in RAN task performance

Finally and most importantly, there is the issue of what cognitive mechanisms lie at the core of RAN task performance. This issue is considered in the section below by addressing the dichotomy of automatic and attention-based processing in naming. The complexity of the task demands in RAN – the need to perform a series of cognitive actions ranging from stimulus recognition to name articulation in a fast, consistent, and coordinated manner – is comparable to the complexity of reading itself (especially for younger children just learning to read). It is unlikely, therefore, that some single universal mechanism will be responsible for making RAN work the way it does. For this reason, it will be desirable to search for possibly several cognitive components that tie together the relationship between RAN and reading.

The explanation connecting poor RAN task performance to difficulties in reading, offered within the framework of Wolf and Bowers' (1999) double-deficit hypothesis, is straightforward. A naming speed deficit and a phonological awareness deficit are believed to be two major and relatively independent factors responsible for reading disabilities of various kinds and degrees of severity. At the core of the naming speed deficit lies a lack of automaticity in linking symbols (the printed word) to names (and the mental representation of the meaning associated with the name). RAN task performance is assumed to measure the ability to link symbols to names and, as the very name of the

RAN task unambiguously suggests, to measure how *automatic* that link is.

Sometimes, authors make this point about automaticity as explicitly (literally) as it is done in the test name. Kuhara-Kojima, Hatano, Saito, and Haebara (1996) call RAN a measure of automaticity of lexical access. Similarly, Roditi (1988) refers to different versions of RAN as tests of naming automaticity. Hutchens (1989) described different RAN tasks as measures of automaticity of word retrieval. Williams (2001) sees automatization of visual-verbal processing as the necessary condition for enhancing naming speed through optometric vision therapy. The term "automaticity" appears among the key concepts that determine RAVE-O (Retrieval, Automaticity, Vocabulary-Elaboration-Orthography), a fluency-based intervention program, designed specifically to overcome the naming speed deficit (Shiffler, 2004; Wolf, 1999). The description of RAN given by Swanson (1989) emphasizes the importance of being able to automatize the processing of visual information and name retrieval, as well as, ability to purge possible interference of each previous name in order to get ready for the next one. Finally, one of the authors of the double-deficit hypothesis perceives a possible link between automaticity of naming visual stimuli (in RAN) and automaticity in reading comprehension (Bowers, 1989).

In other cases, authors have implicated automaticity in RAN performance only indirectly, that is, through reference to elevated demands for speeded response and to the time sensitive nature of the RAN task. For example, Wolf et al. (2000) described the majority of processes involved in RAN performance (e.g., stimulus recognition, meaning activation and memory retrieval, attachment of the proper speech label, articulation) as being dependent on high processing speed and thus requiring some level of automatization for their successful implementation.

Fluent performance on any task (whether reading or not) is most often presumed to be automatic, in other words, carried out rapidly, efficiently and protected from interference. The classic work of Laberge and Samuels (1974) explained reading fluency in terms of automatic word-identification achieved through practice (Rayner et al., 2001). Such automaticity is understood to result from a high level of exposure to and great familiarity with specific words, such as that gained primarily (if not exclusively) through a great deal of practice in reading. Bowers and Ishaik (2003) argue that RAN should be perceived as associated not only with some initial (that is, cognitive) fluency, but also with fluency gained by means of practice. This statement itself distinguishes, by implication at least, the existence of two types of automaticity, one related to the general cognitive fluency of the individual and one related to practice-based fluency. This distinction emphasizes the need to better understand which type of automaticity plays the leading role in RAN.

Automaticity in RAN task performance, rather than emerging as a function of practice with printed text, appears instead to be related to trait characteristics of the readers themselves. This kind of automaticity presumably reflects some characteristic of the organization of cognitive processes, namely, how fast and efficiently one can put together the appropriate operations to perform successfully upon a long sequence of relatively unpracticed and unrelated stimuli (i.e., how fast and through what cognitive mechanisms the level of automatization in any type of complex skills could be achieved).

A similar understanding of automaticity is found in the framework of the dual-task research, in which researchers have claimed that dyslexics are held back in their development of reading skill not just because they lack automaticity in word reading and spelling, but because they also have an impaired ability to perform any task automatically (Fawcett & Nicolson, 1992, 1995; Nicolson & Fawcett, 2000). In a series of specially designed studies using a dual-task paradigm, in which participants performed motor or visual tasks while reading, they observed that dyslexics experienced difficulties with basic, presumably automatic, actions in these domains, as well. This raises the question, then, of how the automaticity presumed to underlie RAN task performance should be understood. To address this question experimentally, as intended in the present study, the construct of "automaticity" needs to be carefully operationalized.

Ever since the idea of automaticity was first introduced to describe cognitive processes not requiring attentional executive control (Anderson, 1983; Kahneman, 1973; Schneider & Shiffrin, 1977), it has become one of the central concepts in the cognitive psychology literature. Automaticity is broadly recognized to be critically important for understanding the nature of skill acquisition, regardless of the particular area of expertise (for example, see Segalowitz & Hulstijn, 2005, for a review with implications for second language learning). Recently, Moors and De Houwer (2006) provided a very detailed and thorough review of different theoretical accounts for automaticity.

Usually, automaticity is described in terms of the rapidity of responses, their effortlessness, the non-involvement of conscious control and the ballistic (unstoppable, or difficult if not impossible to interrupt) nature of responses. Although these distinctive characteristics of automaticity have been emphasized in various conceptual and empirically oriented definitions, it is now clear that automaticity cannot be reduced to a simple combination of “key-features”. Each feature can be separately operationalized and, in principle, they may play independent and substantial roles in RAN task performance. In the present study, operational definitions of automaticity are based on the following:

(1) Neely's (1977) notion of the ballistic (unstoppable or protected from interference) character of an unfolding act as operationally defined in his primed lexical decision task, and

(2) A concept of automaticity as stable and efficient processing, that is, processing that is free of the relatively unstable components that usually accompany the early stages of skill acquisition, but that with practice become restructured to faster processing, as operationally defined by Segalowitz and Segalowitz (1993) in their use of the coefficient of variability to measure intra-individual variability in response time.

Research on the cognitive factors involved in the RAN task has not, however, focused solely on automatic mechanisms. The failure of people with reading impairments to meet the demands of speeded performance on naming tasks has frequently been explained in terms of an impaired hypothetical timing (either general or specific) mechanism. The double-deficit hypothesis pictures the naming speed deficit as a complex problem occurring not at any single stage of performance, but rather as a deficiency in coordinating through time all sub-processes together in some consistent and meaningful fashion. The very idea about "...the importance of timing within and across each of naming's multiple sub-processes ..." (Wolf et al., 2000, p. 393) raises the question how specific such time demands might be.

In theory, the naming speed deficit could reflect either some general problem with timing, even if it manifests itself in some specific domain like reading, or a much more specific timing deficit solely attributed to an individual sub-process or to a link between particular sub-processes. While there has been some empirical evidence to support the idea of a role for a general, low-level temporal processing deficit – that is, difficulties in processing rapidly presented simple units of information (Tallal, Miller, Jenkins, & Merzenich, 1997) – in early dyslexia and speech impairment this evidence has been met with some skepticism due to several failures to replicate major findings favoring the hypothesis (e.g., Marshall, Snowling, & Bailey, 2001; Share, Jorm, Maclean, & Matthews, 2002).

Young and Bowers (1995) and Wolf and Bowers (1999) hypothesized that some kind of precise timing mechanism connects orthographic and phonological processing (integrates orthographic and phonological codes) in RAN performance, resulting in speeded naming of presented stimuli. Because however, this hypothetical timing mechanism applies mainly to symbolic RAN subtasks (i.e., those using letters and digits), whereas quite a strong association between non-symbolic RAN and reading has also been well documented, this explanation emerges as vulnerable as the above-mentioned general temporal processing deficit account.

Savage (2004), in a careful analysis of this whole debate, concluded that "...dyslexics appear to have little difficulty rapidly processing information unless it requires a name or a higher order judgment..." (p. 305). He proposes a possible connection between rapid naming and phonological processing when performance requires a name. However, when performance requires a higher order judgment, controlled or attention-based processing becomes necessary. That is, in one case, rapid naming is associated with automatic processing whereas in the other it is related to attention-based processing.

Indeed, an alternative to the automaticity account of the RAN task performance has emerged in the empirical literature, especially recently. Attention (executive functions / controlled processes) has been more and more often brought to the picture to explain how cognition works when the RAN task is executed. Perhaps the most revealing statement in this regard has been made by one of authors of the original RAN task: "...Coming full circle to its origins, recent research suggests that RAN taps both visual-verbal (language domain) and processing speed (executive domain) contributions to reading..." (Denckla & Cutting, 1999, p. 29). Later, in the same work, there was another interesting suggestion about how implicit executive demands in both phonological awareness and RAN tasks may explain double-deficit symptoms in some cases in which reading disabilities are also accompanied by ADHD.

In general, the comorbidity of developmental dyslexia and ADHD poses a challenge of attributing observed symptoms to either disorder, but may also indicate some overlap in the underlying cognitive mechanisms. For example, echoing Denckla and Cutting (1999), Howe et al. (2006) hypothesized that impairment in rapid naming could result from some cognitive factor common to reading disabilities and ADHD, i.e., supporting the dual-route explanation for dyslexia in older populations. Ho, Chan, Leung, Lee, and Tsang (2005) found the cognitive profile of a comorbid (dyslexia and ADHD) group of children to closely resemble that of the dyslexics group only. According to Närhi and Ahonen (1995), such an overlap should not necessarily be attributed to an attentional deficit, because they found that problems in reading acquisition in the comorbid group were mostly due to factors found in the purely reading impaired group. Nevertheless, it is indicative of commonalities between attention and reading problems captured by RAN task performance. It is not accidental then that Tannock et al. (2000) reported a somewhat reversed but equally suggestive pattern of results. They observed slower performance on a color naming RAN subtask in a group of participants with ADHD and no reading disabilities. Other research by Rucklidge and Tannock (2002) looked into factors discriminating among groups with dyslexia alone, ADHD alone and both. They found that the two ADHD groups were slower on object naming, in addition to having poor behavioral inhibition and slow processing speed, whereas dyslexic participants had verbal working memory deficits and slower verbal retrieval speed. Only the comorbid group demonstrated slower naming of numbers and colors and overall slower reaction times. Brock (1995) also found that the presence of ADHD was associated with worsened reading comprehension outcomes and was associated with impaired performance on a digit naming RAN subtask.

Not all studies of the cognitive factors underlying reading and attention disorders have found patterns in RAN task performance to be the same in the two cases. For example, Raberger and Wimmer (2003) found poor performance on digit and color RAN subtasks was associated with reading deficiency, but not with ADHD. Likewise, some attempts to link poor reading skills and RAN task performance directly through attention based mechanisms have been inconclusive (e.g., Moores, Nicolson & Fawcett, 2003; Nigg, Hinshaw, Carte, & Treuting, 1998; Semrud et al., 2000; van der Sluis, de Jong, & van der Leij, 2004). Nevertheless, there continues to be interest in the possibility that attention-related factors underlie reading problems in general and possibly, RAN task performance in particular.

For example, Lacroix, Constantinescu, Cousineau, de Almeida, Segalowitz, & von Grünau, (2005) made an interesting attempt to tie together the issues of reading difficulties and attention using an RSVP (Rapid Serial Visual Presentation), or the attentional blink paradigm (Raymond, Shapiro, & Arnell, 1992; Shapiro, Arnell, & Raymond, 1997). In this paradigm participants are instructed to respond to each of two designated targets embedded among numerous distracters presented in a very rapid succession. The attentional blink here refers to inability to detect and respond to the second target when it appears too close in time to the correctly processed first one. The Lacroix et al. study yielded the somewhat surprising finding that the depth of attentional blink – measured as the period of time following a first target stimulus in which a second target stimulus cannot be attended to – appeared to be greater in normal readers than in their dyslexic counterparts. One possible explanation for this phenomenon, suggested by the authors, was that information processing in dyslexic subjects was shallower (more surface level processing of the meaning of the stimulus and hence faster), so that processing the first target stimulus did not tie up resources needed to process the second stimulus long enough to interfere. This idea introduced a new angle from which to view attention as a factor in reading – not as a resource available for speeding-up stimulus perception, but as a resource required for thorough information analysis and integration. When this resource is not available, performance that would have been disrupted by a thorough analysis of a recently seen stimulus will now not be disrupted. In Lacroix et al.'s study (2005), this revealed itself as a weaker attentional blink (compared to the normal reader control group).

There are other data, of a different type, implicating attention-based factors in RAN task performance. Poor visual attention was one of the factors worsening RAN task performance in kindergarteners (McBride-Chang & Ho, 2000). Similarly, a significant predictive role of visual attention in a letter naming RAN subtask in more than two hundred first graders was observed by Neuhaus and Swank (2002). In van der Sluis et al. (2004) participants' performance on the Trail Making test and object-naming RAN was strongly related. Very analogous findings of the present research – namely a series of multiple regression analyses showing a much higher contribution of several measures of attention, including the Trail Making, to RAN performance time than that of several measures of automaticity – will be reported below (Chapters 3-5, see also conference presentations in Borokhovski et al. 2004, 2005; Borokhovski, Segalowitz, Sokolovskaya, & Tapler, 2006).

One particularly interesting work was presented recently by Stringer et al. (2004). They reported strong correlations between RAN task performance on non-symbolic (colors) stimuli and several measures of attention including performance time on a Stroop interference task (Cohen & Servan-Schreiber, 1992), performance time on form B of the Trail Making Test (Reitan, 1955, 1958) of general attention, and a sentence span index of working memory (Gottardo, Stanovich, & Siegel, 1996; Daneman & Carpenter, 1980). The selection of attention-based variables was in no sense accidental, but rooted in authors' understanding of the specifics of activities involved in RAN performance. "...The performance of a serial task such as RAN will necessarily involve these classes of functions: attention must be directed to the correct spatial location of the first stimulus and its label activated in working memory, then attention must be shifted to the next stimulus, then the old response must be inhibited while the new response is activated…" (Stringer et al., 2004, p. 895). Compare this description with the one, mentioned earlier, by Swanson (1989): "… continuous list naming is a complex task that requires not only automaticity of name retrieval but also (1) the ability to automatically eliminate each previous name trace and prepare for processing the next, and (2) the ability to access the appropriate name code in the face of competing visual stimuli…" (abstract). From this review of the literature, one can see how the understanding of the RAN task has been gradually shifting away from automaticity towards the recognition of attention as a critical factor, making it all the more important to investigate what makes naming speed a good predictor of reading abilities.

Further support for the idea that attention-related factors may play an important role in connecting RAN task performance to reading is the evidence of the possible involvement of working memory in both RAN and reading (e.g., Bowers & Ishaik, 2003; Cui & Chen, 1998; Strattman, 2001). In addition, there are data (both experimental and neurological) suggesting some basic brain mechanisms responsible for memory (either working or short-term) are involved in rapid naming as well (e.g., Breznitz, 2005; Chincotta, Underwood, Ghani, Papadopoulou, & Wresinski, 1999; Fastenau, Shen, Dunn, Perkins, Hermann, & Austin, 2004; Kirby, et al., 1996; Witt, 2004, among many others). Interestingly, in a structural equation modeling analyses by Fastenau et al. (2004), for example, not only measures of rapid naming and working memory loaded on the same factor in a three-factor solution, but this factor was strongly related to reading performance. Also Wagner et al. (1994) found RAN and working memory to be strongly correlated. There are, however, many studies to the contrary, reporting no or weak relationships between the two. Among them, for example, are Savage et al. (2005a) and Ransby and Swanson (2003).

Brief summary

To summarize, the question about what cognitive factors are responsible for the association RAN task performance has with reading development, as Savage (2004) duly noted, is still very much open and requires more experimental input. The present study aims to address this question further. The research reported below includes three experimental studies and a meta-analysis addressing some aspects of this overarching question.

(1) Study 1 addresses what combination of cognitive factors underlies successful RAN task performance. Is it automaticity or attention, or do both make a substantial contribution to successful performance on the RAN task? (Chapter 3)

(2) Study 2 is designed to complement Study 1 by clarifying to what extent RAN task performance is sensitive to explicit manipulation of attention and to different types of stimuli – symbolic versus non-symbolic (Chapter 4).

(3) Based on the major findings of the first two studies, Study 3 is organized around the following research questions. Is there still a role for automaticity-based explanations of RAN performance, given that attention appears in the present studies to be an important factor determining naming speed phenomena? Which aspects of attention and to what extent do they contribute to successful RAN task performance? Do other factors, such as efficiency of lexical access and working memory capacity, play an important role in RAN task performance and does their contribution add substantially to

our understanding of the cognitive mechanisms of RAN task performance? (Chapter 5)

Finally, some selective features of the RAN-to-reading association and the particular conditions that strengthen or weaken that association are addressed by means of a meta-analysis of a representative sample of correlational data from the relevant empirical literature (Chapter 6).

CHAPTER 3: EXPERIMENTAL STUDY 1

Objectives and rationale

The principal focus of interest for this project – what combination of cognitive factors underlies successful RAN task performance – was articulated in the form of the question in the title of the thesis, “Explorations of the Rapid Automatized Naming (RAN) Task: What should the “A” in RAN stand for?" Study 1 was designed as the first step in addressing the issue. Is it (A)utomaticity (Rapid Automatic Naming) or (A)ttention (Rapid Attention-based Naming), or both that make a substantial contribution to successful performance in the RAN task? This general question can be broken down into the following set of more specific research questions:

1. Do individual differences in the degree of automatic information processing underlie individual differences in RAN task performance, where "automatic" is operationalized either as ballistic processing or as rapid and stable (and consequently more efficient) processing?
2. Do individual differences in the degree of attention control operationalized in terms of shift costs underlie individual differences in RAN task performance?
3. Are automatic and attention-based aspects of RAN task performance equally or differentially linked to reading performance?

Operational definitions of the concepts under consideration and selection of instruments

Four versions of the RAN task, all similar to the original version introduced by Denckla and Rudel in 1976, were prepared using a sequence of 50 letters, digits, colors or object pictures. In each case there were five stimuli used repeatedly. The version using letter and digit stimuli assessed the participants' ability to name stimuli related to reading (henceforth referred to as symbolic RAN stimuli). The versions using color patches or object pictures assessed general naming speed (i.e., non-symbolic RAN stimuli).

To address the major research questions under consideration, automaticity was operationalized in two different ways – in terms of ballistic processing and in terms of rapid, stable processing of reading-relevant stimuli. Attention was operationalized in terms of the cost in shifting between two different processing tasks with reading-relevant stimuli. These are now discussed in turn in greater detail.

Automaticity

There were two indices of a person's ability to process stimuli automatically. The first addressed the degree to which participants were capable of recognizing simple stimuli – letters and digits – in a ballistic (unstoppable) manner. The procedure used was based on a "primed decision" experimental paradigm (Favreau & Segalowitz, 1983; Neely, 1977). In this procedure, participants were given the task of judging whether a letter target was a vowel or a consonant, and whether a digit target was even or odd. Another stimulus preceded each target to which no overt response was required. This stimulus prepared – or *primed* – participants to be ready for a letter or digit as the subsequent target stimulus. The design of the task made it possible to determine if the prime had been processed in a ballistic manner or not.

Consider briefly the general idea behind the primed decision paradigm (see Favreau & Segalowitz, 1983, for a fuller discussion of the use of this technique). The letter prime stimulus in this study was the 5-letter string *ABCDE*, the digit prime stimulus was the 5-digit string *12345*, and the neutral prime was a string of five asterisks (*****). How exactly do primes influence participants' responses to the subsequent targets?

If the prime prepares participants for a letter target and a letter actually appears, then normally their response on that trial will be facilitated, that is, faster than if the prime had been neutral. If the prime wrongly prepares the participant, then the response will be interfered with, that is, slower than if the prime had been neutral. There are two factors that impact on how fast a participant's response will be – prime-target relatedness and prime-target expectancy. A prime and a target may be related (i.e., may belong to same category of digits or letters). A prime may, however, be unrelated to the subsequent target (e.g., prime *ABCDE* with target "7"), but nevertheless correctly signal its category through expectancy. This is possible if the participant has been given explicit instructions, with appropriate preliminary training, to expect a digit target after the letter prime and to expect a letter target after the digit prime.

Both relatedness and expectancy may result in facilitation or interference, depending on how much time separates the appearance of the prime and the target. In general, when the target is expected given the prime that preceded it, there will be facilitation and when it is unexpected (surprise trials in which the expectation is violated) there will be interference. However, expectation can result in facilitation or interference effects only when there is enough time for the individual to fully process the meaning of a prime and the expectations associated with it. When the interval is too short, and if there is automatic or ballistic initial recognition of the prime as a string of letters or digits due to a life of experience which differentiates the two categories very clearly, then the individual will initially be primed for a related stimulus, regardless of whether the instructions were to expect a related stimulus or not.

The more detailed description of all possible experimental conditions resulting from combining expectancy (expect a related target versus an unrelated target), time (long versus short prime-target interval) and letter, digit and neutral primes with letter versus digit targets can be found in Favreau and Segalowitz (1983) and Neely (1977). Here just the logic of inferring ballistic processing of the prime is explained as follows. Consider the condition where the participant is trained to expect an unrelated target (e.g., *12345* – B), and there is a short prime-target interval. On a surprise trial the participant will see a target that is related to the prime (e.g., *12345* – 4). This target is unexpected and so there should be interference and hence a slower response to it. However, because the interval is short, there is no time for the expectancy instructions to override the automatic recognition of the prime as digits and so there will be facilitation. By contrast, in conditions with a long prime-target interval, there will be interference because the target is unexpected, even though it is related to the prime on this surprise trial. The facilitation obtained in the short interval condition on surprise thus emerges as the evidence that the participant could not stop processing the prime in terms of how it was first recognized, i.e., automatically processes it in a ballistic manner.

The second measure of automaticity addressed the degree to which participants were able to process stimuli efficiently. The technique for this was derived from a line of research addressing efficiency in performance (initially in Segalowitz & Segalowitz, (1993) and subsequently in Segalowitz & Frenkiel-Fishman (2005), Segalowitz, Poulsen, & Segalowitz (1999), and Segalowitz, Segalowitz, & Wood (1998); see also

Wagenmakers & Brown, in press). It is based upon the idea of distinguishing between rapid task performance that is due simply to a speeding-up of all the underlying processing components and rapid task performance that is due to a restructured and more efficient deployment of underlying processing components. For details, see Segalowitz and Segalowitz (1993), and Segalowitz and Hulstijn (2005). In brief, the basic idea can be described as follows. Performance can *appear* to be automatic (very rapid) because all the underlying processing components responsible for the performance have become faster, even though the basic cognitive structure of the activity as a whole remains the same (this is called "speed-up" by Segalowitz and Segalowitz, 1993). Alternatively, performance can appear to be automatic because cognitive restructuring has occurred in which the slower components—those that tend to be highly variable in their time of execution and thus contribute lots of "noise" to the overall performance time—are now avoided or eliminated. This situation is referred to as "restructuring" by Segalowitz and Segalowitz (1993) because it involves a new, more efficient activity structure. To distinguish speed-up from restructuring Segalowitz and Segalowitz (1993) proposed examining changes in the coefficient of variability (CV) of the response time. The CV is the ratio of an individual's standard deviation (SD) of reaction time (RT) to the mean RT for that individual throughout the performance of the activity in question. The logic of this measure is quite straightforward. If practice simply results in a speed-up of the processes underlying performance, then the variability (SD) in RT should decrease, at most, proportionally to the RT reduction itself. It leaves CV relatively unchanged (if all the components operate, for example, twice as fast, the RT should decrease by 50% and so should the SD). Suppose now that faster performance is achieved because of restructuring (more efficient organization) of the underlying cognitive processes, so that some of them became redundant, and hence unnecessary. Presumably, these would be the slowest component processes (decision making processes, inefficient search processes, etc.), those that require a larger amount of attentional control in the early phases of learning and practice. In this case overall response time variability should decrease by a much greater proportion than the reaction time itself, resulting in a significant reduction of the corresponding CV index.

Attention

Attention can be understood in terms of sustaining, focusing, dividing, suppressing, or shifting the concentration of conscious resources. In this study, the focus of interest was in how efficient the attention shifting process in participants is, on the assumption that it is attention shifting mainly responsible for managing the complex processing of a large sequence of stimuli involved in the RAN task – namely, attending to a stimulus, recognizing it and identifying (retrieving from memory) its name, saying the name aloud, disengaging from the stimulus and attending to the subsequent one. All these operations appear to be attention sensitive. The test used here to assess attention control was the "Trail Making" test (e.g., Reitan & Wolfson, 1993; Spreen & Strauss, 1991). This test consists of two conditions that require participants to connect a set of 25 circles randomly distributed across a page. In one condition, the circles are numbered from 1 to 25 and must be connected in numerical order. In the other condition half the circles are labeled with numbers (1-12) and half with letters (A-M). The participant must connect the circles by shifting from letters to digits and back in the standard order (A-1-B-2...etc.). The difference in time between the shifting and non-shifting conditions provides an index of attention control (the lower this difference, the lower is the burden of having to shift and hence the greater the degree of attention control).

These measures of automaticity and attention served as predictor variables in a series of hierarchical multiple regression analyses intended to assess the relative contribution of the various automaticity and attention factors in performance on the criterion variables, namely, performance on the individual RAN subtasks.

Finally, to examine whether there is an association between naming speed and reading ability in adults, reading skill was assessed by presenting participants a series of short texts for timed silent reading. This is the most natural everyday reading activity for most purposes in adults. The participants had to read texts silently and then answer simple multiple-choice gist questions to ensure they had comprehended what they had read. Participants were tested in both their first language (English or French as appropriate) and in their second language (French or English). Of greater interest for this particular study, however, were the data from the participants' dominant language (L1) and although second language (L2) data are reported below, they are not the primary focus.

Method

Participants

There were 72 participants (51 women and 21 men, mostly undergraduate students of Concordia University, plus several off-campus volunteers who also responded to the call for participants). Mean age was 26.35 (ranging from 19 to 55, with the median of 22.5 and the mode of 21). All had normal or corrected to normal visual acuity and reported no known learning disabilities.

All participants were functionally bilingual. Forty-four indicated English as their first or dominant[1] language, and 28 indicated French.

Measures and procedure

All participants completed the following: (a) Four versions of the RAN task; (b) Primed decision-making tasks that tested automatic processing; (c) The Trail Making test of attention control; and (d) A reading speed test. Participants also filled out a short biographical questionnaire.

The RAN task Four RAN subtasks (two using letters and digits as symbolic stimuli and two using color patches and object pictures as non-symbolic stimuli) were administered. The following stimuli were used: in the letter condition – *a, d, o, p,* and *s;* in the digit condition – *2, 4, 6, 7,* and *9;* in the color condition – *red, yellow, green, blue,* and *black* squares, and in the object condition line drawings of the following objects – *key, umbrella, watch, scissors,* and *comb*. In each condition the stimuli were presented on a computer screen in 5 rows of 10 items, using PsyScope software (Cohen, MacWhinney, Flatt, & Provost, 1993) with a G4 iMac. Each subtask presentation was always preceeded by detailed instruction and a short (5 stimuli) test trial. Then the participant initiated the actual trial by pressing a designated key on the computer keyboard, which also triggered the time count. When the last stimulus in the set was named, the experimentor stopped the timer by pressing a key on his control pannel connected to the same computer. Thus, time required to say aloud the names of all 50 stimuli on each subtask was recorded by

---

[1] Dominant language here is the main language of all formal education and everyday reading and communication, learned before age of 5 (in two cases – before 8). The dominant language is henceforth referred to as L1, and the participants' second language as L2.

the program as a measure of performance. In the data analyses that follow, performance time on each subtask was treated as an individual variable. We were also interested a priori in the difference in performance time between symbolic and non-symbolic subtasks – the pattern repeatedly observed in the research literature. Performance times on letter and digit subtasks added together served as a measure of symbolic naming speed, and the sum of the performance times on colors and object subtasks served as a measure of non-symbolic naming speed. Individual RAN subtasks were counterbalanced across participants using a Latin Square design. Participants used their dominant language to name the stimuli. Appendix A contains printouts of screen samples featuring each RAN subtask used in the study.

Automaticity measures. A primed decision task was used to test automaticity. Participants saw a continuous set of trials, each consisting of a prime stimulus followed by a single letter target from the set "*a, e, i, u, b, c, d, p*" or a single digit target from the set "*2, 3, 4, 5, 6, 7, 8, 9*". They had to judge whether the letter target was a vowel or consonant and whether the digit target was odd or even by pressing a designated response key. Targets were primed by either the string of digits *12345*, the string of letters *ABCD*, or a neutral string of five asterisks (*****). All information appeared in the center of an iMac standard monitor. Stimulus presentation was managed by a program written in HyperCard 2.3 (Apple Computer, Inc.), which also registered reaction times (RTs) and analyzed participants' responses, recording the number of errors including missed targets. Instructions and screen samples are shown in Appendix B.

Participants took part in two different conditions, several days apart. One was the Expect Related condition, in which they were instructed that a letter string prime indicated that the upcoming target would be a letter, that the digit string prime indicated that the upcoming target would be a digit, and that neutral primes could be followed by either a letter or a digit. The other condition was the Expect Unrelated condition, in which a letter string prime predicted a digit target and a digit string prime predicted a letter target. Prior to each experimental session participants were given a detailed description of the activities to be performed and a training period to ensure that the expectancy instructions were effective. Each training period used only regular and neutral trials under the long SOA condition and lasted until no errors were made in 12 consecutive trials and the average response time for regular trials was at least 10 % faster than for neutral trials.

Both conditions consisted of 480 experimental trials of which 80 % were regular trials (primes and targets appearing as per instructions), 10 % were surprise trials (primes appearing with the "wrong" target) and 10 % were neutral prime trials. Within each condition half of the trials used a short prime-target stimulus onset asynchrony (SOA) interval of 150 ms and half used a long SOA of 1000 ms. These SOAs were distributed equally across regular, surprise and neutral trials.

This paradigm is very labor intensive for the participants, but it is well worth the time and effort spent, because it provides strong information about ballistic processing. The priming effect on surprise short SOA trials of the Expect Unrelated condition served as an index of ballistic processing, that is, reflecting the fact that, given limited time, related characters are processed more easily than unrelated characters, even when their appearance is not expected. We used the *relative* value of this facilitation effect – the neutral-minus-primed trial RT difference divided by the mean RT for the neutral trials in this condition – as an index of automaticity for each participant. This measure is more compatible across participants and takes into account each participant's general RT as seen on the neutral trials as an individual baseline. The CV indices on neutral short SOA trials in the Expect Related (xR) experimental condition served as an index of efficiency-based automaticity (uninfluenced by either expectancy or relatedness factors).

Attention. Attention control was measured using the "Trail Making" test (Spreen & Strauss, 1991) described earlier. This test is comprised of two forms. Form A required participants to connect 25 numbered circles in sequence, and Form B to connect 25 lettered and numbered circles in sequence, but alternating between letters and digits: 1-A-2-B-etc. (see Appendix C). A potential confound was discovered in the original version of the task in a pilot study, one that has been noted as well as by Arbuthnott and Frank (2000). The total distances between items in the original Forms A and B are not equivalent. This was corrected by producing a new version of Form B that was a 180-degree rotation and mirror reflection of Form A and by re-labeling all circles accordingly. Both Forms A and B were to be completed as fast and as accurately as possible and time to complete each form was recorded. The Trail Making test produced two indices that were used in subsequent analyses to assess individual differences in attention. First, performance time on Form B was residualized against time to complete Form A and the residuals served as an attention shifting index. Second, performance time on Form B served as an index of general attention, presumably reflecting more aspects of attention control than the measure of pure shift cost – attention focus in a spatial search and working memory, in particular. These measures – the index of attention shift cost and the index of general attention – were then used in turn as predictors in multiple regression analysis to exlain variance in individual RAN tasks' performance.

Reading speed. Participants' silent reading speed computed as word reading time in ms per word and comprehension in both their first and second languages were measured. Seventeen passages that were from 250-350 words long, about two to three paragraphs each, were used for this test. These passages were adapted from Davy and Davy (1992), a TOEFL practice book for university level second language English. Seventeen translations of these passages were prepared in French by a professional translator who matched the texts for register and difficulty level. Each participant was tested on eight randomly selected passages from the English set and the eight complementary passages in French, with a common warm-up passage at the start of each language block. Associated with each passage was a simple 3-option multiple-choice question that tested for text comprehension. The texts were presented on a computer screen, and the participants advanced through the texts by pressing a key. Total reading time for the text and accuracy in answering the questions were recorded. The index of reading speed was calculated as mean time (in milliseconds) to read each word (total reading time divided by the number of words). This measure (processing time per unit; ms per word) has been described by Ackerman (1987) as statistically more appropriate than the measure of number of units per time (words per minute) often used in reading research. It also seemed to better reflect the reading process – after all, resources are allocated in terms of time needed to process a meaningful segment of text (a word, a sentence or a paragraph), and not in terms of trying to process as many items as possible into a particular span of time.

Questionnaire. A short demographic questionnaire asked participants to provide data about their age, gender, basic academic background, absence/presence of learning disabilities or problems with visual perception, and about their history, expertise, actual use and the degree of comfort in the first and second language (Appendix D).

All participants signed a consent form prior to the experiment and upon completion they were paid $20. Each participant took part in two sessions on two different days several days apart. Because the task based on Neely's (1977) experimental paradigm was the most time consuming, each session began with this task (alternating Expect Related and Expect Unrelated conditions across participants). On the first day the session began by reading and signing the consent form, and on the second day it began with the demographic questionnaire. Other tasks were split evenly between two sessions of testing and carefully counterbalanced across participants (with the reading task in L1 and L2 always administered on different days of testing). Participants were debriefed at the end of the second session. Both consent form and standard debriefing text are given in Appendices E and F, respectively.

Results

Of the 72 participants originally tested, the data from four were excluded. Two of them failed to meet the inclusion criteria on the primed decision task because they showed no facilitation or interference effects after extensive training in the long SOA trials of either the Expect Related or Expect Unrelated conditions. Two other participants performed the reading task with insufficient accuracy on the comprehension tests (their scores were not different from chance, which was 33 %), raising doubts about whether their reading speed data could be used meaningfully.

Data for the remaining 68 participants were retained. For these 68, the mean age was 26.0 years, ranging from 19 to 55 with a mode of 21. There were 48 women and 20 men. English was the dominant language for 41 participants and French for 27. No substantial differences between languages either in RAN task performance time or reading rate were observed.

Raw data were treated to account for possible distortion from outliers using the less conservative approach as outlined in Tabachnick and Fidell (2001). This involved replacing outliers with scores one unit larger (or smaller) than the next most extreme score in the distribution of scores for the corresponding variable.

The results are presented and discussed below, first in terms of the basic findings for each set of measures for each of the measures are presented, together with basic analyses of relationships between the measures. Descriptive statistics of all the major variables in the study are summarized in Table 3.1. All t-tests reported below with respect to basic performance on the experimental tasks are two-tailed. The alpha level of 0.05 was selected to determine the significance of findings, though actual (calculated) p-values are reported as well. Following these primary results, analyses addressing the specific research hypotheses are presented, as they address the major research questions that motivated this study.

RAN Task. Table 3.1 presents the naming times for each of the four subtasks of the RAN task. Indices of symbolic RAN performance were calculated by combining results from the letters and digits subtasks and of non-symbolic by combining results from the colors and objects subtasks. As can be seen from the table, mean naming times ranged from 355 to 760 ms per item. Not surprisingly, participants' fastest performance was on the letter naming RAN subtask and the slowest performance was on the object naming RAN subtask, with the digit naming performance being very close to letter-naming and color-naming – being close to the object naming performance. Combined indices of performance on the so-called symbolic (letter and digit) were significantly faster than the combined indices for the non-symbolic (object and color) subtasks (t (67) = 25.034, $p < .001$).

Automaticity. Table 3.1 also presents the mean RTs for the each of the conditions in the primed decision making task. Priming effects of all types were observed as expected. Results showed that in the long SOA condition there were significant facilitation effects for expected targets and interference effects for unexpected targets whereas in the short SOA condition there were facilitation effects for related targets only. Participants' responses on primed regular (non-surprise) trials with long SOA were significantly faster than those on the corresponding neutral trials (t (67) = 5.257, $p < .001$, and t (67) = 3.638, $p = .001$, for Expect Related [xR] and Expect Unrelated [xU] conditions respectively), whereas on surprise trials under the same conditions there were significant interference effects (slower processing on primed than neutral trials: t (67) = -11.091, $p < .001$ and t (67) = -7.17, $p < .001$ for xR and xU respectively).

There were also significant facilitation effects in the xR short SOA, regular trials (t (67) = 6.265, $p < .001$), and in the xU, short SOA, surprise trials (t (67) = 8.683, $p < .001$). Importantly, this last significant facilitation effect on surprise trials in the short SOA, Expect-Unrelated condition indicates that the test was able to demonstrate ballistic processing.

Table 3.1. Descriptive statistics of the major variables (N=68)

Experimental Task		**Variable**	**Mean**	**SD**
RAN				
	1	Performance time on letters (sec.):	**17.74**	**2.61**
	2	Performance time on digits (sec.):	**18.27**	**2.31**
	3	Performance time on colors (sec.):	**29.84**	**4.36**
	4	Performance time on objects (sec.):	**38.02**	**6.46**
	5	Symbolic (letters & digits combined):	36.11	4.97
	6	Non-symbolic (colors & objects combined):	68.46	11.28
	7	Overall (all subtasks combined):	104.57	13.79
Primed decision		Effect type (condition/SOA/trial):		
	8	Facilitation – xR/long SOA/regular (ms):	25	39.8
	9	Facilitation – xU/long SOA/regular (ms):	17	39.6
	10	Interference – xR/long SOA/surprise (ms):	-74	55.5
	11	Interference – xU/long SOA/surprise (ms):	-70	80.6
	12	Facilitation – xR/short SOA/regular (ms):	25	33.0
	13	Facilitation – xU/short SOA/surprise (ms):	49	43.5
	14	Facilitation (xU, short SOA, surprise trials) adjusted by base-line: ***[Ballistic automaticity index]***	**.069**	**.05**
	15	CV – xU, short SOA, neutral trials:	.179	.064
	16	CV – xR, short SOA, neutral trials: ***[Efficiency-based automaticity index]***	**.181**	**.059**
Trail making				
	17	Form A performance time (sec.):	26.28	7.08
	18	Form B performance time (sec.):	51.49	14.53
	19	Difference in performance time (B–A)	25.21	11.79
	20	Standardized residual (B against A): ***[Primary index of attention shift cost]***	**.001**	**.99**
Silent reading (L1)				
	21	Reading rate (ms per word):	**281.8**	**75.93**
	22	Accuracy (% correct responses):	71.5	15.04
Silent reading (L2)				
	23	Reading rate (ms per word):	366	99.7
	24	Accuracy (% correct responses):	72.7	21.52

Note. **In bold:** Variables used in further analyses.
xR = Expect related target; xU = Expect unrelated target

Table 3.1 also shows the CV indices (the individual's standard deviation of reaction time divided by that person's mean reaction time) for neutral trials in both xR and xU conditions with short SOAs. The latter (the CV obtained from the short interval baseline neutral trials in the xR condition) serves as a primary index of efficiency-based automaticity.

Attention. The Trail Making attention test yielded two basic measures of performance: time required to complete Form A (involving numbered circles only) and Form B (requiring attention shifting between numbered and lettered circles). Average performance time on Form A was significantly faster than on Form B (t (67) = 17.63, $p <$ .001) confirming the existence of a substantial shift cost. The attention shift cost was operationalized as follows. Time to complete Form B was residualized against the time to complete Form A. The residuals obtained in this way reflected those aspects of performance on Form B that could not be predicted from performance on Form A (the effect of shifting attention focus per se), while controlling for individual differences in other factors, such as spatial search, motor skills, and stimulus recognition. See Table 3.1, as well, for the data on the simpler measure of performance time differences between Forms B and A, as well as for the performance times for each form separately.

Reading skill. Silent reading time was calculated as the average time spent on reading a single word (ms per word) in each language. Table 3.1 reports these mean reading times along with the mean comprehension scores. Participants' average reading time in L1 and L2 differed significantly (t (67) = 8.259, $p <$ .001), demonstrating that, though they were functionally bilingual in English and French, the participants did not achieve equal level of reading fluency in their two languages. This ms/word measure was assumed to reflect the silent reading speed necessary to achieve equally high levels of understanding across the L1 and L2 as shown by response accuracy to the gist comprehension questions (71.5 % and 72.7 % respectively). Also, data analysis showed no indication of speed-accuracy trade off for comprehension effects in either language.

Relationships among variables. A correlation analysis revealed the following relationships between the above-mentioned variables (Table 3.2). All correlation coefficients in the table are presented so that the sign matches the direction of the actual relationship between variables (i.e., positive coefficients mean better performance on the corresponding tasks).

Table 3.2. Inter-correlation coefficients for the major variables (N=68)

VARIABLES:	1	2	3	4	5	6	7	8	9	10	11	12	13	14
1. Letter-RAN	-													
2. Digit-RAN	.754***	-												
3. Color-RAN	.455**	.492***	-											
4. Object-RAN	.218*	.211*	.587***	-										
5. Symbolic RAN	.935***	.926***	.501***	.222*	-									
6. Non-symbolic RAN	.320**	.338**	.814***	.921***	.342**	-								
7. Ballistic automaticity	.245*	.180	.147	.041	.219*	.122	-							
8. Automaticity / Efficiency	-.041	.032	.015	.124	-.033	.111	.151	-						
9. Attention (Form A)	.342**	.313**	.387**	.282**	.357**	.388**	-.144	.208*	-					
10. Attention (Form B)	.339**	.252*	.303**	.438***	.304**	.432***	.132	.143	.594***	-				
11. Attention Difference Shift Cost	.213*	.123	.141	.370**	.161	.300**	.249*	.051	.132	.876***	-			
12. Attention Residualized Shift Cost	.169	.082	.091	.336**	.115	.251*	.271*	.024	.000	.804***	.991***	-		
13. Reading rate (L1)	.378**	.314**	.174	.079	.392***	.119	-.053	-.115	.246*	.228*	.114	.077	-	
14. Reading rate (L2)	.286**	.230*	.062	.112	.284**	.112	-.099	.009	.345**	.306**	.121	.076	.570***	-

* $p<.05$, ** $p<.01$, *** $p<.001$. All one-tailed tests.

The list of variables: 1 – RAN performance time on letters task; 2 – RAN performance time on digits task; 3 – RAN performance time on colors task; 4 – RAN performance time on objects task; 5 – RAN performance time on letters and digits tasks combined; 6 – RAN performance time on colors and objects task combined; 7 – Facilitation effect (xU, short SOA, surprise trials) – relative value (adjusted by the corresponding base-line condition); 8 – CV index (xR, short SOA, neutral trials); 9 – Attention: Form A performance time ("Trail Making" test of attention); 10 – Attention: Form B performance time ("Trail Making" test of attention); 11 – Difference in performance time between Form B & Form A on the "Trail Making" test; 12 – Standardized residual (Form B against Form A performance time on the "Trail Making" test) as an index of the attention shift cost; 13 – Reading rate (ms/word) in L1; 14 – Reading rate (ms/word) in L2.

Inter-correlations among different RAN subtasks were all significant, possibly suggesting that shared variance may reflect commonalities in cognitive underpinnings of the naming speed phenomenon in general. However, correlations within each pair of either symbolic or non-symbolic RAN subtasks (i.e., within the same stimulus type) were higher than across symbolic and non-symbolic RAN subtasks (i.e., across stimulus types).

To see whether a relationship would obtain between reading ability and RAN task performance in these adult participants, performance on the RAN subtasks and reading rate were submitted to correlation analyses with. Silent reading rate in L1 was significantly correlated with performance on the symbolic RAN subtasks: $r = .378, p < .01$ and $r = .314, p < .01$, for letters and digits respectively (one-tailed). Silent reading time in L1 was not, however, significantly correlated with performance on the non-symbolic RAN subtasks: $r = .174$ and $r = .079$, for colors and objects respectively. These results are consistent with previously reported relationships between reading ability and RAN task performance (Savage, 2004; Wolf et al. 2000, for reviews). Moreover, when variability shared by the symbolic and non-symbolic RAN tasks was statistically controlled for in partial correlation analyses, only symbolic RAN remained significantly associated with reading: partial $r = .377, p < .01$ (one-tailed). Interestingly, performance on the letters and digits RAN subtasks was also positively correlated with reading rate in participants' *second* language ($r = .286, p = .009$ and $r = .230, p = .029$ respectively, one-tailed). Partial correlation between symbolic RAN and L2 reading speed after controlling for non-symbolic RAN was: $r = .263, p = .016$ (one-tailed). To account for the possibility of a connection between RAN task performance and L2 reading performance that was unique to the L2, L2 reading times were resudualized first against the measure of L1 reading time to statistically remove shared variability reflecting general reading abilities found in both L1 and L2. The resulting measures were then was subjected to the same correlational analyses, none of which emerged significant.

Correlation analyses were conducted involving measures of automaticity and attention (these were the major predictors in the subsequent multiple regression analyses). Ballistic automaticity was found to be significantly correlated only with performance on the letter RAN subtask: $r = .245, p = .022$ (one-tailed); none of the other correlations with ballistsic automaticity and performance with RAN subtasks were statistically significant.

Regarding attention, the correlation coefficient between performance on the objects RAN subtask and the primary index of attention (the performance time on Form B residualized against Form A) was $r = .336, p = .003$ (one-tailed). The other correlations were not statistically significant. When the index of attention used was the performance time difference for completing Form B versus Form A, the results showed that attention was significantly associated with RAN task performance for letters ($r = .213, p = .041$) and for objects ($r = .370, p = .001$) but not for digits ($r = .123, p = .160$) or colors ($r = .141, p = .126$). Interestingly, completion times for Forms A and B of the Trail Making test were significantly correlated without exception with all measures of RAN subtask performance (see Table 3.2).

<u>Multiple regression analyses.</u> As the next step, the main question that motivated this study – what cognitive mechanisms underlie RAN task performance – was addressed through a series of multiple regression analyses as follows. RAN task performance times on individual subtasks served as criterion variables. Predictive variables were indices of

automaticity and attention. Because they were expected to be more influential (as most of the research literature suggests), both measures of automaticity were entered into the equation first, followed by the index of attention shift cost. The results of these analyses are given in Tables 3.3-3.6. Results from the multiple regression analysis for overall RAN performance collapsed across the subtasks using the same predictors are presented in Table 3.7.

As can be seen in the tables, together both indices of automaticity and the index of attention explained about 15.8 % (adjusted $R^2 = .105$) of variability in the letters-based RAN (overall model's significance was $p = .026$). Results were lower for the RAN digits and colors subtasks: $R^2 = .116$ (adjusted $R^2 = .060$) and $R^2 = .143$ (adjusted $R^2 = .088$) respectively, both not significant. Quite a different picture was observed for the object-based RAN subtask. The overall model was highly significant ($p = .002$) explaining about 22 % in RAN performance ($R^2 = .218$, adjusted $R^2 = .168$). Individual contributions of each factor varied across models with some of them approaching or even exceeding the alpha level of significance. Namely, automaticity of ballistic nature and attention contribution to the letter-naming RAN subtask performance was moderately-to-marginally significant ($\beta = .314$, $p = .013$ and $\beta = .254$, $p = .041$, respectively), whereas attention index was highly correlated with the object-naming RAN subtask ($\beta = .377$, $p = .002$), alone explaining up to 15.1 % variability in it (adjusted $R^2 = .111$).

Table 3.3

Results of a multiple regression analysis of RAN (letter naming subtask) performance by index of ballistic automaticity, CV-index of automaticity, and index of attention shift cost (Form B performance time residualized against Form A performance time)

Variable:	r^a	R	R^2	R^2 change	F change	Sign. F	Final β
Ballistic automaticity	.245*	.245	.060	.060	4.226	.044	.314*
CV index of automaticity	.041	.245	.060	.000	.001	.976	.001
Attention shift cost	.169	.346	.120	.060	4.343	.041	.254*

[a]Zero-order correlations. *$p < .05$.

Table 3.4

Results of a multiple regression analysis of RAN (digit naming subtask) performance by index of ballistic automaticity, CV-index of automaticity, and index of attention shift cost (Form B performance time residualized against Form A performance time)

Variable:	r^a	R	R^2	R^2 change	F change	Sign. F	Final β
Ballistic automaticity	.180	.180	.033	.033	2.222	.141	.218
CV index of automaticity	.032	.181	.033	.000	.002	.967	.003
Attention shift cost	.082	.226	.051	.018	1.244	.269	.141

[a]Zero-order correlations. *$p < .05$.

Table 3.5

Results of a multiple regression analysis of RAN (color naming subtask) performance by index of ballistic automaticity, CV-index of automaticity, and index of attention shift cost (Form B performance time residualized against Form A performance time)

Variable:	r^a	R	R^2	R^2 change	F change	Sign. F	Final β
Ballistic automaticity	.147	.147	.022	.022	1.454	.232	.191
CV index of automaticity	-.015	.152	.023	.001	.094	.760	.040
Attention shift index	.091*	.204	.041	.019	1.235	.271	.141

[a]Zero-order correlations. *$p < .05$.

Table 3.6

Results of a multiple regression analysis of RAN (object naming subtask) performance by index of ballistic automaticity, CV-index of automaticity, and index of attention shift cost (Form B performance time residualized against Form A performance time)

Variable:	r^a	R	R^2	R^2 change	F change	Sign. F	Final β
Ballistic automaticity	.041	.041	.002	.002	.114	.737	.165
CV index of automaticity	-.124	.139	.019	.017	1.158	.286	.140
Attention shift index	.336*	.389	.151	.132	9.940	.002	.377**

[a]Zero-order correlations. *$p < .05$.

Table 3.7

Results of a multiple regression analysis of overall RAN performance by index of ballistic automaticity, CV-index of automaticity, and index of attention shift cost (Form B performance time residualized against Form A performance time)

Variable:	r^a	R	R^2	R^2 change	F change	Sign. F	Final β
Ballistic automaticity	.179	.179	.032	.032	2.186	.144	.283
CV index of automaticity	.079	.209	.044	.012	.787	.378	.114
Attention shift index	.247*	.373	.139	.095	7.083	.010	.321**

[a]Zero-order correlations. *$p < .05$.

The above results point more strongly toward attention-based than toward automaticity factors as playing a role of attention based factors in RAN task performance, but the strength of the associations obtained were somewhat weak. Perhaps the cognitive nature of the RAN task might be better revealed in the performance of poorer readers. To address this possibility, the data were separated into two subsets by median split on the participants' first language (L1) reading time. Those 34 participants whose reading time was below the whole sample median of 287 ms/word composed the group of "slower" readers, and the remaining 34 were considered to be the "faster" readers.

Data of multiple regression analysis for overall RAN performance using the same set of predictors are presented in Table 3.7.

The group of slower readers performed on average at the rate of 327 ms per word (SD = 93.1), whereas the mean for the group of faster readers was 223 ms per word (SD = 45.42). An independent sample t-test confirmed significance of this difference in L1 reading rate (t (66) = 10.015, $p < .001$, two-tailed). At the same time, groups did not differ in reading accuracy measured by the percent of correct answers to multiple-choice comprehensive questions (t (66) = .296, $p > .05$). Though obviously having various experience in their second language L1 faster readers also performed faster in L2 reading task than did slower readers (means of 327 ms/word and 405 ms/word accordingly were significantly different – t (66) = 3.492, $p = .001$, two tailed), but their L2 reading accuracy scores were very similar (t (66) = .651, $p > .05$).

Next, the basic set of data analyses was performed once again for faster and slower readers separately. These analyses generally reproduced the overall patterns observed in the whole sample. Not surprisingly, since the sample size was cut by half, several correlation coefficients noticeably diminished in significance, including all representing reading-RAN connection. Among those that stayed statistically significant (all data below – for one-tailed tests), the difference between groups was minimal, but illustrative. For example, faster readers revealed quite a strong connection between the letter naming RAN subtask and the index of ballistic automaticity: $r = .328$, $p = .028$, but showed a somewhat weaker (though still marginally-to-moderately significant) degree of association between the object naming RAN subtask and both indices of attention shift cost: $r = .276$, $p = .057$ for the standardized residual (form B against form A) and $r = .316$, $p = .034$ for the simple difference in performance time between forms B and A. Quite the opposite was true for the group of slower readers. All correlations between different RAN subtasks and either index of automaticity were non-significant, whereas the connection between attention shift cost and performance on the object naming RAN subtask was stronger in slower readers than it was in the entire sample: $r = .390$, $p = .012$ for the standardized residual index and $r = .417$, $p = .007$ for the simple difference index.

In other words, it seems there is at least a tendency for there to be a stronger role for ballistic automaticity in symbolic RAN for faster readers and even a stronger association between attentional control and non-symbolic RAN performance for slower readers. This tendency however, should be perceived with caution because the RAN-to-reading connection was not that salient in both groups taken separately (possibly because of weaker statistical power due to a smaller sample size). The same issue of reduced power affected somewhat the reliability of the multiple regression analyses also undertaken for both groups.

Similarly to the data based on the whole sample, in slower readers, even together, automaticity of both types and attention as they were operationalized in the study as best explained from 1.3 % (for the digit naming RAN subtask in faster readers) up to 27.7 % (adjusted $R^2 = .205$, $p = .02$) for the object naming RAN subtask. This was the only overall significant model; the rest came out to be non-significant. In terms of unique contribution of each predicting variable to different RAN subtask, there were only two statistically significant sets of findings: ballistic automaticity for the letter naming RAN subtask in the group of faster readers ($\beta = .442$, $p = .021$) and attention shift index for the object naming RAN subtask in the group of slower readers ($\beta = .463$, $p = .007$).

Finally, the increase in explained variability in all criterion variables was observed when the index of attention shift cost was replaced by the measure of performance on Form B of the Trail Making test alone (Tables 3.8-3.11). Operationalized in this way, attention appeared to contribute significantly to all individual RAN subtasks, explaining from 8% of the variability in digit naming up to 19 % of the variability in object naming ($\beta = .288$, $p = .020$ and $\beta = .442$, $p < .001$, respectively). The corresponding numbers for letter naming and color naming are 14.3 % ($\beta = .385$, $p = .001$) and 10.4 % ($\beta = .328$, $p = .007$), respectively. It could be argued of course that Form B of the Trail Making test involves sequenced silent naming of letters and digits – a component shared in a sense with the RAN task. Nevertheless, these results could also be suggestive of the important role other aspects of attention required to perform on Form B (in addition to attention shifting) played in explaining rapid naming.

Table 3.8.
Multiple regression analysis of RAN (letter naming subtask) performance by index of ballistic automaticity, CV-index of automaticity, and index of general attention.

Variable:	r^a	R	R^2	R^2 change	F change	Sign. F	Final β
Ballistic automaticity	.245*	.245	.060	.060	4.226	.044	.288*
CV index of automaticity	.041	.245	.060	.000	.001	.976	.052
Attention (Form B)	.339**	.451	.203	.143	11.494	.001	.385**

[a]Zero-order correlations. *$p < .05$, ** $p < .01$, *** $p < .001$

Table 3.9.
Multiple regression analysis of RAN (digit naming subtask) performance by index of ballistic automaticity, CV-index of automaticity, and index of general attention.

Variable:	r^a	R	R^2	R^2 change	F change	Sign. F	Final β
Ballistic automaticity	.180	.180	.033	.033	2.222	.141	.212
CV index of automaticity	.032	.181	.033	.000	.002	.967	.041
Attention (Form B)	.252*	.334	.070	.079	5.696	.020	.286*

[a]Zero-order correlations. *$p < .05$, ** $p < .01$, *** $p < .001$

Table 3.10.
Multiple regression analysis of RAN (color naming subtask) performance by index of ballistic automaticity, CV-index of automaticity, and index of general attention

Variable:	r^a	R	R^2	R^2 change	F change	Sign. F	Final β
Ballistic automaticity	.147	.147	.022	.022	1.454	.232	.190
CV index of automaticity	-.015	.152	.023	.001	.094	.760	.003
Attention (Form B)	.303**	.357**	.127	.104**	7.639	.007	.328**

^{a}Zero-order correlations. *$p < .05$, ** $p < .01$, *** $p < .001$

Table 3.11.
Multiple regression analysis of RAN (object naming subtask) performance by index of ballistic automaticity, CV-index of automaticity, and index of general attention

Variable:	r^a	R	R^2	R^2 change	F change	Sign. F	Final β
Ballistic automaticity	.041	.041	.002	.002	.114	.737	.112
CV index of automaticity	-.124	.139	.019	.017	1.158	.286	.078
Attention (Form B)	.438***	.456	.208	.189***	15.236	.000	.442***

^{a}Zero-order correlations. *$p < .05$, ** $p < .01$, *** $p < .001$

Discussion

Study 1 was designed to address the following research questions:

(1) Do individual differences in the degree of automatic information processing underlie individual differences in RAN task performance, where "automatic" is operationalized either as ballistic processing or as rapid and stable (and consequently more efficient) processing?

(2) Do individual differences in the degree of attention control operationalized in terms of shift costs underlie individual differences in RAN task performance?

(3) Are automatic and attention-based aspects of RAN task performance equally or differentially linked to reading performance?

These questions were addressed in a series of correlational and multiple regression analyses, the major results of which are now discussed in turn, followed by a general discussion. First, however, there is a brief overview of the findings.

With respect to the first research question, Study 1 revealed that automaticity of stimulus recognition, regardless whether it was operationalized as ballistic or rapid and stable (more efficient) processing, did not show any strong connection to non-symbolic RAN task performance and was only weakly correlated with performance time on one of the symbolic RAN subtasks (letter naming). According to the multiple regression analyses, automaticity contributed too little to the variance in either of criterion variables to explain RAN performance in terms of automatic processing. In contrast, with respect to the second research question, the findings indicated a robust association between attention and RAN task performance, on practically all the subtasks, and an especially strong association with non-symbolic (colors and objects) naming. Finally, with respect to the third research question, only performance on the symbolic RAN subtasks was significantly associated with participants' silent reading performance.

Interrelations among major variables

Very much in accord with recent observations in the literature (e.g., Savage & Frederickson, 2004; Stringer et al. 2004), symbolic and non-symbolic RAN subtasks showed significant differences between them in that performance on the symbolic RAN subtasks of naming letters and digits was faster than was performance on the non-symbolic color and object subtasks. In addition, RAN task performance correlated significantly with silent reading time for texts and with some but not all the cognitive factors hypothesized to underlie RAN task performance. This pattern was observed in both participants' languages.

As mentioned earlier, the second language data were not the primary focus of this study. However, the results obtained do suggest that whatever cognitive mechanisms are responsible for the RAN-to-reading connection, that link is not limited to the participants' first language only. To some extent, the second language could be perceived as paralleling in some ways the early reading development in the first language. For example, the reading skills are not fully developed, highly practised nor very efficient, just as is the case with early first language reading. If one views second language reading in this light, then one can ask whether RAN task performance reflects the operation of cognitive factors responsible for reading in general (any language, at any time in reading development) or in reading that is limited to the earlier stages of development, as the time that the acquisition of expertise has just begun (as in early childhood reading). To check for a connection between RAN performance and L2 reading specifically, the measure of reading speed in L2 was residualized against the measure of L1 reading rate to statistically remove shared variability that reflect general reading abilities. The resulting measure is presumed to reflect individual differences uniquely associated with reading in the *second* language and not with reading in general. These residualized measures were then correlated with performance time on each individual RAN subtasks. None of the correlation coefficients was significant or even approached significance, consistent with the idea that RAN task performance reflects the more general regularities of reading, those that would already be accounted for in measures of L1 reading performance.

A significant correlation between naming speed on symbolic RAN subtasks and the measure of reading rate was also found, as expected. This result unequivocally demonstrated that the RAN-to-reading association persists in normal adult readers, whose reading expertise has been fully developed through extensive practice and education, well beyond the early stages of reading acquisition. Performance on non-symbolic RAN subtasks always correlated to reading below the significance level. This very important issue of why symbolic and non-symbolic RAN subtasks may be so different will be in part addressed more closely in the subsequent studies.

There was noticeable difference in patterns of association between RAN subtasks and the measures of automaticity and attention. Very few correlation coefficients with either measure of automaticity approached significance, whereas various measures of attention were significantly correlated with RAN task performance, especially with the non-symbolic sub-tasks.

Of special interest is that both forms of the Trail Making test separately emerged to be strongly connected to performance on all RAN subtasks. In its original form as used in clinical psychological settings, the test serves as a direct measure of attention, not as an attention shift cost index, and it presumably addresses such aspects of attentional control as spatial search and working memory capacity (in addition to the ability to efficiently shift attention in between different types of stimuli required on form B). Although it is beyond the framework selected for the analyses in this study, this fact once again draws attention to the possibility of strong involvement of different aspects of controlled processes in successful RAN task performance.

Multiple regression analyses

In a series of multiple regression analyses with symbolic and non-symbolic RAN subtasks as the criterion variables, attention-related factors were found to have contributed substantially more variance to both types of RAN subtasks, but especially to the non-symbolic ones, whereas neither measure of automaticity was very predictive of RAN task performance. Overall, these findings are nevertheless difficult to interpret because neither of the two automaticity categories of predictors explained a large enough portion of variance in the criterion variables to pinpoint major cognitive mechanisms underlying RAN task performance. However, we cannot rule out the possibility that a larger sample in future experiments might provide enough statistical power to still demonstrate an essential role of automatic processing in RAN task performance.

The sample tested here was drawn from a population of well-educated experienced adult readers, and thus served as an interesting opportunity for addressing the most general cognitive mechanisms underlying RAN performance that are also related to reading performance. Often the predictive power of RAN for reading ability is best shown in young children who are at risk of developing dyslexia or in teenagers and young adults already impaired in reading (e.g., Savage et al., 2005; Wolf et al. 1986). The reading rate measure in a normal, educated, young and middle-aged adult population, on the other hand, represents a continuum without extreme reading disability at the lower pole. To investigate the difference between high functioning readers and less well functioning readers, even if the latter are not showing evidence of a reading disability, it was decided to look at the data by selecting groups with fairly different reading abilities. For this, a median split by reading rate in participants' dominant language was performed, yielding faster and slower readers, and the major analyses reported above were repeated for the corresponding data subsets.

The findings of these correlation and multiple regression analyses on the median-split by L1 reading rate data subsets largely mirrored most of the findings for the entire sample. In particular, there was a difference between symbolic and non-symbolic RAN subtasks in their connection to reading, and a greater contribution of attention-related factors to variability in RAN task performance.

It is always possible that the study overlooked some other factors that contribute to RAN performance. The on-going debate in the literature, however, consistently names automaticity and, to a lesser extent, attention as the two major factors deserving careful consideration with respect to RAN task (Savage, 2004, for a review). In light of this, the likelihood of an entirely new unexplored factor being involved appears to be rather doubtful. Another factor repeatedly emerging in the literature – working memory capacity – is very closely related to executive control, on one hand, and to phonological processing on the other, according to the most widely accepted model (Baddeley & Hitch, 1974; Baddeley & Della Sala, 1996). Once again, this focus on working memory capacity implicates attentional involvement and revives the whole debate about the relative independence of naming speed and phonological awareness deficits.

General discussion and implications for further investigation

Overall, a brief summary of the preliminary results of Study 1 present an intriguing picture. The correlation between RAN task performance and reading was moderate and statistically significant. However, looking at the different RAN subtasks, the connection was almost entirely between reading and the reading-related sub-tasks of RAN, namely the letter and digit naming subtasks. In terms of factors contributing to RAN performance itself, there also was a difference between symbolic and non-symbolic RAN subtasks. Performance on the symbolic RAN task could not be explained by any combination of the automaticity and attention predictors used, whereas for performance on the non-symbolic RAN task, the attention shift cost factor was significant.

This particular pattern in the data poses a challenge because, although the finding is interesting per se, when viewed in terms of the larger picture, it explains little in the original set of research questions. While it is true that attention processes may be an important element underlying non-symbolic RAN task performance, what does it mean if performance on this RAN subtask is only weakly connected to reading? And what is to be made of the weak associations with the symbolic RAN subtask, the one that is more strongly correlated with reading?

A possible resolution may lie with clarifying once again how attention is to be understood within the framework of the present study and in the context of other research in the field. Perhaps, the operational definition of attention used here is too narrow to capture all the nuances of the role attention presumably plays in RAN task performance.

Broadening it could be the key to a better explanation of the RAN-to-reading connection. Earlier, the emphasis was put on attention shift cost. The standardized residual of performance time on Form B against Form A of the Trail Making test was used to measure this cost, supposedly ruling out possible influences from such irrelevant mechanical components of the activity as individual differences in line drawing. However, in operationally defining attention skills in this way, some of the more relevant attentional control components of spatial search and, to some extent, working memory may have been lost. These components are associated respectively with the necessity to find the next target stimulus in the sequence while keeping in memory the previous one (perhaps more important in Form B, but nevertheless also present in Form A).

What would happen if instead the performance time on Form B (as the more demanding task) were used alone as a measure of attention? There are at least, two arguments in favor of such an attempt. First, other research has used this very approach employing the Trail Making test for assessing attention in general (not just its shifting component) in relation to the RAN task (e.g., Närhi, 2002; Stringer et al., 2004; van der Sluis et al., 2004). Second, and no less importantly, Form B undoubtedly addresses more aspects of attentional control (e.g., spatial search and working memory) than merely a shift cost. On the other hand, the fact that there is a partial overlap in stimuli used in symbolic RAN tasks and Trail Making test, warrants particular caution in interpreting findings based on utilization of Form B, instead of the index of attention shift cost. With this in mind, a series of multiple regression analyses with performance time on Form B (replacing in the model the index of attention shift cost) were performed again. The results revealed a substantial increase in explained variance in RAN performance, on all RAN subtasks and especially on non-symbolic ones.

In other words, the ability to efficiently manage attentional resources for spatial search, for maintaining memory for presented in sequences target stimuli in addition to the ability to minimize attention shift cost in the process (as has been initially hypothesized), explained individual differences in rapid naming of both symbolic and non-symbolic RAN stimuli.

In light of these latest findings, the decision was made to use Form B performance as the measure of general attention in the subsequent statistical analyses in the project in addition to the index of attention shift cost.

A fair amount of variance in RAN performance remains unaccounted for, possibly implicating some additional contributing factors. Leaving for now the issue of what these might be open for further discussion, the current study has shown with some degree of confidence that in a hypothetical contest for the role of the most influential cognitive factor responsible for successful RAN performance, results appear to favor attention over automaticity.

Brief summary

To summarize the findings of Study 1 strictly in terms of the major research questions, the following can be said:

- Individual differences in the degree of automatic information processing – whether operationalized as reflecting ballistic processing (priming effects) or rapid, stable, efficiént processing (the coefficient of variability measure) – had little connection to performance speed on any of the RAN subtasks.

- In contrast, individual differences in the degree of attention control, operationalized as an attention shift cost, appeared to underlie RAN task performance to a much greater degree than did measures of automatic processing.

Study 2 now follows to investigate further the influence on naming speed in the RAN task of such factors as attention demand, stimulus type and ultimate set size of the stimuli. This is accomplished through special modifications of the RAN task.

CHAPTER 4: EXPERIMENTAL STUDY 2

Objectives and rationale

Study 2 was designed to complement Study 1 by clarifying some issues that had arisen at the stage of preliminary analyses. The results of the first study revealed a strong involvement of attention in RAN task performance and showed a substantial difference between symbolic and non-symbolic RAN subtasks. The goal of Experiment 2 was to extend the experimental procedures used in Study 1 in order to address some additional research questions:

1. How sensitive is RAN task performance to explicit manipulation of attention demands?
2. How important to RAN task performance is the "set size" factor, that is, the size of the potential "universe" or source set from which the actual target stimuli to be named are drawn from?
3. Does stimulus familiarity, as function of frequency in printed text, play any role in RAN task performance and its link to reading rate?

The findings of Study 1 have clearly indicated a high degree of involvement of attention-related factors in RAN task performance, and at the same time they raised important questions about the different RAN subtasks. Performance on the symbolic (letters and digits) and non-symbolic (colors and objects) RAN subtasks were not only significantly different in terms of performance time and some the underlying mechanisms but also, and more importantly, in the degree of connection between RAN and reading.

The following assumptions guided the design and implementation of Study 2. RAN task performance, aside from its production (articulation) component, rests on the two major types of expertise. These two are: (1) the ability to quickly recognize each individual stimulus in the presented sequence and establish a link to its correct name, and transform that name into the appropriate speech sounds and (2) the ability to efficiently disengage from each individual stimulus after it has been named, and engage in the naming of the subsequent stimulus. The first assumption is fully consistent with the framework provided by the double-deficit hypothesis (Wolf & Bowers, 1999), whereas the second assumption emphasizes the potential role of attention-related factors. There is also the possibility that successful performance on RAN tasks relies on ability to process large sequences of individual stimuli, thus implicating attention in an even broader sense. Viewed from this perspective, automaticity of stimulus recognition and efficient management of attentional resources remain the focus of interest as the two greatest contributors to naming speed.

Given the results of Study 1, it could be speculated that, of automaticity and attention-based factors, RAN task has much less to do with automatic processing, at least on the level of single stimulus recognition. In its very essence, RAN performance would appear to depend on adequately directed and efficiently shifted attention. Initially (in children just learning how to read), all RAN subtasks are good predictors of reading outcomes. With time and practice in everyday reading, the growing familiarity of letters and digits may help to perfect performance in naming them, making this process more automatic. This automatized ability to name, however, cannot completely replace the important contribution of attention, and that is why, perhaps, one sees in the naming of non-symbolic stimuli that the role of attention does not diminish over time. Non-symbolic naming might even become more demanding because practice with language creates additional mental representations that have to be search for names (including written and spoken names) for a very large number of objects (effectively unlimited), whereas the representations of letters and digits remains more or less the same throughout one's life (the possible exception would be the learning of other writing systems, but this is likely to have a very small impact on the ability to rapidly name letters and numbers written in the script of one's first language).

Under these circumstances, the predictive power of symbolic RAN tasks for reading remains intact. Performance on the non-symbolic RAN tasks, on the contrary, is no longer connected to reading to the same extent. Other, more powerful factors (growing vocabulary, real life experience and academic knowledge, etc.) come into play. In terms of the relative involvement of the different components of RAN task performance, it means approximately the following: symbolic RAN task performance is based upon two major factors (first and foremost, it depends on practice effects, and somewhat secondarily on attention), whereas non-symbolic RAN task performance still mostly relies on the efficiency of attentional control. In other words, for normal readers, the "A" in RAN should really stand for attention, not automaticity, but to a different extent for the symbolic and non-symbolic subtasks.

If the above account is correct, it is worth looking more closely at what stimuli features matter most when used in symbolic and non-symbolic RAN subtasks. Presumably, some combination of the following factors needs to be considered:

- *Natural sequencing.* It should be important to examine the contribution of stimulus sequencing in the performance of the RAN task (another factor that clearly distinguishes symbolic and non-symbolic RAN subtasks). For example, letters and digits are more likely than objects or colors to be processed in short sequences (letters as bigrams or trigrams, digits as two or three digit sequences), whereas objects and colors are not likely to be chunked as sequences of two or three items. Practice reading a language and dealing with numbers presents a person with a rich set of sequential experiences with letters and digits, and some combinations of letter sequences, for example, will be more naturally familiar because they are more frequent and hence are more likely to be perceived and processed in sequence than others.

- *Symbolic/Non-symbolic status of the stimulus.* The nature of the link between a stimulus and its name (which also determines some basic inherited difference between symbolic and non-symbolic stimuli in RAN) may be important. For example, a given letter of the alphabet or digit will evoke its name because the visual form the item takes will normally closely resemble some basic or prototypical mental representations of that item. In the case of objects, a given line drawing used as a stimulus in the RAN task may depart greatly from a mental representation of the prototype for that object (e.g., a line drawing picture of a clock will likely not correspond to the prototypical mental image of a clock as well as does, say, the letter "A" correspond to a mental image of an "A".
- *Size of the stimulus source set.* It should be important to examine the impact of the total number of potential stimuli in the “universe” (the full source set) from which the stimuli used in a given RAN task subset was drawn from (e.g., the 26 letters of the alphabet or the 10 digits compared to the virtually unlimited number

of objects or substantially smaller but still very considerable number of shades of different colors.

- *Attention load handling demands.* Finally, individual differences in how efficiently attention resources are managed should substantially influence RAN performance across all types of stimuli, if indeed attention remains an important determinant of RAN task performance.

To test these assumptions, Study 2 employed a new series of RAN tasks that were carefully modified to manipulate the factors of (1) familiarity in combinations of symbolic stimuli (relative frequency of bigrams), (2) stimulus type (symbolic and non-symbolic), (3) source set size, and (4) attention load demands – with the two last factors varying within the two stimulus types.

Modified versions of the RAN task

Overall 10 new RAN subtasks were developed for this study. Two of them addressed the difference in familiarity with the elements of printed text by using as stimuli (symbolic) bigrams of different relative frequencies as they appear in printed English texts. The same 5 letters – *a, d, o, p,* and *s* – as used in the original letter naming RAN subtask were put into pairs in all possible combinations, and the relative frequency for each bigram was obtained using data from Pommerening (2000). For example, the English bigram *sa* has a high relative frequency of 11.4 (number of appearances per 1000 characters in an average printed text), whereas the bigram *ao* is extremely rare, appearing in printed texts on average only 0.2 times per 1000 characters (see also Jones & Mewhort, 2004, who provided somewhat different numbers, though reflecting highly similar proportions across all bigrams utilized here). These relative frequencies then were used to create two bigram-based versions of the letter naming RAN subtask. In the High Frequent version, the mean of the relative frequencies of all the bigrams used was 7.86 (per 1000 characters of printed text), whereas in the Low Frequent version the mean was only 2.54. The "5 lines by 10 items per line" matrix used in the RAN task yielded a set of 9 x 5 = 45 bigrams (the pairs formed by the last letters of each line with the first letters of the next lines were not counted). In accordance with the original letter naming RAN subtask, each of the 5 letter stimuli appeared 10 times each in the High Frequent and Low Frequent modified versions (see Appendix G).

The remaining 8 modified versions of the RAN task were constructed by manipulating the following characteristics: symbolic versus non-symbolic nature of the stimuli to be named, heavy versus light attention load in the task (as described below) and source set size (large versus small). These manipulations were crossed (2 x 2 x 2) to yield the 8 new RAN task subtypes. The details of this construction follow.

- *Stimuli type* (symbolic/non-symbolic). The symbolic RAN subtasks used letter stimuli and the non-symbolic subtasks used pictures of objects and animals.
- *Source set size*. Source set size was manipulated as follows. In the symbolic RAN subtask (letters), the Large set size version used 5 consonants (*d, n, p, s,* and *v*) as stimuli and the Small set size version used 5 vowels (*a, e, i, o*, and *u*) as stimuli. In the non-symbolic RAN subtask (objects), the Large set size version used line drawings of 5 unrelated objects (*bell, book, clock, flag,* and *star*) as stimuli and the Small set size version used line drawings of 5 animal pictures (*bear, cat, cow, dog,* and *pig*) as stimuli. The names of the pictures were matched for length and all were drawn from nouns with relatively high frequency.

- *Attention load.* Attention was manipulated by asking participants to perform a concurrent activity while naming stimuli on the screen. In the Light Attentional Load condition the participants were required to press the space bar on the computer keyboard each time they named the last stimulus in the row (i.e., 5 times), to simply indicate the completion of each line of stimuli, without otherwise pausing in reading the names of the stimuli. In the Heavy Attentional Load condition, the participants were required to press the space bar on the computer keyboard each time a particular combination of stimuli was encountered, without otherwise pausing in reading the names of the stimuli (participants were instructed as to what particular stimulus pair watch for). The target pair occurred 5 times in the set of 50 items.

To summarize, there were 10 modified RAN subtasks created for this study. For convenience these will be labeled as M-RAN tasks (Modified-RAN) with additional labels as follows (see Appendix H for examples).

1. M-RAN-High-Frequency-Bigram. This subtask used letter stimuli composed of high frequency bigrams, involving both consonants and vowels.
2. M-RAN-Low-Frequency-Bigram. This subtask used letter stimuli composed of low frequency bigrams, involving both consonants and vowels.
3. M-RAN-Symbolic-Small-Light. This subtask used letter stimuli (*symbolic*) composed of vowels (*small* source set) with the *light* attention load instructions (press the space bar at the end of each line).

4. M-RAN-Symbolic-Small-Heavy. This subtask used letter stimuli (*symbolic*) composed of vowels (*small* source set) with the *heavy* attention load instructions (press the space bar upon encountering a designated stimulus pair).
5. M-RAN-Symbolic-Large-Light. This subtask used letter stimuli (*symbolic*) composed of consonants (*large* source set) with the *light* attention load instructions (press the space bar at the end of each line).
6. M-RAN-Symbolic- Large-Heavy. This subtask used letter stimuli (*symbolic*) composed of consonants (*large* source set) with the *heavy* attention load instructions (press the space bar upon encountering a designated stimulus pair).
7. M-RAN-Non-symbolic-Small-Light. This subtask used picture stimuli (*non-symbolic*) composed of line drawings of animals (*small* source set) with the *light* attention load instructions (press the space bar at the end of each line).
8. M-RAN- Non-symbolic-Small-Heavy. This subtask used picture stimuli (*non-symbolic*) composed of line drawings of animals (*small* source set) with the *heavy* attention load instructions (press the space bar upon encountering a designated stimulus pair).
9. M-RAN- Non-symbolic-Large-Light. This subtask used picture stimuli (*non-symbolic*) composed of line drawings of unrelated objects (*large* source set) with the *light* attention load instructions (press the space bar at the end of each line).
10. M-RAN- Non-symbolic-Large-Heavy. This subtask used letter picture stimuli (*non-symbolic*) composed of line unrelated objects (*large* source set) with the *heavy* attention load instructions (press the space bar upon encountering a designated stimulus pair).

The primary goal of this study was to investigate the role of the above-mentioned attention and stimulus type and set size factors on RAN performance by using suitably modified subtasks and to investigate their possible influence on the RAN-reading link. The following general outcomes were hypothesized.

Regarding the comparison between the High and Low frequency bigram versions of the RAN task, it was expected that because high frequency bigrams are more familiar, their processing will proceed faster, resulting in shorter RAN performance time. This anticipated outcome is depicted as Scenario 1 in Figure 4.1. A finding conforming to this pattern will affirm the importance of exposure to letter patterns.

Regarding the eight RAN subtasks involving orthogonal manipulation of symbolic versus non-symbolic stimuli, light versus heavy attention load and larger versus small source set, the chief possible outcomes were as follows.

It was expected that there would be slower performance on non-symbolic subtasks compared to symbolic because these involve less familiar stimuli (whose naming is less automatized due to higher variability in how the recognized stimulus is mapped to its proper label). This outcome is depicted as Scenario 2 in Figure 4.2. A finding conforming to this pattern will affirm the importance of the symbolic/non-symbolic distinction described earlier, consistent with the idea that practice with letters and digits makes a difference in performance.

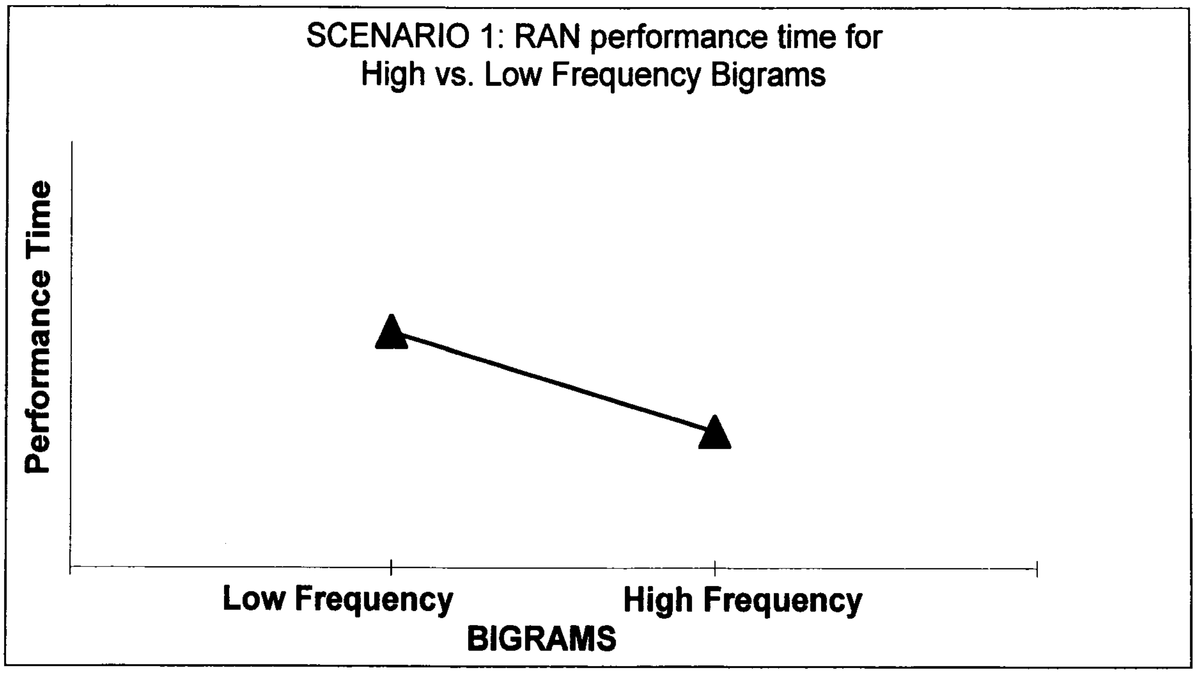


Figure 4.1. A hypothetical scenario reflecting expected pattern in performance times on bigram-based modified RAN subtasks

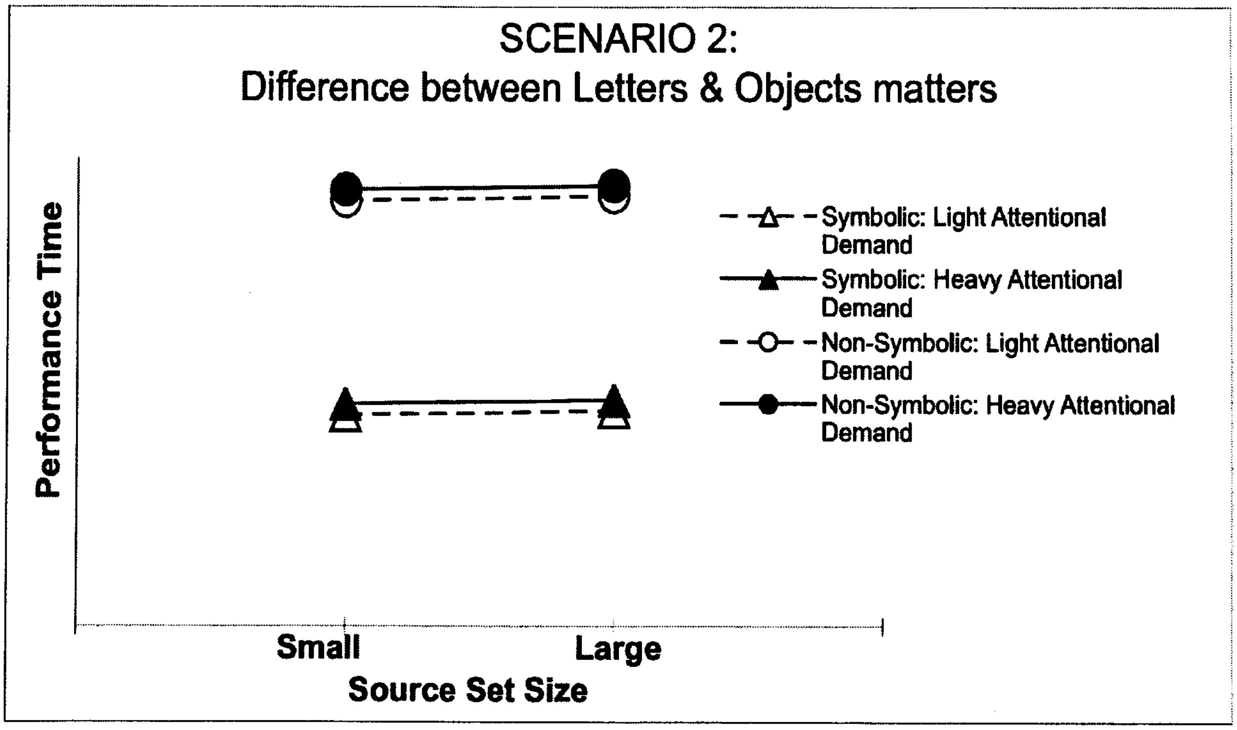


Figure 4.2. A hypothetical scenario reflecting expected pattern in performance times on modified RAN subtasks if stimulus type matters the most

It was expected that under the heavy attentional load condition performance would be slower compared to the light attentional load condition because, for the reasons given above, attention factors are expected to plan an important role in adult RAN task performance. This outcome is depicted as Scenario 3 in Figure 4.3.

It was expected that performance would be slower on subtasks based on stimuli drawn from a large source set compared to a small source set, indicating that ease of memory search is a factor in RAN task performance. This outcome is depicted as Scenario 4 in Figure 4.4.

The above expectations are all about main effects. With so many variables, however, there is the possibility of interaction effects. There is no theoretical motivation for predicting any particular interaction effect, although clearly it would be interesting to see if any emerge. One intuitively plausible interaction effect is shown in Figure 4.5. Here, the outcome depicted reflects the possibility that the factors of attentional demand and source set would affect RAN performance differently in symbolic and non-symbolic subtasks. Namely, in more automatized symbolic subtasks source size would influence performance time to a greater extent, while non-symbolic subtasks that are more attention-based would be more sensitive to manipulations of the attentional load factor. Though some could argue in favor of the exact opposite prediction – that manipulations within each domain would be less influential. That is the intensity of attentional load would rather affect symbolic, whereas effect of the set size manipulation would be more noticeable in non-symbolic subtasks.

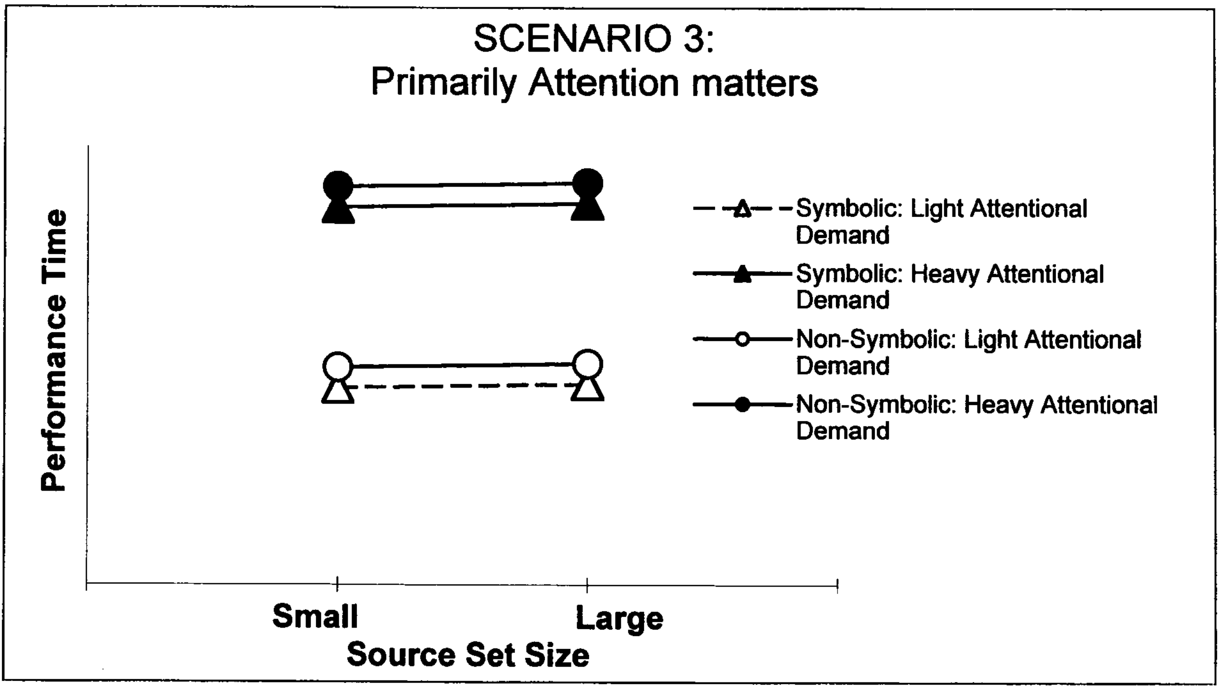


Figure 4.3. A hypothetical scenario reflecting expected pattern in performance times on modified RAN subtasks if attention matters the most

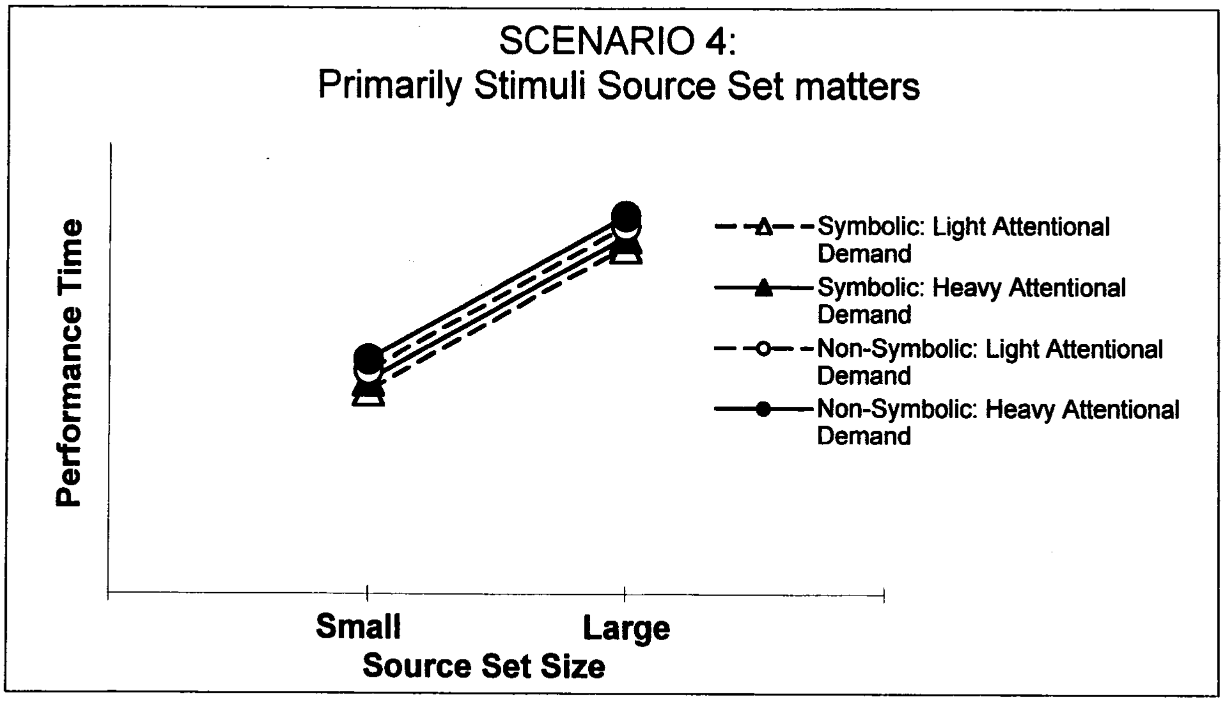


Figure 4.4. A hypothetical scenario reflecting expected pattern in performance times on modified RAN subtasks if source set size matters the most

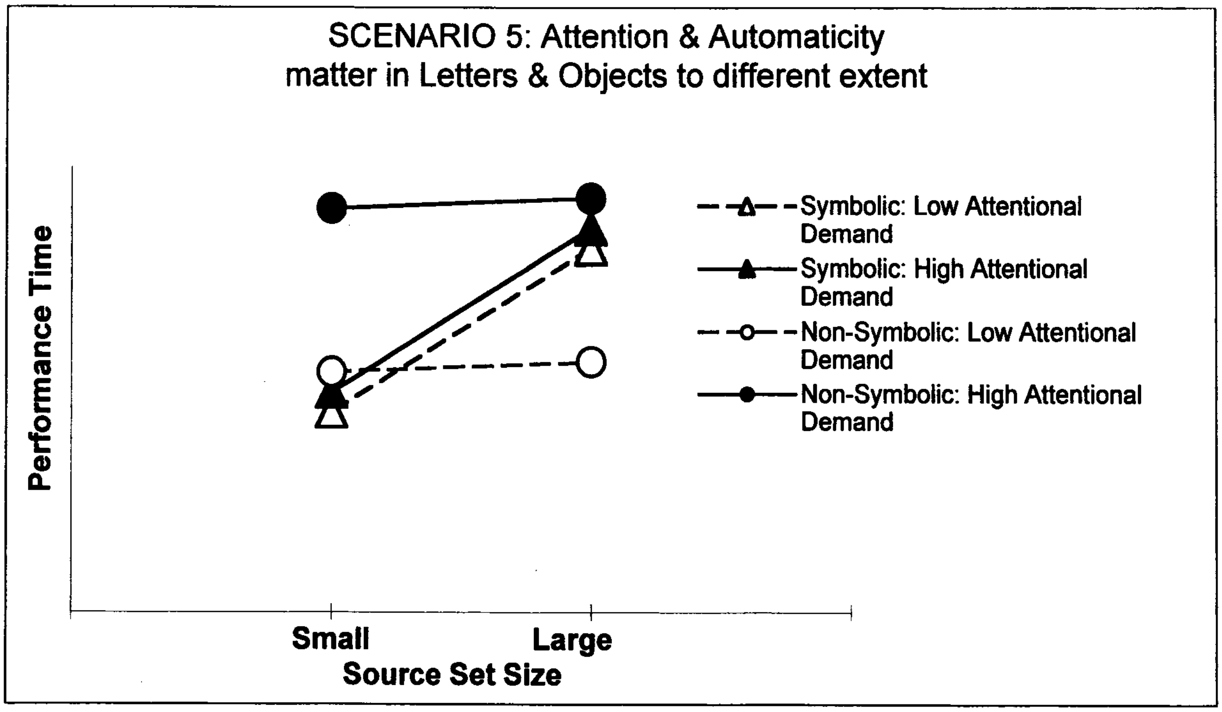


Figure 4.5. A hypothetical scenario reflecting expected pattern in performance times on modified RAN subtasks if attention and source set size influence naming speed symbolic and non-symbolic subtasks to a different degree

Another important expectation was that, perhaps with the exception of the inherently strong association between performance on symbolic (letter based) RAN subtasks and reading rate, the more challenging modified RAN subtasks (the ones resulting in overall slower naming speed) would also show a higher degree of association with reading speed, thus confirming the greater role of the corresponding factors in it with respect to reading. This expectation is based on the assumption that what makes the RAN task work as a reliable predictor of reading is some set of cognitive mechanisms shared by both activities.

Method

Participants

Sixteen participants (11 women and 5 men, ranging in age from 19 to 42 with a mean of 24.5, median of 22.5, and the mode of 21) composed the sample for Study 2. These 16 participants had all been tested in Study 1, and they received the new tasks in addition to the tasks described in Study 1. They all met the criteria for inclusion as described in Study 1. Thirteen named English as their dominant language and the remaining three were fluently bilingual (they indicated both languages as dominant, although they reported had French as the mother tongue).

Materials

Ten modified versions of the RAN task manipulating three factors – attention load, source set size, stimulus type and familiarity factors—were created for purposes of this study. In all other respects, these subtasks were similar to the original RAN task as described in the previous chapter.

M-RAN-High-Frequency-Bigram. Five letters – *a, d, o, p,* and *s,* – each repeated ten times were mixed to produce pairs (bigrams) with the highest possible index of relative frequency, as determined in Pommerening (2000).

M-RAN-Low-Frequency-Bigram. Five letters – *a, d, o, p,* and *s,* – each repeated ten times were mixed to produce pairs (bigrams) with the lowest possible index of relative frequency, as determined in Pommerening (2000).

For the remaining eight modified subtasks the stimuli were orthogonally varied as follows:

The subtasks M-RAN-Symbolic-Small-Light and M-RAN-Symbolic-Small-Heavy used as stimuli the vowels: *a, e, i, o,* and *u* (symbolic; small source set) and presented with the Light Attention load (the task of pressing a space bar each time when the last character in each raw is named) and the Heavy Attention load instructions respectively (the task of pressing a space bar in response to each encounter of the combination "*e-a*").

The subtasks M-RAN-Symbolic-Large-Light and M-RAN-Symbolic-Large - Heavy used as stimuli the consonants: *d, n, p, s,* and *v* (symbolic; large source set) and presented with the Light Attention load (the task of pressing a space bar each time when the last character in each raw is named) and the Heavy Attention load instructions respectively (the task of pressing a space bar in response to each encounter of the combination "*n-p*").

The subtasks M-RAN-Non-symbolic-Small-Light and M-RAN-Non-symbolic-Small-Heavy used line drawing pictures of the animals: *bear, cat, cow, dog,* and *pig* (symbolic; small source set) and presented with the Light Attention load (the task of pressing a space bar each time when the last character in each raw is named) and the Heavy Attention load instructions respectively (the task of pressing a space bar in response to each encounter of the combination "*cow-dog*").

The subtasks M-RAN-Non-symbolic-Large-Light and M-RAN-Non-symbolic-Large-Heavy used line drawing pictures of the unrelated objects: bell, book, clock, flag, and star (symbolic; large source set) and presented with the Light Attention load (the task of pressing a space bar each time when the last character in each raw is named) and the

Heavy Attention load instructions respectively (the task of pressing a space bar in response to each encounter of the combination "*clock-star*").

Procedure and design

All participants completed the full set of tasks according to the Study 1 procedure, in addition to undertaking the extra set of experimental tasks specific to Study 2. These new tasks required less than 10 minutes per day on each of the two days of testing involved in Study 1. All the modified RAN subtasks were administered in the same mode as the original RAN subtasks were – on a computer screen of a G4 iMac in 5 rows of 10 items, using PsyScope software (Cohen et al. 1993). Performance time on each subtask was recorded by the program, while a CD recording of the spoken responses was also made using a CD recorder (Marantz CDR 300) to enable further analysis of uncorrected mistakes in stimulus naming and other aspects of performance.

In other respects the procedure for Study 2 was the same as for Study 1, including measures of silent reading rate and comprehension as well as the original RAN subtasks and those used to generate primary indices of different aspects of automaticity and attention shift cost.

As the modified RAN tasks were added to the Study 1 procedure, the order of their presentation was carefully counterbalanced across participants by conditions and proximity to other tasks, so that nobody received modified RAN subtasks in the same order in the same combination with either of the neighboring activities that were specific to Study 1.

Results

For all the analyses reported below, the alpha level for significance was set at $p < .05$. All t-tests and correlation coefficients are one-tailed, unless otherwise is specified. Outliers were handled the same way as in Study 1. Descriptive statistics for all variables analyzed in Study 2 are given in Table 4.1.

On average, for the core tasks (those that were common for both Studies 1 and 2), the 16 participants' performance in Study 2 was quite similar to that of the entire sample of 52. For example, none of t-tests comparing RAN task performance of 16 participants of Study 2 to the performance of the remaining 52 participants in the sample turned out to be significant. The same was true for reading performance in both languages. The only significant difference in results between the participants of Study 2 and the rest of the sample was observed for measures of attention. Overall, Study 2 participants were faster than the other participants in Study 1 in performing the task on Form B of the Trail Making test (t (66) = 2.961, p = .004), with no significant difference in performance on Form A. This difference was subsequently reflected in the calculated index of attention shift cost (t (66) = 2.543, p = .013).

Overall, performance was somewhat slower on the eight modified RAN subtasks than on the corresponding original subtasks. This was likely due to the introduction of the additional task of pressing the space bar either in response to the last stimulus in the row (in the light attention demand condition) or in response to the specified target (under the heavy attention load condition). Naming stimuli in both bigram-based RAN subtasks was performed the fastest among all.

Table 4.1. Descriptive statistics of the major variables (N=16)

Task		Variable	Mean	SD
RAN				
	1	Performance time on letters (sec.):	**18.16**	**2.02**
	2	Performance time on digits (sec.):	**18.49**	**2.09**
	3	Performance time on colors (sec.):	**30.54**	**4.49**
	4	Performance time on objects (sec.):	**40.34**	**6.82**
	5	Symbolic (letters & digits combined):	36.89	4.45
	6	Non-symbolic (colors & objects combined):	72.02	12.32
	7	Overall (all subtasks combined):	108.91	13.24
Primed decision		Effect type (condition/SOA/trial):		
	8	Facilitation – xR/long SOA/regular (ms):	25.	22.3
	9	Facilitation – xU/long SOA/regular (ms):	26.	38.5
	10	Interference – xR/long SOA/surprise (ms):	-53.	44.1
	11	Interference – xU/long SOA/surprise (ms):	-57.	56.0
	12	Facilitation – xR/short SOA/regular (ms):	14.	25.2
	13	Facilitation – xU/short SOA/surprise (ms):	42.	36.2
	14	Facilitation (xU, short SOA, surprise trials) relative to base-line***[Ballistic automaticity index]***:	**.06**	**.05**
	15	CV – xU, short SOA, neutral trials:	.17	.06
	16	CV – xR, short SOA, neutral trials: ***[Efficiency-based automaticity index]***	**.17**	**.04**
Trail making				
	17	Form A performance time (sec.):	24.10	6.84
	18	Form B performance time (sec.):	**42.58**	**12.34**
	19	Difference in performance time (B–A)	18.48	9.38
	20	Standardized residual (B against A): ***[Primary index of attention shift cost]***	**.005**	**.99**
Reading (L1)				
	21	Reading rate (ms per word):	**272**	**92.1**
	22	Accuracy (% correct responses):	67.0	13.37
Reading (L2)				
	23	Reading rate (ms per word):	336	95.5
	24	Accuracy (% correct responses):	71.1	22.83

Table 4.1. Descriptive statistics of the major variables (N=16) continues

Modified RAN				
	25	M-RAN-Symbolic-Small-Light (sec.):	**21.72**	**2.09**
	26	M-RAN-Symbolic-Large-Light (sec.):	**20.12**	**2.81**
	27	M-RAN-Non-Symbolic-Small-Light (sec.):	**34.91**	**5.94**
	28	M-RAN-Non-Symbolic-Large-Light (sec.):	**38.33**	**9.53**
	29	M-RAN-Symbolic-Small-Heavy (sec.):	**26.76**	**4.68**
	30	M-RAN-Symbolic-Large-Heavy (sec.):	**27.03**	**5.20**
	31	M-RAN-Non-Symbolic-Small-Heavy (sec.):	**44.65**	**7.65**
	32	M-RAN-Non-Symbolic-Large-Heavy (sec.):	**45.90**	**10.49**
	33	M-RAN-High-Frequency-Bigram (sec.):	**16.20**	**1.60**
	34	M-RAN-Low-Frequency-Bigram (sec.):	**17.30**	**2.18**

In bold: Variables used in further analyses.

Modified RAN subtasks. The naming times obtained for the 10 modified RAN subtasks were submitted to analyses as follows. The first analysis addressed the question whether, in the symbolic version of the RAN task, the bigram frequency had an impact on naming times. For this analysis, the naming times from the M-RAN-High-Frequency-Bigram and the M-RAN-Low-Frequency-Bigram conditions were compared. The results showed that letter targets in sequences composed of high frequent bigrams were named significantly faster than those in sequences composed of low frequency bigrams (t (15) = 3.276, $p = .005$, two-tailed).

The next analysis addressed the questions about whether the symbolic versus nonsymbolic nature of the RAN task stimuli, the source set size, and attention load all play roles in RAN task performance and whether there are interactions between these factors. For this purpose, the naming times were submitted to a 2x2x2 repeated measures ANOVA where the factors were Type (symbolic, non-symbolic stimuli), Source Set Size (large, small) and Attention Load (heavy, light). As expected, the analysis revealed a significant main effect for stimulus type (F (1,15) = 131.22, MSe = 70,787,953.39, $p <$ .001, partial $\eta^2 = .897$), indicating faster naming for symbolic stimuli. The analysis also revealed a significant main effect for attention load (F (1,15) = 62.12, MSe = 27,543,164.06, $p < .001$, partial $\eta^2 = .806$), indicating faster naming under the light attentional demand. There was no main effect for source set size (F (1,15) = 1.063, $p >$ .05). See Figure 4.6, and Appendix I for the ANOVA summary table.

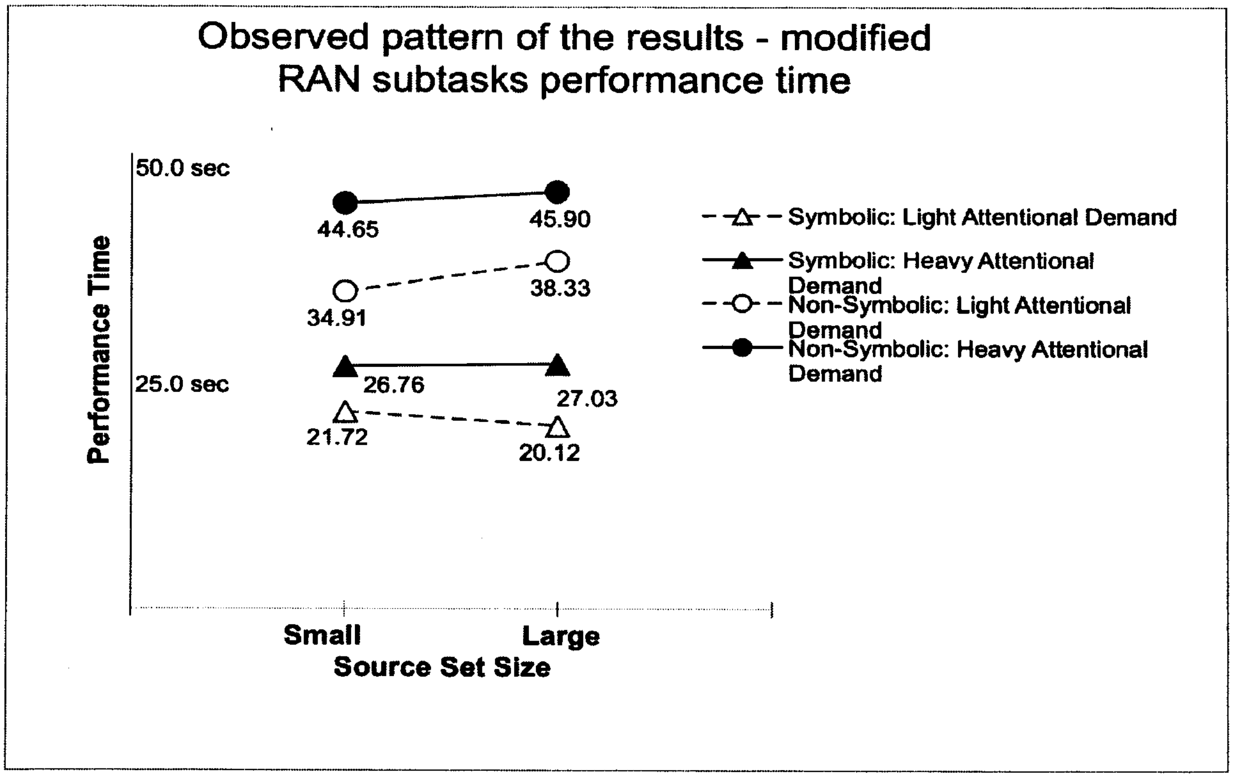


Figure 4.6. Observed pattern of performance times on modified RAN subtasks

The 2x2x2 interaction effect was not significant, suggesting that the effects of attention and stimulus type were consistent across conditions. However, there was a significant interaction effect of stimulus source set size by stimulus type (F (1,15) = 18.973, MSe = 3,775,251.33, p = .001, partial η^2 = .558). The nature of this interaction was that among non-symbolic stimuli, those drawn from a smaller source set (pictures of animals) were named significantly faster than those drawn from a larger source set (pictures of unrelated common objects), whereas within symbolic stimuli, the reverse was true: in that those drawn from a smaller source set (vowels) were named significantly slower than those drawn from a larger source set (consonants).

Relationships among variables. Correlational analyses were run to examine the relationships among the different variables and their connection to reading and to performance on the original RAN task, as well as to all variables used as predictors of RAN task performance in the subsequent multiple regression analyses. These are shown in Tables 4.2, 4.3 and 4.4. For all these analyses, n = 16.

The pattern of inter-correlations among the individual RAN subtasks, both the original and the modified ones, emerged to be quite strong (not surprisingly because they overlap greatly in the basic task demand – rapid naming). RAN subtasks using stimuli of the same type (symbolic; non-symbolic) composed pairs that were most highly correlated, whereas the least correlated RAN subtasks were those with stimuli of different types. For example, performance on the original letter-naming subtask was correlated with performance on the task requiring the naming of vowels (under both low and the high attentional demand conditions, and with naming of frequent and rare bigrams (all r-values $\geq$ .690, all p-values $\leq$ .01). The same was true for the naming of

Table 4.2. Inter-correlation coefficients among original and modified RAN subtasks (N=16)

VARIABLES:	1	2	3	4	5	6	7	8	9	10	11	12	13	14
1. Letter-RAN	-													
2. Digit-RAN	.596**	-												
3. Color-RAN	.072	.331	-											
4. Object-RAN	-.066	-.086	.406	-										
5. M-RAN-Symbolic-Small-Light	.716**	.647**	.094	.128	-									
6. M-RAN-Symbolic-Large-Light	.475*	.675**	.583**	.350	.519*	-								
7. M-RAN-Non-Symbolic-Small-Light	-.016	.171	.474*	.805***	.264	.594*	-							
8. M-RAN-Non-Symbolic-Large-Light	-.055	.040	.325	.916***	.206	.430	.894***	-						
9. M-RAN-Symbolic-Small-Heavy	.737**	.612**	.562**	.176	.645**	.652**	.203	.325	-					
10. M-RAN-Symbolic-Large-Heavy	.462*	.341	.397	.723**	.542*	.647**	.762***	.672**	.633**	-				
11. M-RAN-Non-Symbolic-Small-Heavy	.306	.319	.517**	.586**	.327	.633**	.671**	.731**	.665**	.678**	-			
12. M-RAN-Non-Symbolic-Large-Heavy	.268	.338	.597**	.644**	.274	.737**	.755***	.764***	.580*	.750**	.907***	-		
13. M-RAN-High-Frequency-Bigram	.690**	.655**	.199	-.056	.569**	.624**	-.031	.137	.595**	.287	.214	.266	-	
14. M-RAN-Low-Frequency-Bigram	.722**	.740**	.471*	.029	.493**	.785***	.125	.276	.790***	.458*	.607**	.647**	.791***	-

* p<.05, ** p<.01, *** p<.001. All one-tailed tests

The list of variables:

1 – RAN performance time on letters task; 2 – RAN performance time on digits task; 3 – RAN performance time on colors task; 4 – RAN performance time on objects task; 5 – Modified RAN: light attentional load, vowel letters; 6 – Modified RAN: light attentional load, consonant letters; 7 – Modified RAN: light attentional load, pictures of animals; 8 – Modified RAN: light attentional load, pictures of common objects; 9 – Modified RAN: heavy attentional load, vowel letters; 10 – Modified RAN: heavy attentional load, consonant letters; 11 – Modified RAN: heavy attentional load, pictures of animals; 12 – Modified RAN: heavy attentional load, pictures of common objects; 13 – Modified RAN: based on frequent bigrams; 14 – Modified RAN: based on rare bigrams.

Table 4.3. Inter-correlation coefficients for the major variables (N=16)

VARIABLES:	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
1. M-RAN-Symbolic-Small-Light	-															
2. M-RAN-Symbolic-Large-Light	.519*	-														
3. M-RAN-Non-Symbolic-Small-Light	.264	.594*	-													
4. M-RAN-Non-Symbolic-Large-Light	.206	.430	.894***	-												
5. M-RAN-Symbolic-Small-Heavy	.645**	.652**	.203	.325	-											
6. M-RAN-Symbolic-Large-Heavy	.542*	.647**	.762***	.672**	.633**	-										
7. M-RAN-Non-Symbolic-Small-Heavy	.327	.633**	.671**	.731**	.665**	.678**	-									
8. M-RAN-Non-Symbolic-Large-Heavy	.274	.737**	.755***	.764***	.580*	.750**	.907***	-								
9. M-RAN-High-Frequency-Bigram	.569**	.624**	-.031	.137	.595**	.287	.214	.266	-							
10. M-RAN-Low-Frequency-Bigram	.493**	.785***	.125	.276	.790***	.458*	.607**	.647**	.791***	-						
11. Ballistic automaticity	.262	-.081	-.058	-.077	-.193	-.091	-.273	-.384	.235	-.136	-					
12. Automaticity/Efficiency	.457*	.211	.230	.306	.052	.164	.176	.199	.130	.142	.389	-				
13. Attention: Form B	.409	.670**	.320	.203	.641**	.706***	.650**	.618**	.515*	.573*	-.010	.062	-			
14. Attention shift cost	.254	.294	.404	.483*	.197	.537*	.318	.291	.165	.047	.107	-.068	.736***	-		
15. Reading rate (L1)	.170	.309	.176	-.024	.449*	.204	.365	.280	.533**	.638**	.132	-.091	.380	.011	-	
16. Reading rate (L2)	-.155	-.215	.224	-.001	.044	-.145	.195	.165	.316	.403	.053	.049	.208	-.116	.625**	-

* p<.05, ** p<.01, *** p<.001. All one-tailed tests

The list of variables:

1 – Modified RAN: light attentional load, vowel letters; 2 – Modified RAN: light attentional load, consonant letters; 3 – Modified RAN: light attentional load, pictures of animals; 4 – Modified RAN: light attentional load, pictures of common objects; 5 – Modified RAN: heavy attentional load, vowel letters; 6 – Modified RAN: heavy attentional load, consonant letters; 7 – Modified RAN: heavy attentional load, pictures of animals; 8 – Modified RAN: heavy attentional load, pictures of common objects; 9 – Modified RAN: based on frequent bigrams; 10 – Modified RAN: based on rare bigrams;.11 – Facilitation effect (xU, short SOA, surprise trials) – relative value (adjusted by the corresponding base-line condition); 12 – CV index (xR, short SOA, neutral trials); 13 – Attention: Form B performance time ("Trail Making" test of attention); 14 – Standardized residual (Form B against Form A performance time on the "Trail Making" test) as an index of the attention shift cost; 15 – Reading rate (ms/word) in L1; 16 – Reading rate (ms/word) in L2.

common objects in the original and both modified RAN subtasks (low and high demand for attention control) (all *r*-values > .64, all *p*-values ≤ .01).

Analyses of correlations between performance on the modified RAN subtasks and the reading measures and indices of automaticity and attention revealed the following patterns. Regarding correlations between indices of automaticity and performance on the modified RAN subtasks, only the CV index of automaticity was significantly correlated with the speed of naming vowels, under the light attentional load condition ($r = .457$, $n = 16$, $p = .038$). No other correlation with an automaticity index was statistically significant.

In contrast, correlations between indices of attention and RAN performance did yield several significant results. Performance time on Form B of the Trail Making test and the speed of naming consonants under the low attentional load condition were significantly correlated ($r = .670$, $p < .01$). Also, all subtasks under the high attentional load condition correlated significantly with naming vowels, consonants, pictures of animals, and pictures of common objects ($r = .641$, $p < .01$; $r = .706$, $p < .001$; $r = .650$, $p < .01$; and $r = .618$, p < .01, respectively).

The correlations between performance on the modified RAN subtasks and reading were not strong. Only the correlation between RAN-M-Symbolic-Small-Heavy and reading reached significance ($r = .449$, $p = .040$). The correlation between RAN-M-Non-Symbolic-Small-Heavy and reading showed a trend only ($r = .365$, $p = .082$). However, the magnitudes of these correlations are compatible with the significant correlations between measures of RAN task performance and reading rate observed in Study 1, and perhaps the small n of 16 was responsible for the low power in these analyses.

Performance on both the High-Frequency and Low-Frequency bigram-based RAN subtasks was strongly correlated with L1 silent reading speed ($r = .533$, $p = .017$, and $r = .638$, $p = .004$, respectively).

Finally, when the intercorrelations between the variables for the 52 participants in Study 1 are compared with the analogous correlations obtained for the 16 participants in Study 2, these patterns of correlation are fairly consistent (see Table 4.4 below and Table 3.2 in Chapter 3)

Multiple regression analyses. To address the major research questions about factors underlying RAN task performance, the data were submitted to a series of multiple regression analyses.

First, a word of caution. The multiple regression statistical technique typically requires samples of much larger size (Tabachnick & Fidell, 2001), than the one used in Study 2 to produce more reliable (trustworthy) results. With only sixteen participants, the findings discussed below should be treated very carefully to avoid premature conclusions. Even the most sound statistical results, at best, represent tendencies to be verified in follow-up studies (including Study 3 in the next chapter) on more diverse samples. For this reason, as well, adjusted R^2 will be reported in addition to the statistics presented in the corresponding tables.

Table 4.4. Inter-correlation coefficients for the major variable shared by Study 1 & Study 2 (N=16)

VARIABLES:	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**
1. Letter-RAN	-													
2. Digit-RAN	.596**	-												
3. Color-RAN	.072	.331	-											
4. Object-RAN	-.066	-.086	.406	-										
5. Symbolic RAN	.892***	.875***	.228	-.076	-									
6. Non-symbolic RAN	-.033	.092	.745***	.877***	.034	-								
7. Ballistic automaticity	.076	.236	-.399	-.080	.165	-.308	-							
8. Automaticity/Efficiency	.221	.312	-.196	.038	.304	-.059	.389	-						
9. Attention (Form A)	.673**	.453*	.573*	.226	.653**	.425*	-.135	.168	-					
10. Attention (Form B)	.580**	.418	.313	.559*	.559*	.540*	-.010	.062	.658**	-				
11. Attention (Forms B–A)	.272	.219	-.006	.570*	.259	.400	.085	-.040	.136	.836***	-			
12. Attention shift cost	.165	.148	-.099	.539*	.156	.335	.107	-.068	-.025	.736**	.987***	-		
13. Reading rate (L1)	.541*	.326	.112	-.038	.516*	.027	.132	-.091	.549*	.380	.100	.011	-	
14. Reading rate (L2)	.184	.265	.055	-.086	.257	-.026	.053	.049	.437*	.208	-.045	-.116	.625**	-

* p<.05, ** p<.01, *** p<.001. All one-tailed tests

The list of variables:

1 – RAN performance time on letters task; 2 – RAN performance time on digits task; 3 – RAN performance time on colors task; 4 – RAN performance time on objects task; 5 – RAN performance time on letters and digits tasks combined; 6 – RAN performance time on colors and objects task combined; 7 – Facilitation effect (xU, short SOA, surprise trials) – relative value (adjusted by the corresponding base-line condition); 8 – CV index (xR, short SOA, neutral trials); 9 – Attention: Form A performance time ("Trail Making" test of attention); 10 – Attention: Form B performance time ("Trail Making" test of attention); 11 – Difference in performance time between Form B & Form A on the "Trail Making" test; 12 – Standardized residual (Form B against Form A performance time on the "Trail Making" test) as an index of the attention shift cost; 13 – Reading rate (ms/word) in L1; 14 – Reading rate (ms/word) in L2.

Exactly as in Study 1, in these multiple regression analyses, performance on the modified RAN subtasks served as the criterion variables to be explained by the following predictor variables, in order to determine what factors best explain performance on RAN tasks:

(1) The index of ballistic automaticity (relative facilitation effect on surprise trials with the short SOA in the "expect unrelated target" condition of the primed decision making task);

(2) The index of efficiency (automaticity) in stimulus recognition (the CV-index), calculated for neutral trials with the short SOA in the "expect related target" condition of the primed decision making task; and

(3) The index of general attention (performance time on Form B of the Trail Making test).

The following statistically significant findings were obtained (see Tables 4.5 – 4.14 for details). The overall model for the consonant naming RAN subtask, i.e., involving symbolic stimuli from a large source set under the condition of light attentional load, was significant ($R^2 = .501$, adjusted $R^2 = .376$, $p = .034$). It was the only significant result for the condition of light attentional load, whereas three out of four models, with modified RAN subtasks under the condition of heavy attentional load as criterion variables, showed significant findings. These were: $R^2 = .533$, adjusted $R^2 = .416$, p = .024, for M-RAN-Symbolic-Large-Heavy (naming consonants), $R^2 = .561$, adjusted $R^2 = .451$, p = .017, for M-RAN-Non-Symbolic-Small-Heavy (naming pictures of animals), and $R^2 = .631$, adjusted $R^2 = .546$, p = .006, for M-RAN-Non-Symbolic-Large-Heavy (naming pictures of common objects).

Table 4.5

Results of a multiple regression analysis of modified RAN (M-RAN-Symbolic-Small-Light) subtask performance by index of ballistic automaticity, CV-index of automaticity, and attention index

Variable:	r[a]	R	R^2	R^2 change	F change	Sign. F	Final β
Ballistic automaticity	.262	.262	.069	.069	1.030	.327	.114
CV index of automaticity	.457	.466	.217	.149	2.469	.140	.388
Attention (Form B)	.409	.605	.366	.148	2.805	.120	.386

[a] Zero-order correlations. $*p < .05$, $**\ p < .01$, $***\ p < .001$

Table 4.6

Results of a multiple regression analysis of modified RAN (M-RAN-Symbolic-Large-Light) subtask performance by index of ballistic automaticity, CV-index of automaticity, and attention index

Variable:	r[a]	R	R^2	R^2 change	F change	Sign. F	Final β
Ballistic automaticity	-.081	.081	.007	.007	.092	.766	-.166
CV index of automaticity	.211	.275	.076	.069	.975	.341	.235
Attention (Form B)	.670**	.708	.501**	.425**	10.221	.008	.654**

[a] Zero-order correlations. $*p < .05$, $**\ p < .01$, $***\ p < .001$

Table 4.7

Results of a multiple regression analysis of modified RAN (M-RAN-Non-Symbolic-Small-Light) subtask performance by index of ballistic automaticity, CV-index of automaticity, and attention index

Variable:	r[a]	R	R^2	R^2 change	F change	Sign. F	Final β
Ballistic automaticity	-.058	.058	.003	.003	.047	.831	-.154
CV index of automaticity	.230	.281	.079	.075	1.065	.321	.259
Attention (Form B)	.521*	.575	.331	.252	4.515	.055	.503

[a] Zero-order correlations. $*p < .05$, $**\ p < .01$, $***\ p < .001$

Table 4.8

Results of a multiple regression analysis of modified RAN (M-RAN-Non-Symbolic-Large-Light) subtask performance by index of ballistic automaticity, CV-index of automaticity, and attention index

Variable:	r[a]	R	R^2	R^2 change	F change	Sign. F	Final β
Ballistic automaticity	-.077	.077	.006	.006	.083	.777	-.212
CV index of automaticity	.306	.373	.139	.133	2.007	.180	.359
Attention (Form B)	.502*	.604	.365	.226	4.279	.061	.477

[a] Zero-order correlations. $*p < .05$, $**\ p < .01$, $***\ p < .001$

Table 4.9

Results of a multiple regression analysis of modified RAN (M-RAN-Symbolic-Small-Heavy) subtask performance by index of ballistic automaticity, CV-index of automaticity, and attention index

Variable:	r^a	R	R^2	R^2 change	F change	Sign. F	Final β
Ballistic automaticity	-.193	.193	.037	.037	.543	.473	-.226
CV index of automaticity	.052	.238	.057	.019	.265	.615	.101
Attention (Form B)	.641**	.674	.454	.398*	8.751	.012	.632*

[a]Zero-order correlations. *$p < .05$, ** $p < .01$, *** $p < .001$

Table 4.10

Results of a multiple regression analysis of modified RAN (M-RAN-Symbolic-Large-Heavy) subtask performance by index of ballistic automaticity, CV-index of automaticity, and attention index

Variable:	r^a	R	R^2	R^2 change	F change	Sign. F	Final β
Ballistic automaticity	-.091	.091	.008	.008	.116	.738	-.154
CV index of automaticity	.164	.235	.055	.047	.647	.436	.181
Attention (Form B)	.706**	.730	.533**	.477**	12.259	.004	.693**

[a]Zero-order correlations. *$p < .05$, ** $p < .01$, *** $p < .001$

Table 4.11

Results of a multiple regression analysis of modified RAN (M-RAN-Non-Symbolic-Small-Heavy) subtask performance by index of ballistic automaticity, CV-index of automaticity, and attention index

Variable:	r^a	R	R^2	R^2 change	F change	Sign. F	Final β
Ballistic automaticity	-.273	.273	.075	.075	1.130	.306	-.377
CV index of automaticity	.176	.410	.168	.094	1.465	.248	.283
Attention (Form B)	.650**	.749**	.561**	.392**	10.726	.007	.628**

[a]Zero-order correlations. *$p < .05$, ** $p < .01$, *** $p < .001$

Table 4.12

Results of a multiple regression analysis of modified RAN (M-RAN-Non-Symbolic-Large-Heavy) subtask performance by index of ballistic automaticity, CV-index of automaticity, and attention index

Variable:	r^a	R	R^2	R^2 change	F change	Sign. F	Final β
Ballistic automaticity	-.384	.384	.148	.148	2.425	.142	-.520*
CV index of automaticity	.199	.539	.291	.143	2.624	.129	.365
Attention (Form B)	.618*	.798**	.631**	.346**	11.425**	.005	.590**

[a]Zero-order correlations. *$p < .05$, ** $p < .01$, *** $p < .001$

Table 4.13
Results of a multiple regression analysis of modified RAN (M-RAN-High-Frequency-Bigram) subtask performance by index of ballistic automaticity, CV-index of automaticity, and attention index

Variable:	r^a	R	R^2	R^2 change	F change	Sign. F	Final β
Ballistic automaticity	.235	.235	.055	.055	.818	.381	.238
CV index of automaticity	.130	.239	.057	.002	.024	.878	.005
Attention (Form B)	.515*	.568	.322	.265	4.702	.051	.517

[a]Zero-order correlations. $*p < .05$, $** p < .01$, $*** p < .001$

Table 4.14
Results of a multiple regression analysis of modified RAN (M-RAN-Low-Frequency-Bigram) subtask performance by index of ballistic automaticity, CV-index of automaticity, and attention index

Variable:	r^a	R	R^2	R^2 change	F change	Sign. F	Final β
Ballistic automaticity	-.136	.136	.019	.019	.265	.615	-.203
CV index of automaticity	.142	.252	.064	.045	.625	.443	.187
Attention (Form B)	.573*	.613	.375	.312*	5.987	.031	.560*

[a]Zero-order correlations. $*p < .05$, $** p < .01$, $*** p < .001$

All other models were non-significant ranging in their overall explanatory power from 32.2 % (adjusted $R^2 = .153, p = .183$) in the M-RAN-High-Frequency-Bigram subtask to 45.4 % (adjusted $R^2 = .318, p = .056$, almost approaching significance) in the M-RAN-Symbolic-Small-Heavy subtask (naming vowels under the condition of heavy attentional load).

In other words, the set of predictors used was capable of explaining from 32 % and up to 63 % of variability in different modified RAN subtasks.

It is interesting to note that the most important predictor in practically all of the above analyses appeared to be the index of general attention. The unique contribution of attention varied across RAN subtasks, but was always higher than (or equal to, in one case) the contribution of either index of automaticity. Specifically, for the subtasks with the light attentional load, the attention factor alone explained 14.8 % (adjusted R^2 change $= .110, p = .120$) of the variance in M-RAN-Symbolic-Small-Light subtasks (naming of vowels). The index of general attention accounted for 42.5 % of the variance (adjusted R^2 change $= .442, p = .008$) in naming consonants (M-RAN-Symbolic-Large-Light subtask). It accounted for 25.2 % of the variance (adjusted R^2 change $= .226, p = .055$) in naming pictures of animals (M-RAN-Non-Symbolic-Small-Light subtask), and it accounted for 22.6 % of the variance (adjusted R^2 change $= .200, p = .061$) in naming pictures of common unrelated objects (M-RAN-Non-Symbolic-Large-Light subtask).

In the case of the modified RAN subtasks associated with the heavy attentional demand, attention alone explained even more variability in the criterion variables: 39.8 % (adjusted R^2 change $= .407, p = .012$) in naming vowels (M-RAN-Symbolic-Small-Heavy subtask); 47.7 % (adjusted R^2 change $= .506, p = .004$) in naming consonants (M-RAN-

Symbolic-Large-Heavy subtask); 39.2 % (adjusted R^2 change = .410, p = .007) in naming pictures of animals (M-RAN-Non-Symbolic-Small-Heavy subtask); and 34.6 % (adjusted R^2 change = .364, p = .005) in naming pictures of unrelated common objects (M-RAN-Non-Symbolic-Large-Heavy subtask).

Also, even in the presumably most automatized of all modified RAN subtasks – the one based on the High Frequency bigrams – the attention factor accounted for greater variance in naming performance compared to either of the indices of automaticity: R^2 change = .265, .241 after adjustment, p = .051 (compared to unadjusted 5.5 % for ballistic automaticity and 0.2 % for CV index of efficiency). Similarly, in the case of the Low Frequency bigram RAN subtask: R^2 change = .312, .299 after adjustment, p = .031 (unadjusted 1.9 % and 4.5 % for the ballistic and efficiency-related indices of automaticity, respectively).

Discussion

Findings with regard to the research questions

Study 2 was designed as a follow-up to Study 1 to address the following research questions:

1. How sensitive is RAN task performance to explicit manipulation of attention demands?
2. How important to RAN task performance is the "set size" factor, that is, the size of the potential "universe" or source set from which the actual target stimuli to be named are drawn from?

3. Does stimulus familiarity, as function of frequency in printed text, play any role RAN task performance and its link to reading rate?

The findings are now discussed in turn in the light of these questions.

First of all, we compared the findings from Study 1 (n = 52) and Study 2 (n = 16) on all the major variables to assure the consistency in the data set. No meaningful differences were found (a minor difference in Form B of the Trail Making test performance time was found between Study 1 and Study 2 in that participants were significantly faster in Study 2). This increases confidence that the results obtained in the present Study are reliable and likely to be representative of adult performance on the RAN task.

Next, the results are discussed in relation to the three research questions listed above. The first two of them concerned how sensitive RAN task performance is to attention demands and the source set size. As reported earlier, the ANOVA of performance time on the modified RAN subtasks yielded statistically significant main effects of stimuli type and attention load factors.

The observed pattern resembled most closely that shown in Figure 4.2. There were clear differences in naming time between symbolic and non-symbolic stimuli. However, in addition, difference was observed between subtasks involving the heavy versus light attentional load, as illustrated in Figure 4.3. Finally, partly in accord with the pattern shown in Figure 4.5 attentional load demands affected naming to different degrees in symbolic versus non-symbolic RAN subtasks. These results once again demonstrate that participants take significantly longer to recognize and name aloud pictures than letters. In agreement with the hypothesized outcomes, heavier attentional demands slowed the naming process down significantly across all stimuli types and set sizes, including symbolic ones. Given that light and heavy attentional load conditions were perfectly matched in their mechanical components (pressing the space bar on a computer keyboard 5 times per individual subtask), the difference in naming time can be attributed entirely to how much attentional control was required for successful task execution. The heavy attention load condition presumably involved working memory (remembering the particular "target" combination of stimuli to respond to) throughout the task in a way not involved in the light attentional load condition (press the space bar at the end of each line). This idea is supported in recent RAN research (e.g., Stringer et al., 2004, among others) that also implicated working memory in RAN task performance, among other cognitive factors. Interestingly, these attention results contrast with the low degree with which the automaticity measures accounted for variance in RAN task performance (less than 5% of the variance).

With respect to the second research question addressing the effect of the source set size factor on RAN task performance time, Study 2 found no significant main effect of this variable. However, the results revealed a significant interaction effect involving source set size and stimulus type. There was faster naming of pictures of animals (drawn from the smaller source set, in agreement with what was expected) on non-symbolic RAN subtasks and of consonants (drawn from the larger source set, contrary to the original expectations) on symbolic RAN subtasks than on the corresponding small source set (vowels) and larger source set (unrelated objects), respectively.

Finally, as a response to the third research question, the results also revealed that naming of letters in the condition involving high frequency bigrams was faster than in the conditions involving low frequency bigrams. This result likely reflects the effect of practice in reading (exposure to printed text) in symbolic RAN task performance.

Together, these results address the three research questions that motivated this study. First, it is clear that performance on the RAN task reflects the attentional load created by the task stimuli, and that attentional factors are more important than are automaticity factors, at least in an adult population. Second, the results indicated that source set size for the stimuli used in a particular RAN task can affect naming time, but here the results were complex. When the stimuli were unlikely to have been highly overlearned (line drawing pictures of animals and other objects), the fact that stimuli came from a large set size was associated with slower naming compared to stimuli from the smaller source set. This result implicates memory in RAN task performance with non-symbolic stimuli (non-letter stimuli).

In contrast, when the stimuli were likely to have been overlearned because of a history of reading (letters), the fact that stimuli from the large source set (consonants) was associated with faster naming compared to stimuli from the smaller source set. This finding is paradoxical at first sight. If letter names are automatically retrieved, then there should be no source set size effect and hence no difference in naming consonant versus vowels. Moreover, if there is a slight difference in automaticity of letter recognition of vowels and consonants, one would expect the difference to favour faster responding for the smaller source set (vowels) but instead there was faster responding for the larger source set (consonants). Whatever the explanation for this result (for instance, typical phonological training tends to emphasize the sustained pronunciation of vowels – producing longer lasting sounds), it seems unlikely that RAN task performance reflected automaticity of name retrieval.

In addition to the major research questions, this study also looked at relationships among variables, those common for Studies 1 and 2, and the set of modified RAN subtasks, unique for Study 2. Perhaps, one of the most interesting results was that RAN subtask performance based on the low frequency bigrams correlated significantly with naming on all RAN subtasks except for the low attentional demand task involving vowel naming and did so noticeably more strongly than with the subtask involving high frequent bigrams. One could probably speculate that this particular modification of the RAN task shares the most with either type of others – efficient recognition of highly practiced symbols and efficient management (presumably through higher attentional control) of their more challenging (less familiar) combinations.

Interrelations among variables

With regard to correlations between modified RAN subtasks and participants' L1 reading speed, three significant coefficients of correlation were observed, all for subtasks involving symbolic stimuli: vowels under the condition of high attention load, frequent and rare bigrams. As expected, all modified RAN subtasks under the condition of high attention load showed the strongest correlations with the primary measure of attention – Form B of the Trail Making test performance time.

Related to the last research question, correlational analysis explored whether RAN task performance in this sample would be related to reading ability and whether familiarity of the letter sequences, varied here as a function of bigram frequency, would correlate with reading performance. Indeed, both bigram-based modified RAN subtasks were highly correlated to L1 reading rate, providing another indication that practice in reading influences RAN-to-reading association. Interestingly, performance on the subtasks utilizing the low frequent, and hence less familiar, bigram patterns showed somewhat stronger correlations with reading than did more familiar high frequent bigram subtasks. This result might reflect the possibility that the more challenging task (the low frequency bigram condition) provided processing challenges that could differentiate strong performers better than did the easier task, and thus results that would correlate more strongly with performance on the even more challenging reading task.

Finally, the multiple regression analyses revealed, as in Study 1, that attention-related factors accounted for more of the variability in participants' performance on the different RAN subtasks than did automaticity-related factors. The unique contribution of the index of general attention in some cases exceeded 40 % of explained variance in the case of several RAN subtasks, and not surprisingly even more in subtasks with additional attentional demands (high attention demand modified RAN subtasks). Indeed, the association of attention with performance in the modified RAN subtasks, according to multiple regression analyses in the present study, appears to be higher than observed in the original RAN subtasks. This result thus replicates the original finding, once again pointing to the importance of attention-related factors in RAN task performance. Indeed, considering that even those four subtasks under the condition of light attentional demand still in fact carried some extra load (presumably on working memory) of responding to the last stimulus in each row. As such, they were more dependent on attention-related factors, than the original RAN subtasks were. No wonder then that the contribution of attention to RAN task performance was even higher for those four RAN modifications with the extra task of responding to particular combinations of targets. Very interestingly, in this subset of modified RAN subtasks, it appears that keeping track of more familiar (automatically recognized stimuli – vowel and consonant letters) in order to properly respond to their target combinations, took even more attentional resources than it did for their more variable counterparts (presumably less automatically recognized pictures of animals and common objects).

To summarize, Study 2 has shown that both symbolic and non-symbolic version of the RAN task are noticeably sensitive to direct manipulations of attention demand characteristics, resulting in significantly slower naming, when attention demands are higher. More importantly, when attention was challenged, as it was in the high load condition, the connection of RAN task performance to reading (as well as the inter-correlations among different RAN subtasks) appeared to become stronger. Altogether, the findings suggest that it is the development of attention control that appears to be most strongly involved in successful rapid serial naming, although practice in reading by young adults is able to automatize the naming of symbolic stimuli.

Brief summary

In terms of the study research questions it was found that the RAN task is sensitive to the explicit manipulation of the attention factor, whereas the set size factor played much more modest role in determining its performance time. Stimulus familiarity, on the other hand, presumably being a function of frequency of occurrence in printed text and exposure through practice in reading, appeared to be an important factor in linking RAN task performance to reading speed.

CHAPTER 5: EXPERIMENTAL STUDY 3

Objectives and rationale

Following up on the two previous studies, Study 3 is based on the main findings reported so far that: (1) automaticity of stimulus recognition, as operationalized in those studies, was not associated in any substantial way with RAN task performance, and (2) attention-related factors were significantly associated with RAN task performance. Differences were also found in the way performance in various individual RAN subtasks was associated with performance time and degree of association with reading rate, as a function of the RAN stimulus type and the scope of attention load, but not the stimulus source set size. The study reported in the present chapter explored these findings further by addressing the following research questions:

1. *Automaticity*: If automaticity of stimulus recognition is not associated with RAN task naming speed (as turns out to be the case), are other forms of automaticity operationalized in other ways (i.e., not as ballistic processing or efficient stimulus recognition), nevertheless related to RAN task performance?
2. *Attention*: Can particular aspects of attention be identified as being associated with successful RAN task performance?
3. *Other factors*: Are other factors, such as efficiency of lexical access and working memory capacity, capable of substantially adding to our understanding of the cognitive mechanisms of RAN task performance?

These research questions are now considered in turn.

Automaticity

In the two studies presented earlier, automaticity was operationalized in terms of ballistic processing and as efficiency of stimulus recognition, and in neither case did automaticity emerge as a strong and reliable predictor of naming speed in any of the original or modified RAN subtasks. Moreover, automaticity variables were always found to be less important than attention variables in association strength with RAN task performance. In Study 3 yet another way of operationalizing automaticity was explored to see if a significant association with RAN task performance might still be found. Instead of using the complex and time consuming procedure based on the primed decision making paradigm (Neely, 1977; Favreau & Segalowitz, 1983), the relatively simpler measure of automatic identification of letters and digits provided by the Ruff 2&7 test (Ruff & Allen, 1995) was employed. What most distinguishes this measure from the indices used before is the mode of stimulus presentation. In the Ruff 2&7 test, target stimuli are embedded among easily distinguishable distracters (e.g., letter targets among digit foils; digit targets among letter foils) in a pencil and paper task requiring the participant to cross out as many targets as possible within a given time limit. As described below, this task purports to distinguish automatic versus non-automatic target detection. In some ways, the Ruff 2&7 task is more similar to the RAN task in terms of stimulus presentation mode (all the stimuli are presented simultaneously in a visual, linear arrangement) than is the primed decision making task (stimuli are presented singly and for very brief durations). If the failure to link automaticity to the speed of naming resulted from an incompatibility in the mode of stimulus presentation between the RAN task and the measures of automaticity used, perhaps this new task of automaticity will be more successful. If, however, the association of this measure of automaticity and RAN task naming speed remains weak, then the conclusion that automaticity of stimulus recognition is not a major factor in RAN performance will again have been supported.

Attention

Given the earlier findings reported here and by others pointing to attention as a factor underlying RAN task performance, it is appropriate to further explore which aspects of attention are implicated. Recently, the literature in this area has revealed more and more support for the idea that attention-related phenomena may be associated with reading phenomena and thus, perhaps, with naming speed measures associated with reading skill. For example, cases of co-morbidity of reading impairments with ADHD have been reported (e.g., Narhi & Ahonen, 1995), especially cases in which RAN was among predictors or diagnostic tools for the ADHD (e.g., Rucklidge & Tannock, 2002; Howe et al., 2006) and, even more interestingly, for the attention deficit without the hyperactivity component (e.g., Hynd, Lorys, Semrud-Clikeman, & Nieves, 1991). This set of examples is yet again illustrated why attention should be taken into account when addressing the cognitive nature of the RAN task.

There are also reports based on neurological and behavioral data (e.g., Hutchens, 1988, 1989; Neuhaus & Swank, 2002; Misra et al. 2004) implicating general or visual attention in RAN task performance. Measures such as the Trail Making test and different indices of working memory have been included in recent studies exploring the RAN task (Narhi, 2002; Savage et al., 2005a; Stringer et al., 2004; van der Sluis et al. 2004, etc.). Such studies also indicate a growing interest in attention as a factor underlying RAN phenomena.

The results from Study 1 and Study 2 suggested it could be beneficial to look more closely at such factors as efficiency of spatial search, attention shift cost and working memory. For example, presumably all of these factors were involved in completing Form B of the Trail Making test of general attention in the previous studies reported here. For this reason, in Study 3 spatial search and shift efficiency as aspects of attention/executive processing were operationalized and used as predictors in a series of multiple regression analyses with different RAN subtasks as criterion variables. Though it is also closely related to attention control, working memory cannot be explained solely in attentional terms, and thus, it was addressed further in this study independently, under the category of Other Factors.

Other factors

Finally, Study 3 aimed to explore other cognitive factors that possibly contribute to RAN task performance. In the multiple regression analyses performed in Study 1, the model used two predictor measures of automaticity and one of attention. In no case were these factors able to explain more than 30 % of the variability in the criterion variable, suggesting that perhaps there are other factors, not yet been considered, shaping RAN phenomena. Study 3 explored what some of these other factors might be.

Within the framework of this project, two factors have already been mentioned as potentially prominent for RAN task performance: working memory and efficiency of lexical access. Indeed, working memory has not only been closely associated with attention, for example in the widely accepted model of Baddeley and Hitch (1974) (Engle, 2002), but working memory has also repeatedly been considered in reading research among factors important for reading development (de Jong &van der Leij, 1999;

Engle, Cantor, & Carullo, 1992; Ransby & Swanson, 2003; Russell, 2002, among many others) and development of related (e.g., math) skills (Swanson, 2004 & 2006). No less importantly, the predictive power of the Trail Making test Form B performance for RAN performance may very well reflect the commonalities between the two tasks associated with shared demand for working memory. Indeed, in the Trail Making test, there is an obvious necessity to maintain in working memory information about the last attended target in order to properly navigate from target to target through alternating arrays of digits and letters. Similarly, in the RAN task, naming speed may be directly related to participants' ability to process stimuli (identify them and search for corresponding name) not individually but in small chunks, thus implicating working memory, as well. The similarity is even more striking for the modified RAN subtasks under the condition of high attentional demand. In such subtasks there is a need to keep in working memory a particular combination of stimuli (the target) to respond to by pressing a designated key, while maintaining the speeded naming of all presented stimuli. In light of the above considerations about the possibly important role played by memory in RAN performance, a measure of working memory capacity was added to the list of predictors of RAN performance in Study 3.

Another potentially important factor in RAN performance is efficiency of lexical access. In a sense, this concept is very close to automaticity as it was operationalized in Studies 1 and 2 in terms of rapid and stable performance (reflected by a CV-index), but now applied at the level of word recognition (e.g., Kuhara-Kojima et al., 1999). This is an expertise that is even more closely related to practice in reading, and perhaps better associated not just with the symbolic, but also with the non-symbolic RAN subtasks, in which lexical access (that is, searching for the names of target objects, though presented pictorially) should matter. In the lab where the present research was conducted, a measure of automaticity of lexical access has been used for years to assess cognitive fluency underlying second language proficiency (Segalowitz & Hulstjin, 2005; Segalowitz & Segalowitz, 1993). It has been a central hypothesis in the original RAN literature that naming speed in RAN reflects, above all else, the speed or automaticity of retrieving the proper label for each of the presented stimuli. This is presumably especially true when the range of labels to select from is practically unlimited (as it is for non-symbolic RAN). Consequently, in Study 2 an attempt to examine the importance of the range of potential labels was made by manipulating the source set size from which the stimuli (letters, pictures, etc.) were drawn for the modified RAN subtasks.

The CV measure of automaticity in a letter/digit primed decision-making task had been used as a measure of automaticity of stimulus recognition in Studies 1 and 2. Those attempts failed to find a relationship between the automaticity of retrieving stimulus names and RAN performance. Perhaps, however, the measures selected were not appropriate to address the automaticity that is the most essential for RAN task performance. To test this assumption, in the present study these measures were replaced by a different measure – the efficiency of lexical access in a lexical access task, the so-called "Living/Non-living" task, which has been experimentally validated in studies conducted in our lab (e.g., Segalowitz & Fishman-Frenkiel, 2005). The CV index of judging whether rapidly presented English words named a living or non-living object, residualized against the CV index of judging directions of arrows (the control condition) was used to assess automaticity of lexical retrieval. This measure seemed to be more directly related to fluent reading than is automaticity of single letter or digit name retrieval.

Method

Participants

102 volunteers were initially recruited to participate in Study 3. The call for participants named only one inclusion criterion – English had to be participants' dominant language (that is, preferably the mother tongue or at least learned no later than in elementary school and extensively used since then in all formal education and most of everyday activities and communication). Judging from participants' responses to the demographic questionnaire which primarily targeted their language background, six of them did not meet one or several of these inclusion criteria (five had first learned English after the age of eight and/or were using other languages outside class, and one was so fully bilingual he hesitated to indicate which of two languages was dominant). Data from those six participants were nevertheless collected, but not used in the subsequent analyses. There were, thus, ninety-six participants (63 women and 33 men) whose data were retained for analysis. Their age ranged from 17 to 62, with the mean of 27.89 (median = 23 and mode = 20). None of them was monolingual, and English was the dominant language (68 participants named English also as their mother tongue). On average, they reported that they had been using English for 26.07 years (*SD* = 11.13), though some came from a variety of language backgrounds. The most frequently indicated second language was French (66 times).

Measures

Study 3 employed a combination of assessment tools addressing the major variables in question. Among these tasks were the original RAN subtasks and Trail Making test used in Study 1, complemented by the ten modified versions of RAN used in Study 2. Several new tasks were introduced in Study 3. These new tasks included: (1) The Nelson-Denny standardized test of reading skills (Brown, Fishco, & Hanna, 1993); (2) The Ruff 2&7 task (Ruff, Niemann, Allen, Farrow, & Wylie, 1992) addressing speed, accuracy, and efficiency of automatic detection and controlled search of symbolic stimuli; (3) The 'letters & digits span' working memory subtest of the Wechsler's WAIS-III battery (Kaufman & Lichtenberger, 1999; Tulsky, & Price, 2003); (4) A measure of efficiency of lexical access (CV index) in the "Living/Non-living" task, developed in our research lab (Segalowitz & Fishman-Frenkiel, 2005). Each measure employed is briefly considered now.

RAN Tasks. Four original RAN subtasks (naming letters, digits, colors and objects) as described in detail in Study 1 were used unchanged in Study 3. The ten modified RAN subtasks designed for Study 2 were also used: eight subtasks involving the naming of vowels, consonants, pictures of animals and common objects under conditions of either low or high attention demand plus two using high versus low frequent bigrams.

Trail Making test. The Trail making test (Reitan & Wolfson, 1993; Spreen & Strauss, 1991), as used in Study 1 and Study 2, was used in Study 3. The administration of Forms A and B was counterbalanced with the other tasks across participants. Time of completion Form B served as the primary index of general attention in addition to the index of attention shift cost (as described in Study 1).

Nelson-Denny Reading test. The Nelson-Denny standardized test of reading skills (Brown et al. 1993) – forms G and H – for college students was administered as a measure of reading performance (see Appendix J). The test provided measures of reading rate and comprehension.

Each participant received two text fragments, about one page or 600 words long each, one at the beginning of the experimental session and one at the end, from forms G and H respectively, counterbalanced across participants. Participants were instructed to read silently as fast as possible, while at the same time reaching full understanding of the text and being prepared to answer comprehension questions when finished. After the first minute of reading they were asked to mark the line they were reading at the time by crossing or circling the number appearing in the right margin of the given page against each line of text. This number represented the number of words a participant had read in one minute and served as the test measure of reading speed. In this Study, as well as before in Studies 1 and 2, however, following a suggestion by Ackerman (1987), reading speed was converted from words per minute to milliseconds per word and in all subsequent analyses as a measure of reading rate. The average percent of correct responses to the set of questions at the end of each text fragment served as the index of reading comprehension.

Ruff 2&7 test of Selective Attention. Measures of automatic and controlled processing came from the Ruff 2&7 test (Ruff et al., 1992). This paper-and-pencil test belongs to a broad category of so-called cancellation tasks. The Ruff2&7 test requires speeded but accurate identification and deletion (cancellation by crossing with a single line) of designated targets randomly embedded among numerous distracters. These distractors can be from a different category than the target stimuli (e.g., letter distractors for the targets 2 and 7), making the target-background difference highly salient and thus making much easier to detect the targets, or they can be from the same category as the target stimuli, reducing greatly the target-background difference and thus making it much harder to detect the targets. The first condition is referred to as "automatic detection", and the second is referred to as "controlled search". It was presumed that the first condition could provide a good measure of automaticity in stimuli recognition (to replace the one based on the primed decision making paradigm used in Studies 1 and 2), whereas the second condition would produce a measure of controlled processing. In particular, it could represent the aspect of attention associated with the spatial search, which means, among other things, the opportunity to be more specific in exploring the role of different components of attention in RAN task performance.

In the original version of the Ruff 2&7 test, participants are given 20 blocks (boxes that contains three lines of 40 characters each) of stimuli to process under each condition. The targets are the digits 2 and 7. In half the trials (10 blocks) they are embedded among randomly presented letters of the English alphabet (the automatic detection condition) and in other half (10 blocks) of trials they are embedded among other digits (the controlled search condition). Blocks representing different conditions are mixed at random. In the present study, half the blocks in each condition were converted into symmetrical tasks with letters B & G as the target stimuli and either digits (the automatic detection condition) or other letters (the controlled search condition) as distractors. Subsequently, 2&7 and B&G versions of the task (5 automatic detection blocks and 5 controlled search blocks in each) were given to participants separately with the corresponding instructions in a counterbalanced order. Each block of stimuli consisted of 3 lines of characters (10 targets and 30 distracters per line) and separated on a task page from each other by a frame surrounding these three lines. Participants were asked to identify and cancel (eliminate by crossing with a single line) the designated targets, working as fast and as possible but trying not to miss a single target. Time to complete each block of three lines was set to 15 seconds. Therefore, every 15 seconds participants heard the voice signal "next" and had to stop working on the current block and move to the next one, and so on until they completed all blocks in each of two symmetrical forms of the task. Appendix K contains samples of the original (with digits 2 and 7 as target stimuli) and modified (with letters B & G as target stimuli) forms of the test.

In compliance with the manual for the Ruff2&7 test, for each block the number of correct hits (correctly deleted targets) and the number of omissions (missed targets) and false alarms (wrongly crossed out distractors) errors were tabulated to yield the following performance indices: (1) Automatic detection speed = the total number of hits when targets and distracters were characters from different categories; (2) Automatic detection accuracy = the percentage of correctly identified targets out of the total number of processed characters (including errors) in letter- and digit-based task under the "automatic detection" condition; (3) Controlled search speed = the total number of hits when targets and distracters belonged to the same category of characters; and (4) Controlled search accuracy = the percentage of correctly identified targets out of the total number of processed characters (including errors) in letter- and digit based tasks under the 'controlled search' condition. In addition, for the purposes of the present study, the following indices were used: (1) Automatic search efficiency = the product of the automatic detection speed and automatic detection accuracy, and (2) Controlled search efficiency = the product of controlled detection speed and controlled detection accuracy.

Working memory. To elicit a measure of working memory capacity, Study 3 employed the corresponding subscale (Letter-Number Sequencing subtest) of the WAIS-III battery of tests of intelligence (Kaufman & Lichtenberger, 1999; Tulsky & Price, 2003). The task consists of 21 sequences alternating single letters and digits of gradually increasing length: each of the first three sequences has three characters to it (letter-digit-letter, digit-letter-digit, and letter-digit-letter – with no particular regularity in selection of the characters and with no repetition of any character within the same sequence). The next three sequences are composed of four characters each (digit-letter-digit-letter, etc.), and so on until the length of last three sequences reaches eight characters. They are normally presented to participants orally. In the case of Study 3, it was done with a pre-recorded CD played out on the Marantz CDR 300 device to assure the consistency of the presentation mode across all experimental sessions, with the experimenter manually controlling the initiation of each sequence. The form for registering participants' responses is given in Appendix L.

Participants' task was to listen to each sequence, trying to remember all items in it, and after the presentation is over to reproduce them orally but rearranging them so that all digits are named first in ascending order followed by letters in alphabetical order. Accomplishing this successfully resulted in adding one point to participants' total score on the working memory scale (i.e., one point per correctly named sequence). Any deviation from it (a missed or misplaced character) was considered a mistake and received a score of zero. The maximum achievable total score, thus, is equal to 21. Each sequence was only presented once. There was no particular time restriction to respond (with reasonable limits). The task stopped when either all sequences were presented or when three mistakes were made in a row.

Living/Non-living Task. Finally, the computer-based Living/Non-living task (Segalowitz & Fishman-Frenkiel, 2005) provided the measure of lexical access efficiency. Programmed with HyperCard 2.3 and implemented using a standard i-Mac computer, the task required participants to judge whether each of 32 target words (English nouns) presented in the center of the computer monitor depicted a living or an inanimate object. Participants were asked to give their response by pressing as fast as possible the designated keys on the computer keyboard. Maximum stimulus duration time was 2000 milliseconds. The program recorded reaction time and whether the response was correct. Targets were presented in blocks of sixteen. In addition to two blocks of English nouns there were two control blocks with arrows pointing right or left and the task for participants was to indicate by pressing a right or left key the direction of the arrow. Based on data collected from all 64 trials, the program then calculated the mean reaction time and standard deviation (based on correct responses only) separately for the arrow direction judgment and for the living/non-living judgment. Following the same logic described for efficiency-based automatic processing in Study 1, the index of efficiency of performance (CV – coefficient of variability – the ratio of standard deviation over the mean reaction time) on each type of task was calculated. The arrow-condition data were used to provide a measure of efficiency of lexical access that was independent of individual differences in pattern recognition and the mechanical components of performance, presumably shared by both tasks. To accomplish this, the CV index for judging words was regressed against the CV index for judging the direction of arrows. The resulting standardized residual served as a measure of efficiency of lexical access.

Procedure

Prior to the beginning of each experimental session, all participants read and signed a consent form and responded to a short demographic questionnaire, primarily addressing their language background (same as in Study 1, Appendices E & D, respectively). As was stated before, two different forms of the Nelson-Denny reading test were the opening and the concluding tasks of each experimental session. In between, participants received all other tasks (described above) in a counterbalanced order. Testing sessions lasted on average 60-65 minutes. At the end participants were debriefed (see Appendix F). There were two types of compensation for those participated in the study. Some received 10 $ upon completion of all tasks, while some eligible (psychology students at Concordia University) instead, by their choice, could receive extra points for one of selected courses according to the policy of the Departmental Participants Pool (http://www.psychology-concordia.ca/Participants /index.html).

Results

First, a brief overview of general patterns in the data and correlations among major variables. Descriptive statistics for the Study 3 variables are presented in Table 5.1.

In general, with regard to variables common across all three studies, the results of the present study very much resembled those of Studies 1 and 2. This was particularly true for all the RAN subtasks, both original and modified. Some (see for example, all symbolic RAN subtasks without manipulation of the attention factor) showed practically identical means and standard deviations. The only exception was a difference in performance time on Form B of the Trail Making test between Study 3 and the combined dataset of Studies 1 & 2 (t (162) = 6.199, $p < .001$, two-tailed).

Modified RAN subtasks. A 2x2x2 repeated measure ANOVA on modified RAN subtasks performance data revealed the following results (see Figure 5.1). The factors were: Attention Load (light vs. heavy), Stimulus Type (symbolic vs. non-symbolic), and Source Set Size (small vs. large).

Main effects were significant for attention load (F (1,95) = 246.944, MSe = 26,840,134.7, $p < .001$, partial $\eta^2 = .722$) and stimulus type (F (1,95) = 910.722, MSe = 69,782,870.6, $p < .001$, partial $\eta^2 = .906$), but not for source set size (F (1,95) = 1.298, MSe = 6,341,085.5, $p = .257$, partial $\eta^2 = .013$). Participants' naming was faster for symbolic stimuli across conditions, and also under the light attentional demand condition (the corresponding means are reported in Table 5.1). The pattern was very similar to the one earlier observed in Study 2.

Table 5.1. Descriptive statistics of the major variables (N=96)

Experimental Task		**Variable**	**Mean**	**SD**
Original RAN				
	1	Performance time on letters (sec.):	**18.27**	**3.03**
	2	Performance time on digits (sec.):	**18.51**	**3.32**
	3	Performance time on colors (sec.):	**30.05**	**5.11**
	4	Performance time on objects (sec.):	**38.87**	**6.70**
	5	Symbolic (letters & digits combined):	37.06	6.07
	6	Non-symbolic (colors & objects combined):	68.93	10.77
	7	Overall (all subtasks combined):	105.99	14.73
Modified RAN				
	8	M-RAN-Symbolic-Small-Light (sec.):	**21.96**	**3.79**
	9	M-RAN-Symbolic-Large-Light (sec.):	**19.22**	**3.50**
	10	M-RAN-Non-Symbolic-Small-Light (sec.):	**35.34**	**6.01**
	11	M-RAN-Non-Symbolic-Large-Light (sec.):	**37.18**	**6.96**
	12	M-RAN-Symbolic-Small-Heavy (sec.):	**25.79**	**5.78**
	13	M-RAN-Symbolic-Large-Heavy (sec.):	**24.80**	**4.89**
	14	M-RAN-Non-Symbolic-Small-Heavy (sec.):	**43.02**	**8.74**
	15	M-RAN-Non-Symbolic-Large-Heavy (sec.):	**43.59**	**8.11**
	16	Frequent bigram based RAN (sec.):	**16.53**	**2.57**
	17	Rare bigram based RAN (sec.):	**17.86**	**2.73**
Trail Making test				
	18	Form A performance time (sec.):	25.16	6.43
	19	Form B performance time (sec.):	**38.51**	**11.07**
	20	Difference in performance time (B–A)	13.35	8.88
	21	Standardized residual (B against A):	**0.001**	**0.991**
Nelson-Denny reading test				
	22	Reading rate (ms per word), Form G:	253	64.7
	23	Reading rate (ms per word), Form H:	220	58.1
	24	Average reading rate (ms per word):	**236.4**	**57.9**
	25	Accuracy (% correct responses) Form G:	65.2	23.64
	26	Accuracy (% correct responses) Form H:	58.3	20.25
	27	Average accuracy (% correct responses):	**61.8**	**18.69**
Working Memory index	**28**	(Maximum possible = 21):	**14.4**	**2.17**

Table 5.1. Descriptive statistics of the major variables (N=96) continues

Living/Non-living task				
	29	Mean RT (arrow direction, ms):	523	96.4
	30	Mean RT (English words, ms):	784	144.0
	31	CV (arrow direction):	0.14	0.01
	32	CV (English words):	0.21	0.01
	34	Lexical access efficiency (CV standardized. residual):	**0.004**	**.990**
Ruff 2&7 test				
	35	Automatic detection speed (number of characters per time unit):	198.32	33.40
	36	Automatic detection accuracy (%):	93.58	5.55
	37	Automatic detection efficiency:	**184.76**	**28.38**
	38	Controlled search speed (number of characters per time unit):	155.89	26.77
	39	Controlled search accuracy (%):	87.78	8.55
	40	Controlled search efficiency:	**136.34**	**24.38**

In bold: Variables used in further analyses.

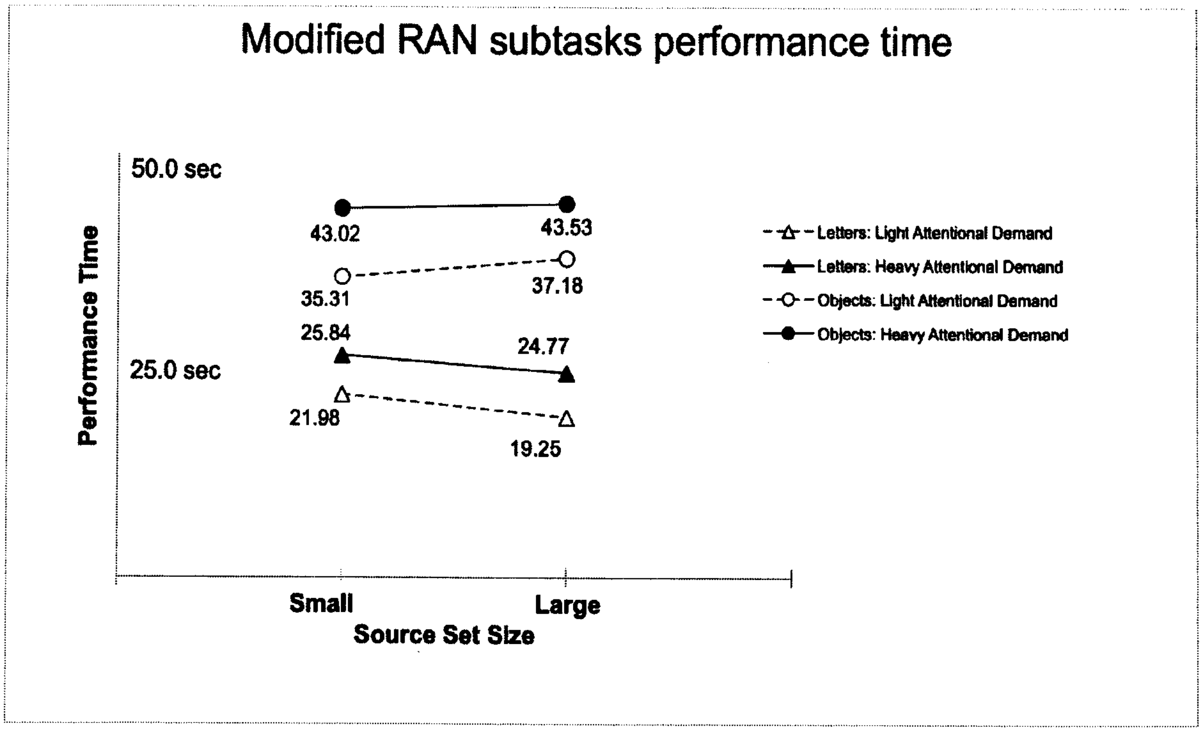


Figure 5.1. Observed pattern of performance times on modified RAN subtasks

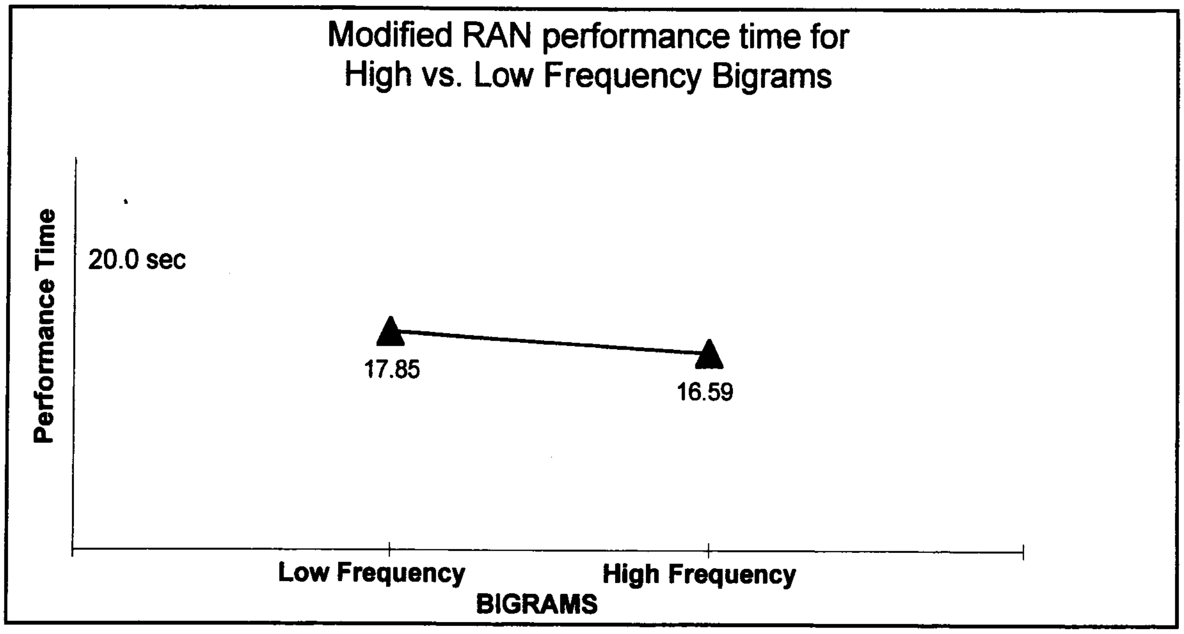


Figure 5.2. Observed difference in performance time between modified RAN subtasks based on relatively more frequent and rare bigrams

The significant 2x2x2 interaction (F (1,95) = 11.137, MSe = 9,798,119.2, p = .001, partial η^2 = .105) suggested, however, that effects did not reveal themselves equally across conditions. Further analyses showed two other significant interaction effects: attention by stimulus type (F (1,95) = 23.696, MSe = 1,083,842.2, $p < .001$, partial η^2 = .200) – slower performance with the heavy attention load on non-symbolic subtasks than on symbolic ones, and stimulus type by source set size (F (1,95) = 27.544, MSe = 6,477,196.3, $p < .001$, partial η^2 = .225) reflecting the fact that larger source set size slowed down naming of non-symbolic, but not of symbolic stimuli, the same pattern previously observed in Study 2. See Figure 5.1, and Appendix M for the ANOVA summary table. With respect to the bigram-based modified RAN subtasks, performance was significantly faster for the relatively more frequent bigrams than for the relatively rarer bigrams (See Figure 5.2): t (95) = 8.935, $p < .001$, two-tailed.

Interrelations among variables. Correlational data are presented in Table 5.2 (across the individual RAN subtasks), Table 5.3 (inter-correlations among the study major variables in addition to the modified RAN subtasks), and Table 5.4 (inter-correlations among the study major variables in addition to the original RAN subtasks).

Inter-correlations among individual (original and modified) RAN subtasks emerged even stronger than observed in Study 2. In general, correlations were stronger within the category (symbolic to symbolic and non-symbolic to non-symbolic) and weaker across categories of stimulus type used in individual RAN subtasks. Among the most highly correlated were the following pairs of RAN subtasks. Within the category of symbolic stimuli: naming letters and digits in the original RAN (r = .823, $p < .001$), naming letters in the original RAN and two modified RAN subtasks – M-RAN-

Symbolic-Large-Light ($r = .831, p < .001$) and M-RAN-Frequent-Bigrams ($r = .806$, $p<.001$), as well as naming frequent and rare bigrams ($r = .851, p < .001$). Within the category of non-symbolic stimuli: naming pictures of animals and pictures of common objects both under the light and heavy attentional demand experimental conditions ($r = .682$, $p<.001$ and $r = .668$, $p<.001$, respectively), as well as naming colors and objects in the original RAN ($r = .658$, $p<.001$).

As usual, of the highest interest for this project were correlations between different RAN subtasks and measures of reading performance.

Table 5.2. Inter-correlation coefficients among original and modified RAN subtasks (N=96)

VARIABLES:	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**
1. Letter-RAN	-													
2. Digit-RAN	.823***	-												
3. Color-RAN	.405***	.437***	-											
4. Object-RAN	.468***	.404***	.658***	-										
5. M-RAN-Symbolic-Small-Light	.702***	.659***	.417***	.490***	-									
6. M-RAN-Symbolic-Large-Light	.831***	.806***	.419***	.489***	.754***	-								
7. M-RAN-Non-Symbolic-Small-Light	.214*	.153	.617***	.622***	.274**	.273**	-							
8. M-RAN-Non-Symbolic-Large-Light	.410***	.259*	.559***	.655***	.448***	.421***	.668***	-						
9. M-RAN-Symbolic-Small-Heavy	.597***	.529***	.544***	.432***	.598***	.612***	.413***	.385***	-					
10. M-RAN-Symbolic-Large-Heavy	.493***	.468***	.394***	.443***	.487***	.565***	.339**	.367***	.645***	-				
11. M-RAN-Non-Symbolic-Small-Heavy	.159	.133	.501***	.620**	.244*	.226*	.703***	.535***	.478***	.446***	-			
12. M-RAN-Non-Symbolic-Large-Heavy	.314**	.214*	.544***	.582**	.331**	.320**	.628***	.703***	.497***	.442***	.682***	-		
13. M-RAN-Frequent-Bigrams	.806***	.751***	.405***	.427***	.712***	.795***	.252*	.424***	.585***	.533***	.148	.267**	-	
14. M-RAN-Rare-Bigrams	.781***	.700***	.381***	.469***	.715***	.803***	.274**	.418***	.608***	.537***	.231*	.343**	.851***	-

* p<.05, ** p<.01, *** p<.001. All one-tailed tests

The list of variables:

1 – RAN performance time on letters task; 2 – RAN performance time on digits task; 3 – RAN performance time on colors task; 4 – RAN performance time on objects task; 5 – Modified RAN: light attentional load, vowel letters; 6 – Modified RAN: light attentional load, consonant letters; 7 – Modified RAN: light attentional load, pictures of animals; 8 – Modified RAN: light attentional load, pictures of common objects; 9 – Modified RAN: heavy attentional load, vowel letters; 10 – Modified RAN: heavy attentional load, consonant letters; 11 – Modified RAN: heavy attentional load pictures of animals; 12 – Modified RAN: heavy attentional load, pictures of common objects; 13 – Modified RAN: based on frequent bigrams; 14 – Modified RAN: based on rare bigrams.

Table 5.3. Inter-correlation coefficients for the major variables (N=96)

VARIABLES:	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
1. M-RAN-Symbolic-Small-Light	-															
2. M-RAN-Symbolic-Large-Light	.754***	-														
3. M-RAN-Non-Symbolic-Small-Light	.274**	.273**	-													
4. M-RAN-Non-Symbolic-Large-Light	.448***	.421***	.668***	-												
5. M-RAN-Symbolic-Small-Heavy	.598***	.612***	.413***	.385***	-											
6. M-RAN-Symbolic-Large-Heavy	.487***	.565***	.339**	.367***	.645***	-										
7. M-RAN-Non-Symbolic-Small-Heavy	.244*	.226*	.703***	.535***	.478***	.446***	-									
8. M-RAN-Non-Symbolic-Large-Heavy	.331**	.320**	.628***	.703***	.497***	.442***	.682***	-								
9. Automatic detection	.140	.182	.130	.068	.183	.239*	.185	.241*	-							
10. Lexical access	-.046	.106	.170	.139	.142	.025	.133	.161	-.087	-						
11. Attention: Form B	.299**	.247**	.424***	.407***	.322**	.247**	.444***	.483***	-.371**	.273**	-					
12. Attention shift cost	.410***	.244**	.376***	.439***	.253**	.208*	.339**	.481***	.113	-.140	.804***	-				
13. Working memory	.378***	.407***	.479***	.306**	.516***	.488***	.451***	.403***	.209*	-.026	.285*	.334**	-			
14. Controlled search	.250*	.173	.287**	.221*	.269**	.346***	.362***	.415***	.646***	-.138	.468***	.305**	.221*	-		
15. Reading rate	.283**	.362***	.163	.105	.415***	.255**	.180*	.203*	-.021	.215*	.197	.083	.374***	-.030	-	
16. Reading accuracy	-.024	.134	.253*	.119	.368***	.229*	.360***	.343***	-.075	.208*	.313**	.171	.433***	-.140	.431***	-

* p<.05, ** p<.01, *** p<.001. All one-tailed tests

The list of variables:

1 – Modified RAN: light attentional load, vowel letters; 2 – Modified RAN: light attentional load, consonant letters; 3 – Modified RAN: light attentional load, pictures of animals; 4 – Modified RAN: light attentional load, pictures of common objects; 5 – Modified RAN: heavy attentional load, vowel letters; 6 – Modified RAN: heavy attentional load, consonant letters; 7 – Modified RAN: heavy attentional load, pictures of animals; 8 – Modified RAN: heavy attentional load, pictures of common objects; 9 – Automatic detection efficiency index in Ruff 2&7 test; 10 – Lexical access efficiency index (CV for English nouns residualized against CV for arrows); 11 – Attention: Form B performance time ("Trail Making" test of attention); 12 – Standardized residual (Form B against Form A performance time on the "Trail Making" test) as an index of the attention shift cost; 13 – Working memory index; 14 – Controlled search efficiency index in Ruff 2&7 test; 15 – Reading rate (ms/word); 16 – Reading comprehension.

Table 5.4. Inter-correlation coefficients for the major variables (N=96)

VARIABLES:	1	2	3	4	5	6	7	8	9	10	11	12	13	14
1. Letter RAN	-													
2. Digit RAN	.823***	-												
3. Color RAN	.405***	.437***	-											
4. Object RAN	.468***	.404***	.658***	-										
5. Frequent bigrams	.806***	.751***	.405***	.427***	-									
6. Rare bigrams	.781***	.700***	.381***	.469***	.851***	-								
7. Automatic detection	.158	.146	.264**	.189	.088	.198	-							
8. Lexical access	.098	.088	.253*	.146	.102	-.008	-.087	-						
9. Attention: Form B	.278**	.176	.529***	.414***	.261*	.328**	-.371**	.273**	-					
10. Attention shift cost	.286**	.191	.444***	.306**	.210*	.266**	.113	-.140	.804***	-				
11. Working memory	.399***	.400***	.451***	.370**	.407***	.406***	.209*	-.026	.285*	.334**	-			
12. Controlled search	.101	.083	.345**	.344**	.115	.214*	.646***	-.138	.468***	.305**	.221*	-		
13. Reading rate	.389***	.402***	.307**	.187	.402***	.423***	.021	.215*	.197	.083	.374***	-.030	-	
14. Reading accuracy	.138	.128	.259*	.155	.136	.201*	-.075	.208*	.313**	.171	.433***	.140	.431***	-

* p<.05, ** p<.01, *** p<.001. All one-tailed tests

The list of variables:

1 – Original RAN (letters); 2 – Original RAN (digits); 3 – Original RAN (colors); 4 – Original RAN (objects); 5 – Modified RAN (frequent bigrams); 6 – Modified RAN (rare bigrams); 7 – Automatic detection efficiency index in Ruff 2&7 test; 8 – Lexical access efficiency index (CV for English nouns residualized against CV for arrows); 9 – Attention: Form B performance time ("Trail Making" test of attention); 10 – Standardized residual (Form B against Form A performance time on the "Trail Making" test) as an index of the attention shift cost; 11 – Working memory index; 12 – Controlled search efficiency index in Ruff 2&7 test; 13 – Reading rate (ms/word); 14 – Reading comprehension.

Study 3 used the standardized reading test for measures of both reading speed and reading comprehension. Both were looked at in the correlational analyses. The vast majority of the RAN subtasks were significantly correlated with the measure of reading speed. Only four (out of fourteen) RAN subtasks did not show such a connection to reading rate: naming objects in the original RAN ($r = .187, p = .069$) and naming pictures of animals under the heavy attentional demand experimental condition ($r = .180, p = .080$), as well as naming pictures of animals and objects under the light attentional demand experimental condition. For the rest, correlation coefficients ranged from $r = .203, p = .048$ (for naming objects under heavy attentional load) to $r = .423, p < .001$ (for naming less frequent bigrams).

The index of reading comprehension was more strongly associated with the non-symbolic RAN subtasks. Coefficients of correlation exceeded significance level for four out of six of them: naming colors in the original RAN ($r = .259, p = .011$), naming pictures of animals under the light attentional demand experimental condition ($r = .253, p = .013$), as well as naming animals and objects – both under the heavy attentional demand experimental condition ($r = .229$, p = .025 and $r = .360, p < .001$, respectively). In contrast, among eight symbolic RAN subtasks only three showed significant correlation with reading comprehension: naming relatively rare bigrams ($r = .201, p = .049$) and naming vowels and consonants under the heavy attentional demand experimental condition ($r = .368, p < .001$ and $r = .229, p = .025$, respectively). In addition, in terms of correlations involving variables served as predictors in the subsequent multiple regression analyses, the following several deserve special attention.

As Tables 5.3 and 5.4 show, the index of working memory was significantly correlated with all RAN subtasks (on average higher with non-symbolic and attention-wise more demanding ones). Also, it was significantly correlated with both measures of reading performance – speed and comprehension: $r = .374, p < .001$ and $r = 433, p < .001$, respectively.

The CV measure of efficiency of lexical access, obtained by the means of the "Living/Non-living" task, showed the following correlations with the reading performance: $r = .215, p = .035$ with reading speed, and $r = .208, p = .042$ with reading comprehension.

Multiple regression analyses. Finally, the issue of primary interest for the project – the cognitive nature of the RAN task – was addressed in a series of multiple regression analyses, in which the criterion measures were performance times on the various RAN subtasks. In the first round of analyses, the following set of predictors was used: (1) the index of efficiency of automatic search, (2) the CV index of efficiency of lexical access, and (3) the index of general attention (see the *Method* section for the detailed description of the procedures to calculate each). The results of this first round of multiple regression analyses with all RAN subtasks (original and modified) as the criterion variable are presented in Tables 5.5 – 5.18 below.

Table 5.5
Results of a multiple regression analysis of the original RAN letters subtask performance by indices of automatic detection efficiency, efficiency of lexical access and general attention

Variable:	r^a	R	R^2	R^2 change	F change	Sign. F	Final β
Automatic detection efficiency	.158	.158	.025	.025	2.402	.125	.064
Efficiency of lexical access	.098	.179	.032	.007	.694	.407	.025
Attention (Form B)	.278**	.285	.081	.049*	4.908	.029	.247*

[a]Zero-order correlations. *$p < .05$, ** $p < .01$, *** $p < .001$

Table 5.6
Results of a multiple regression analysis of the original RAN digits subtask performance by indices of automatic detection efficiency, efficiency of lexical access and general attention

Variable:	r^a	R	R^2	R^2 change	F change	Sign. F	Final β
Automatic detection efficiency	.146	.146	.021	.021	2.054	.155	.094
Efficiency of lexical access	.088	.165	.027	.006	.549	.461	.045
Attention (Form B)	.176	.201	.041	.013	1.285	.260	.129

[a]Zero-order correlations. *$p < .05$, ** $p < .01$, *** $p < .001$

Table 5.7
Results of a multiple regression analysis of the original RAN color subtask performance by indices of automatic detection efficiency, efficiency of lexical access and general attention

Variable:	r^a	R	R^2	R^2 change	F change	Sign. F	Final β
Automatic detection efficiency	.264**	.264	.070	.070**	7.069	.009	.081
Efficiency of lexical access	.253**	.351	.123	.053*	5.640	.020	.118
Attention (Form B)	.529***	.546	.298	.175***	22.994	.000	.467***

[a]Zero-order correlations. *$p < .05$, ** $p < .01$, *** $p < .001$

Table 5.8
Results of a multiple regression analysis of the original RAN object subtask performance by indices of automatic detection efficiency, efficiency of lexical access and general attention

Variable:	r^a	R	R^2	R^2 change	F change	Sign. F	Final β
Automatic detection efficiency	.189	.189	.036	.036	3.478	.065	.042
Efficiency of lexical access	.146	.229	.053	.017	1.666	.200	.037
Attention (Form B)	.414***	.417	.174	.121***	13.511	.000	.388***

[a]Zero-order correlations. *$p < .05$, ** $p < .01$, *** $p < .001$

Table 5.9

Results of a multiple regression analysis of the M-RAN-Frequent-Bigrams subtask performance by indices of automatic detection efficiency, efficiency of lexical access and general attention

Variable:	r^a	R	R^2	R^2 change	F change	Sign. F	Final β
Automatic detection efficiency	.088	.088	.008	.008	.763	.393	.010
Efficiency of lexical access	.102	.129	.017	.009	.848	.359	.033
Attention (Form B)	.261*	.263	.069	.053*	5.190	.025	.256*

[a]Zero-order correlations. *$p < .05$, ** $p < .01$, *** $p < .001$

Table 5.10

Results of a multiple regression analysis of the M-RAN-Rare-Bigrams subtask performance by indices of automatic detection efficiency, efficiency of lexical access and general attention

Variable:	r^a	R	R^2	R^2 change	F change	Sign. F	Final β
Automatic detection efficiency	.198	.198	.039	.039	3.834	.053	.087
Efficiency of lexical access	.008	.200	.040	.001	.064	.801	.104
Attention (Form B)	.328**	.353	.096	.085**	8.890	.004	.324**

[a]Zero-order correlations. *$p < .05$, ** $p < .01$, *** $p < .001$

Table 5.11

Results of a multiple regression analysis of the M-RAN-Symbolic-Small-Light subtask performance by indices of automatic detection efficiency, efficiency of lexical access and general attention

Variable:	r^a	R	R^2	R^2 change	F change	Sign. F	Final β
Automatic detection efficiency	.140	.140	.020	.020	1.887	.173	.032
Efficiency of lexical access	-.046	.152	.023	.003	.330	.567	.138
Attention (Form B)	.299**	.329	.108	.085**	8.765	.004	.325**

[a]Zero-order correlations. *$p < .05$, ** $p < .01$, *** $p < .001$

Table 5.12

Results of a multiple regression analysis of the M-RAN-Symbolic-Large-Light subtask performance by indices of automatic detection efficiency, efficiency of lexical access and general attention

Variable:	r^a	R	R^2	R^2 change	F change	Sign. F	Final β
Automatic detection efficiency	.182	.182	.033	.033	3.208	.077	.105
Efficiency of lexical access	.106	.203	.041	.008	.799	.374	.044
Attention (Form B)	.247**	.269	.072	.031	3.072	.083	.196

[a]Zero-order correlations. *$p < .05$, ** $p < .01$, *** $p < .001$

Table 5.13

Results of a multiple regression analysis of the M-RAN-Non-Symbolic-Small-Light subtask performance by indices of automatic detection efficiency, efficiency of lexical access and general attention

Variable:	r[a]	R	R^2	R^2 change	F change	Sign. F	Final β
Automatic detection efficiency	.130	.130	.017	.017	1.621	.206	.031
Efficiency of lexical access	.170	.205	.042	.025	2.454	.121	.058
Attention (Form B)	.424***	.429	.184	.142***	15.984	.000	.420***

[a]Zero-order correlations. *$p < .05$, ** $p < .01$, *** $p < .001$

Table 5.14

Results of a multiple regression analysis of the M-RAN-Non-Symbolic-Large-Light subtask performance by indices of automatic detection efficiency, efficiency of lexical access and general attention

Variable:	r[a]	R	R^2	R^2 change	F change	Sign. F	Final β
Automatic detection efficiency	.068	.068	.005	.005	.435	.511	.096
Efficiency of lexical access	.139	.150	.022	.018	1.701	.195	.029
Attention (Form B)	.407***	.418	.175	.152***	16.966	.000	.435***

[a]Zero-order correlations. *$p < .05$, ** $p < .01$, *** $p < .001$

Table 5.15

Results of a multiple regression analysis of the M-RAN-Symbolic-Small-Heavy subtask performance by indices of automatic detection efficiency, efficiency of lexical access and general attention

Variable:	r^a	R	R^2	R^2 change	F change	Sign. F	Final β
Automatic detection efficiency	.183	.183	.034	.034	3.275	.074	.075
Efficiency of lexical access	.142	.223	.050	.016	1.576	.212	.060
Attention (Form B)	.322**	.334	.112	.062*	6.396	.013	.277*

^{a}Zero-order correlations. *$p < .05$, ** $p < .01$, *** $p < .001$

Table 5.16

Results of a multiple regression analysis of the M-RAN-Symbolic-Large-Heavy subtask performance by indices of automatic detection efficiency, efficiency of lexical access and general attention

Variable:	r^a	R	R^2	R^2 change	F change	Sign. F	Final β
Automatic detection efficiency	.239*	.239	.057	.057*	5.672	.019	.117
Efficiency of lexical access	.025	.239	.057	.000	.002	.968	.043
Attention (Form B)	.247**	.296	.088	.031	3.111	.081	.196

^{a}Zero-order correlations. *$p < .05$, ** $p < .01$, *** $p < .001$

Table 5.17

Results of a multiple regression analysis of the M-RAN-Non-Symbolic-Small-Heavy subtask performance by indices of automatic detection efficiency, efficiency of lexical access and general attention

Variable:	r^a	R	R^2	R^2 change	F change	Sign. F	Final β
Automatic detection efficiency	.185	.185	.034	.034	3.339	.071	.024
Efficiency of lexical access	.133	.219	.048	.014	1.344	.249	.013
Attention (Form B)	.444***	.445	.198	.150***	17.195	.000	.432***

ᵃZero-order correlations. *$p < .05$, ** $p < .01$, *** $p < .001$

Table 5.18

Results of a multiple regression analysis of the M-RAN-Non-Symbolic-Large-Heavy subtask performance by indices of automatic detection efficiency, efficiency of lexical access and general attention

Variable:	r^a	R	R^2	R^2 change	F change	Sign. F	Final β
Automatic detection efficiency	.241*	.241	.058	.058*	5.820	.018	.073
Efficiency of lexical access	.161	.279	.078	.020	1.990	.162	.032
Attention (Form B)	.483***	.489	.239	.161***	19.447	.000	.447***

ᵃZero-order correlations. *$p < .05$, ** $p < .01$, *** $p < .001$

The most important results emerging from these analyses are the following. First, overall the indices of automatic detection efficiency were not strong predictors of RAN task performance ($\Delta R^2 \leq .07$). In several cases, though, the contribution of automaticity to explaining variability in RAN performance achieved the level of significance (e.g., for naming colors in the original RAN: $\Delta R^2 = .07$, p = .009, and also for naming consonants and pictures of common objects: $\Delta R^2 = .057$, $p = .019$ and $\Delta R^2 = .058$, $p = .018$, respectively – both under the heavy attentional demand experimental condition). Second, the CV measure of efficiency of lexical access reached significance only once, contributing 5.3% ($p = .020$) into variability of color naming on the original RAN. Finally, the contribution of the index of general attention was always a strong predictor of naming speed across individual RAN subtasks (see ΔR^2 values in Tables 5.5 through 5.18), only in three cases falling short of reaching significance. The proportion of explained variability varied from 4.9 % to 17.5 %.

The attention factor, once again, emerged as a strong predictor of RAN task performance. In order to look more closely at what aspects of attention were involved in this effect in particular, on the next step of the data analyses, the general attention factor (performance time on Form B of the Trail Making test) was itself subjected to multiple regression as the criterion variable. The predictors were: (1) the index of efficiency of controlled searches, (2) the index of working memory, and (3) the index of attention shift cost (as in Study 1). The individual contributions varied as a function of the order in which they were entered into the analyses. Briefly, however, these three measures together explained 70.1 % (adjusted $R^2 = .691$, $p < .001$) of variability in the index of general attention. Though some portion of variability remained unexplained, this result allowed for greater flexibility in the subsequent multiple regression analyses, in which the index of general attention was substituted by its three hypothesized subcomponents to be used as predictors of naming speed in all individual RAN subtasks as the criterion variable.

Tables 5.19 – 5.32 present results of these additional analyses, though just some of them, those of the highest relevance to the project major research questions, are discussed below in greater detail.

The percent of explained variability in RAN performance increased on average 11.56 % compared to the first round of the multiple regression analyses. This could mean, among other things, that each subcomponent brought to the equation some extra value, which lay beyond the 70% of variability in general attention explained by the joint effect of these three subcomponents. This increase in variability accounted for, for the most part, appears to be due to the factor of working memory, which alone explained from 7.5% to 22.0% in different individual RAN subtasks.

Though it would be possible to discuss the models for each individual RAN subtask, at this point we will only consider those subtasks that showed the strong associations with the assessed reading outcomes. On balance, the cognitive nature of the RAN task has been brought into spot-light of researchers' interest primarily because of its connection to reading.

The strongest correlations between RAN task performance and reading rate were obtained in two of the modified RAN subtasks. These were the following: naming the letters in less frequent bigrams ($r = .423, p < .001$) and naming vowels under the heavy attentional demand experimental condition ($r = .415, p < .001$). The other measure of reading performance – comprehension – was most strongly correlated with naming vowels and pictures of animals ($r = .368, p < .001$ and $r = .360, p < .001$, respectively), both under the heavy attentional demand experimental condition. These results indicate that in general attention-wise more challenging RAN subtasks, as largely expected, carry a high degree of association with different aspects of reading performance. It is also the reason to single them out of the entire list of RAN subtasks, as most representative examples, in a search for cognitive factors underlying RAN task performance.

None of the analyses indicated that indices of automaticity accounted for a large proportion of variance in RAN task performance. In naming rare bigrams, the index of efficiency of automatic detection almost approached significance ($\Delta R^2 = .039, p = .053$). The contribution of the CV index of efficiency of lexical access was also negligible. In contrast, the joint contribution of attention-related factors in these three RAN subtasks was always significant (up to 25.9 % in naming pictures of animals under the heavy attentional demand experimental condition).

In particular, the task of naming vowels under the condition of heavy attentional demand (most related to both reading rate and comprehension) showed the following results. The index of automatic detection efficiency explained 3.4 % of the variance in naming speed (though falling short of being a significant contributor, $p = .074$). The same amount was explained by the index of controlled search efficiency ($\Delta R^2 = .034, p = .069$). The contribution from the index of lexical access efficiency was very modest ($\Delta R^2 = .016, p = .212$). The biggest portion of variance in naming speed was explained by the factor of working memory – 22.0 % ($p < .001$), with only a fraction of a percent ($\Delta R^2 = .001, p = .685$) added by the index of attention shift cost.

Table 5.19

Results of a multiple regression analysis of the original RAN letters subtask performance by indices of automatic detection efficiency, efficiency of lexical access, controlled search efficiency, working memory and attention shift cost

Variable:	r^a	R	R^2	R^2 change	F change	Sign. F	Final β
Automatic detection efficiency	.158	.158	.025	.025	2.402	.125	.140
Efficiency of lexical access	.098	.179	.032	.007	.694	.407	.074
Controlled search efficiency	.101	.180	.032	.000	.011	.917	.131
Working memory	.399***	.418	.175	.143***	15.744	.000	.335***
Attention shift cost	.286**	.451	.203	.028	3.181	.078	.186

[a]Zero-order correlations. *$p < .05$, ** $p < .01$, *** $p < .001$

Table 5.20

Results of a multiple regression analysis of the original RAN digits subtask performance by indices of automatic detection efficiency, efficiency of lexical access, controlled search efficiency, working memory and attention shift cost

Variable:	r^a	R	R^2	R^2 change	F change	Sign. F	Final β
Automatic detection efficiency	.146	.146	.021	.021	2.054	.155	.124
Efficiency of lexical access	.088	.165	.027	.006	.549	.461	.074
Controlled search efficiency	.083	.166	.028	.001	.048	.826	.112
Working memory	.400***	.417	.174	.146***	16.112	.000	.372
Attention shift cost	.191	.423	.179	.005	.512	.476	.076

[a]Zero-order correlations. *$p < .05$, ** $p < .01$, *** $p < .001$

Table 5.21

Results of a multiple regression analysis of the original RAN color subtask performance by indices of automatic detection efficiency, efficiency of lexical access, controlled search efficiency, working memory and attention shift cost

Variable:	r^a	R	R^2	R^2 change	F change	Sign. F	Final β
Automatic detection efficiency	.264**	.264	.070	.070**	7.069	.009	.063
Efficiency of lexical access	.253**	.351	.123	.053*	5.640	.020	.191*
Controlled search efficiency	.345**	.406	.165	.042*	4.640	.034	.127
Working memory	451***	.557	.311	.145***	19.175	.000	.314***
Attention shift cost	.444***	.608	.370	.060**	8.528	.004	.270**

[a] Zero-order correlations. *$p < .05$, ** $p < .01$, *** $p < .001$

Table 5.22

Results of a multiple regression analysis of the original RAN object subtask performance by indices of automatic detection efficiency, efficiency of lexical access, controlled search efficiency, working memory and attention shift cost

Variable:	r^a	R	R^2	R^2 change	F change	Sign. F	Final β
Automatic detection efficiency	.189	.189	.036	.036	3.478	.065	.075
Efficiency of lexical access	.146	.229	.053	.017	1.666	.200	.092
Controlled search efficiency	.344**	.361	.130	.077**	8.186	.005	.279*
Working memory	.370**	.473	.224	.094***	11.038	.001	.279**
Attention shift cost	.306**	.487	.237	.013*	1.572	.213	.128

[a] Zero-order correlations. *$p < .05$, ** $p < .01$, *** $p < .001$

Table 5.23

Results of a multiple regression analysis of the M-RAN-Frequent-Bigrams subtask performance by indices of automatic detection efficiency, efficiency of lexical access, controlled search efficiency, working memory and attention shift cost

Variable:	r^a	R	R^2	R^2 change	F change	Sign. F	Final β
Automatic detection efficiency	.088	.088	.008	.008	.763	.393	.012
Efficiency of lexical access	.102	.129	.017	.009	.848	.359	.084
Controlled search efficiency	.115	.146	.021	.004	.418	.520	.005
Working memory	.407***	.417	.174	.153***	16.844	.000	.381***
Attention shift cost	.210*	.422	.178	.004	.484	.488	.074

^{a}Zero-order correlations. *$p < .05$, ** $p < .01$, *** $p < .001$

Table 5.24

Results of a multiple regression analysis of the M-RAN-Rare-Bigrams subtask performance by indices of automatic detection efficiency, efficiency of lexical access, controlled search efficiency, working memory and attention shift cost

Variable:	r^a	R	R^2	R^2 change	F change	Sign. F	Final β
Automatic detection efficiency	.198	.198	.039	.039	3.834	.053	.077
Efficiency of lexical access	.008	.200	.040	.001	.064	.801	.047
Controlled search efficiency	.214*	.231	.053	.014	1.326	.253	.057
Working memory	.406***	.430	.185	.131***	14.634	.000	.335***
Attention shift cost	.266**	.446	.199	.014	1.571	.213	.131

^{a}Zero-order correlations. *$p < .05$, ** $p < .01$, *** $p < .001$

Table 5.25

Results of a multiple regression analysis of the M-RAN-Symbolic-Small-Light subtask performance by indices of automatic detection efficiency, efficiency of lexical access, controlled search efficiency, working memory and attention shift cost

Variable:	r[a]	R	R^2	R^2 change	F change	Sign. F	Final β
Automatic detection efficiency	.140	.140	.020	.020	1.887	.173	.037
Efficiency of lexical access	-.046	.152	.023	.003	.330	.567	.103
Controlled search efficiency	.250*	.265	.070	.047*	4.640	.034	.140
Working memory	.378***	.426	.182	.112***	12.406	.001	.257**
Attention shift cost	.410***	.504	.254	.073**	8.754	.004	.298**

[a] Zero-order correlations. *$p < .05$, ** $p < .01$, *** $p < .001$

Table 5.26

Results of a multiple regression analysis of the M-RAN-Symbolic-Large-Light subtask performance by indices of automatic detection efficiency, efficiency of lexical access, controlled search efficiency, working memory and attention shift cost

Variable:	r[a]	R	R^2	R^2 change	F change	Sign. F	Final β
Automatic detection efficiency	.182	.182	.033	.033	3.208	.077	.091
Efficiency of lexical access	.106	.203	.041	.008	.799	.374	.078
Controlled search efficiency	.173	.213	.045	.004	.388	.535	.007
Working memory	.407***	.428	.183	.138***	15.363	.000	.351***
Attention shift cost	.244**	.439	.192	.009	1.039	.311	.107

[a] Zero-order correlations. *$p < .05$, ** $p < .01$, *** $p < .001$

Table 5.27

Results of a multiple regression analysis of the M-RAN-Non-Symbolic-Small-Light subtask performance by indices of automatic detection efficiency, efficiency of lexical access, controlled search efficiency, working memory and attention shift cost

Variable:	r^a	R	R^2	R^2 change	F change	Sign. F	Final β
Automatic detection efficiency	.130	.130	.017	.017	1.621	.206	.120
Efficiency of lexical access	.170	.205	.042	.025	2.454	.121	.121
Controlled search efficiency	.287**	.324	.105	.063*	6.428	.013	.204
Working memory	.479***	.542	.293	.189***	24.282	.000	.393***
Attention shift cost	.376***	.567	.321	.028	3.728	.057	.185

[a]Zero-order correlations. *$p < .05$, ** $p < .01$, *** $p < .001$

Table 5.28

Results of a multiple regression analysis of the M-RAN-Non-Symbolic-Large-Light subtask performance by indices of automatic detection efficiency, efficiency of lexical access, controlled search efficiency, working memory and attention shift cost

Variable:	r^a	R	R^2	R^2 change	F change	Sign. F	Final β
Automatic detection efficiency	.068	.068	.005	.005	.435	.511	.115
Efficiency of lexical access	.139	.150	.022	.018	1.701	.195	.086
Controlled search efficiency	.221*	.266	.071	.048*	4.766	.032	.139
Working memory	.306**	.381	.145	.075**	7.952	.006	.182
Attention shift cost	.439***	.491	.241	.096***	11.360	.001	.342***

[a]Zero-order correlations. *$p < .05$, ** $p < .01$, *** $p < .001$

Table 5.29

Results of a multiple regression analysis of the M-RAN-Symbolic-Small-Heavy subtask performance by indices of automatic detection efficiency, efficiency of lexical access, controlled search efficiency, working memory and attention shift cost

Variable:	r^a	R	R^2	R^2 change	F change	Sign. F	Final β
Automatic detection efficiency	.183	.183	.034	.034	3.275	.074	.033
Efficiency of lexical access	.142	.223	.050	.016	1.576	.212	.106
Controlled search efficiency	.269**	.290	.084	.034	3.443	.067	.160
Working memory	.516***	.551	.304	.220***	28.754	.000	.471***
Attention shift cost	.253**	.552	.305	.001	.165	.685	.040

^{a}Zero-order correlations. *$p < .05$, ** $p < .01$, *** $p < .001$

Table 5.30

Results of a multiple regression analysis of the M-RAN-Symbolic-Large-Heavy subtask performance by indices of automatic detection efficiency, efficiency of lexical access, controlled search efficiency, working memory and attention shift cost

Variable:	r^a	R	R^2	R^2 change	F change	Sign. F	Final β
Automatic detection efficiency	.239*	.239	.057	.057*	5.672	.019	.025
Efficiency of lexical access	.025	.239	.057	.000	.002	.968	.021
Controlled search efficiency	.346***	.347	.121	.064*	6.665	.011	.273*
Working memory	.488***	.546	.298	.178***	23.059	.000	.439***
Attention shift cost	.208*	.546	.299	.000	.026	.873	.016

^{a}Zero-order correlations. *$p < .05$, ** $p < .01$, *** $p < .001$

Table 5.31

Results of a multiple regression analysis of the M-RAN-Non-Symbolic-Small-Heavy subtask performance by indices of automatic detection efficiency, efficiency of lexical access, controlled search efficiency, working memory and attention shift cost

Variable:	r[a]	R	R^2	R^2 change	F change	Sign. F	Final β
Automatic detection efficiency	.185	.185	.034	.034	3.339	.071	.111
Efficiency of lexical access	.133	.219	.048	.014	1.344	.249	.076
Controlled search efficiency	.362***	.377	.142	.094**	10.113	.002	.303*
Working memory	.451***	.541	.293	.150***	19.317	.000	.360***
Attention shift cost	.339**	.554	.307	.014	1.875	.174	.133

[a]Zero-order correlations. *$p < .05$, ** $p < .01$, *** $p < .001$

Table 5.32

Results of a multiple regression analysis of the M-RAN-Non-Symbolic-Large-Heavy subtask performance by indices of automatic detection efficiency, efficiency of lexical access, controlled search efficiency, working memory and attention shift cost

Variable:	r[a]	R	R^2	R^2 change	F change	Sign. F	Final β
Automatic detection efficiency	.241*	.241	.058	.058*	5.820	.018	.042
Efficiency of lexical access	.161	.279	.078	.020	1.990	.162	.084
Controlled search efficiency	.415***	.429	.184	.106***	11.973	.001	.282*
Working memory	.403***	.537	.289	.105***	13.380	.000	.243**
Attention shift cost	.481***	.606	.368	.079***	11.203	.001	.310***

[a]Zero-order correlations. *$p < .05$, ** $p < .01$, *** $p < .001$

Overall, the results show that the contribution of attention-related factors was statistically important, in contrast to the overall contribution of automaticity factors, which were not. It was true across all individual RAN subtasks. Just to give the most salient examples, here are some results worth mentioning.

The joint contribution of attention-related factors was as high as 29.0 % (M-RAN-Non-Symbolic-Large-Heavy, Table 5.32) or 27.9 % (M-RAN-Non-Symbolic-Small-Light, Table 5.27), but never less than 15.1 % (M-RAN-Symbolic-Large-Light, Table 5.26). In some cases, this contribution was distributed relatively evenly among all three attention-related predictors. For example, in M-RAN-Non-Symbolic-Large-Light (Table 5.28) the relative contribution of predictors was: 4.8 % of the index of controlled search efficiency, 7.5 % of the index of working memory, and 9.6 % of the index of attention shift cost. In M-RAN-Non-Symbolic-Large-Heavy (Table 5.32) these numbers respectively were: 10.6 %, 10.5 %, and 7.9 %. In many others, the major single contributor was the index of working memory.

In contrast, neither the index of automatic search nor, importantly, the CV index of efficiency of lexical access accounted for significant amounts of variability in RAN task performance. In nine out of 14 RAN subtasks the individual contribution of the index of automatic search efficiency to naming speed was not significant ($\Delta R^2 \leq .039$, $p \geq .053$). The CV index of efficiency of lexical access performed even worse: only one significant contribution of 5.3 % ($p = .020$) in naming colors on the original RAN tasks (Table 5.21). In all other models the proportion of variance in RAN task performance by this factor was not significant ($\Delta R^2 \leq .025$, with $p \geq .121$). These results indicate that automaticity factors do not play an important role in RAN task performance.

Finally, the index of working memory, in particular, accounted for significant amounts of variability in performance on all individual RAN subtasks, varying from 7.8%, $p = .006$ (M-RAN-Non-Symbolic-Large-Light, Table 5.28) to 22.0 %, $p < .001$ (M-RAN-Symbolic-Large-Heavy, Table 5.30). These results indicate that working memory factors play an important role in RAN task performance.

Discussion

Study 3 was designed as a follow-up to Studies 1 and 2. It aimed to address three major research questions:

1. *Automaticity*: Does automaticity of stimulus recognition remain a factor with little or no association with RAN task naming speed when automaticity is operationalized in other ways (i.e., not as ballistic processing or efficient stimulus recognition)?
2. *Attention*: Can particular aspects of attention be identified as being associated with successful RAN task performance?
3. *Other factors*: Are other factors, such as efficiency of lexical access and working memory capacity, capable of substantially adding to our understanding of the cognitive mechanisms of RAN task performance?

The major results are discussed here first in terms of commonalities and differences with the results obtained in the previous studies, followed by discussion of patterns of cross-correlations and multiple regression analyses that addressed the major research questions directly.

The set of measures overlapping with Studies 1 and 2 yielded very similar data on all RAN subtasks, both original and modified. Except for one case, none of all possible t-test comparisons revealed significant differences between the results of Study 3 and the results in the combined datasets of Studies 1 and 2. The only statistically significant difference between Study 3 and the other two was observed in participants' performance on Form B of the Trail Making test of attention: performance was significantly faster in Study 3.

Modified RAN subtasks

The ANOVA on the modified RAN subtasks data yielded significant main effects for the factors of attention demand and the type of stimuli, largely mirroring the Study 2 findings. Heavy attentional demand resulted in significantly slower naming indicating its high sensitivity to attention-related factors and their potentially important role in RAN task performance. Symbolic stimuli were named faster than non-symbolic stimuli across all conditions, once again suggesting that there is a difference in underlying cognitive mechanisms between symbolic and non-symbolic RAN subtasks.

Also, as in Study 2, there was no significant effect for the set size factor. However, the stimulus type by set size interaction effect was significant: larger source set size significantly slowed RAN performance on non-symbolic, but not on symbolic subtasks. This could be interpreted in terms of a practice effect on naming symbolic characters. The significant attention by stimulus type interaction indicated that attention may be involved to RAN task performance to different degrees in symbolic and non-symbolic subtasks.

To briefly summarize this subset of the data, Study 3 revealed, as was found earlier, that RAN task performance is very sensitive to task demands regarding attentional control, whether these demands arise from having to process symbolic stimuli that are less practiced (and presumably less automatized), or are due to additional task demands superimposed on the RAN task itself (to monitor for the ends of lines or occurrence of particular stimulus pairs). In other words, whenever more attention is required, RAN performance is substantially slowed down.

Also in line with the Study 2 findings, a significant difference was detected in the performance time between modified RAN subtasks based on relatively more frequent and relatively rare bigrams. The surface-level interpretation could be quite simple: less practiced combinations of characters are named more slowly. However, taken one step further, the result could also indirectly implicate some attentional involvement. First of all, it may indicate that stimuli in the RAN task are not processed completely separately from one another, which perhaps is one of major factors linking RAN to reading. Moreover, the lack of automaticity may be due to the need for more controlled (attention-related) resources to achieve the same processing results, even some low level of attention, which can then be abandoned when a higher level of automatization is achieved. This difference in bigram-based RAN subtasks deserves further consideration.

All together, these data, somewhat acknowledging the role of practice, strongly indicate that there is major contribution of attention to RAN task performance. The question arises, then, how does this results contribute to the connection between the naming speed and reading?

Interrelations among variables

Inter-correlations among the individual (original and modified) RAN subtasks obtained in this study were even stronger than those observed in Study 2. While some correlations were stronger than others, looking at the whole dataset of inter-correlations, it appears that the subtask generally most highly correlated with the other subtasks, irrespective of the type of stimuli, was rare bigram naming, once again placing this particular subtask in the spotlight as potentially bridging automatic and attention-based aspects of rapid naming.

What is also important here, is that all RAN subtasks appeared to be interconnected, consistent with the idea that there are at least some cognitive mechanisms shared by all of them, despite differences between symbolic and non-symbolic RAN subtasks and the modifications that were introduced into the various subtypes.

In Study 3 a standardized reading test was used, allowing consideration of not only reading rate, but also reading comprehension. Most of the RAN subtasks correlated significantly with reading rate in Study 3 (more than in Study 2, likely due to the larger sample size in Study 3). In general, it appears that the patterns in correlation coefficients for the symbolic RAN subtasks were very consistent across studies. First, symbolic RAN had stronger connection to reading speed, and second, within the symbolic category, those RAN subtasks associated with higher attentional demand had a tendency to show somewhat stronger correlation with the reading rate measure.

As for reading comprehension, correlations were noticeably stronger for the RAN subtasks based on non-symbolic stimuli compared to symbolic stimuli. It was also true for the subtasks associated with the heavy attentional demand, indicating that the cognitive mechanisms that are tapped into by these RAN subtasks should also be crucial for understanding the message behind printed text, probably regardless the reading speed.

The measure of working memory provided the most consistent pattern for a single variable of significant correlations with performance on all RAN subtasks and with both speed and comprehension measures of reading performance, potentially implicating working memory as an important link connecting RAN task performance to reading ability.

Another interesting result concerns the CV index of efficiency of lexical access, obtained in the "Living/Non-living" task. This measure was primarily intended to further explore the cognitive nature of RAN task, but it was also expected to be associated with reading measures. These expectations were basically confirmed.

Multiple regression analyses

Finally, with respect to the primary research questions for Study 3, two rounds of multiple regression analyses were performed, with the following results.

In the first round of multiple regression analyses, performance time on all individual RAN subtasks was the criterion variable. The predictor variables were: (1) the index of efficiency of automatic search (calculated from the Ruff 2&7 test data as described above in the method section), (2) the CV index of efficiency of lexical access (CV index for judging English words residualized against CV index for judging direction of arrows in the "Living/Non-living task), and (3) Form B of the Trail Making test performance time. The measure of automatic detection efficiency in the Ruff 2&7 test served as an alternative measure to those used before for automatic processing. The index of general attention had already proven to be an important correlate of RAN task performance. The CV index of efficiency of lexical access was added to the model to explore other potential predictors, because in Studies 1 and 2 a large portion of the variability in RAN task performance had remained unexplained.

Automaticity. In Study 2, automaticity was found to not be a significant predictor of RAN task performance. In Study 3, when automaticity was operationalized differently from Study 2, the results were similar, consistent with the idea that automaticity is not a significant predictor of RAN task performance. Together, these results call into question whether RAN task performance really reflects automatic aspects of naming. The few cases where evidence for automaticity either approached or reached significance involved naming colors on the original RAN, naming rare bigrams and some RAN subtasks under the condition of heavy attentional demand. Somewhat surprisingly, this particular pattern of results suggests that automatic processing may contribute to faster naming when attention is challenged, whereas it appears to be less relevant in the presumably more automatic naming of symbolic stimuli in the original RAN subtasks and under the conditions of light attentional load. Also, the contribution of the index of efficiency of lexical access was overall negligible.

Attention. In Study 2, attention was found to be a significant predictor of RAN task performance. In Study 3, when the same ways of operationalizing attention were used, the results were similar, confirming the earlier findings. Compared to the first two predictors, the index of general attention (performance on Form B of the Trail Making Test) was considerably more powerful. This index failed to show a significant association with RAN task performance in only three cases – naming digits in the original RAN task and naming consonants in both attention manipulated conditions. These are the subtasks that presumably represented cases of the most highly automatized types of the stimuli across all RAN subtasks. Study 3 thus provided further strong confirmation of the overall important role of attention in RAN task performance, warranting the closer investigation of particular components of attention that might contribute to naming speed and to the link between RAN performance and reading.

Earlier it was hypothesized that the index of general attention (performance time on Form B of the Trail Making test) used in Study 1 and Study 2 has individual components related to more specific aspects of attention-related cognitive factors. In particular spatial search ability, working memory capacity, and efficiency of shifting attention from one stimulus (or a chunk of consecutive stimuli) to another were identified. Consequently, in the second round of multiple regression analyses, the index of general attention was replaced by three hypothesized subcomponents: (1) the index of efficiency of controlled search (calculated from the Ruff 2&7 test data as described above in the method section), (2) the index of working memory capacity (a subscale of WAIS-III IQ battery), and (3) the index of attention shift cost (performance time on Form B of the Trail Making test residualized against performance time on Form A). This set of three attention-related predictors proved to be very successful in explaining variability in the index of general attention.

The results of the second round of multiple regression analyses were as follows. The three attention-related predictors increased the models' overall power to explain variability RAN task performance. These findings justified employing these models interchangeably depending on the circumstances, for example using fewer predictors in less powerful analyses with smaller samples. For purposes of the current research, on the other hand, the model with five predictors allowed for more detailed exploration of factors thought to be involved in the RAN task performance. In particular, the strongest of the three predictors was the index of working memory. The results also indicated that after working memory was taken into account, attention shift cost did not predict much additional variance, indicating that the two factors probably share a lot of variability, at least with regard to the RAN task performance (e.g., in Study 3, in particular, the correlation between working memory and attention shift cost was $r = .334$, $p = .001$). The contribution of the index of efficiency of controlled search was moderate, though in many cases, significant, adding another piece to the picture that describes involvement of attention-related factors in naming speed.

The role of attention factors – and working memory in particular – in explaining variability in RAN task performance was especially clear in RAN subtasks that were most strongly correlated with the two measures of reading skills. This pattern may be interpreted as an indication of two things. First, the processing of symbolic stimuli in RAN is not accomplished item-by-item, but is organized into manageable sequences (chunks) that vary in size dependent on individual differences in working memory capacity. Second, that the role played in the processing of non-symbolic stimuli of attention shifting abilities actually implicates working memory.

Brief summary

Thus, by way of overall summary, in terms of the main research questions, it was found that RAN task performance is not well accounted for by automatic processing skills (neither at the level of single-character or entire-word recognition), whereas it is well accounted for by attention-related factors, and by working memory in particular.

CHAPTER 6:

A STAGE TWO META-ANALYSIS OF THE EMPIRICAL EVIDENCE OF THE ASSOCIATION BETWEEN RAN TASK PERFORMANCE AND READING ABILITIES

This chapter reports on a stage two[2] meta-analysis that explores the strength of association between RAN task performance and reading measures. It summarizes data from a representative sample of 65 empirical studies reporting correlations (*k*=422, N=6495 – for the studies that employed cross-sectional design, and *k*=108, N=2060 – for the studies that employed longitudinal design)[3] between different RAN sub-tasks and various measures of reading performance. The goal is to address the following research questions:

1. What is the point estimate (an average effect size) of the degree of association between the RAN task and reading?
2. What factors (methodological and substantive study features) affect (increase or reduce) the strength of this association and to what extent?

Since the early eighties, meta-analysis (Glass, McGaw, & Smith, 1981), as a type of a systematic review, has been an extremely valuable methodology for integrating research findings across primary empirical studies addressing related questions. Its constantly refined methodology (e.g., Bernard & Naidu, 1990; Hedges, Shymansky, &

---

[2] The term "Stage Two meta-analysis" is used to distinguish the reported project from (1) a complete (full-scale meta-analysis) which would have entailed the most exhaustive literature search and review, and (2) from a stage one meta-analysis, which typically also deals with a representative sample of relevant empirical research, but does not go further than the stage of effect size extraction.

[3] Here *k* represents the total number of cases (coefficients of correlation analyzed), whereas *N* represents the total sample size (the total number of participants).

Woodworth, 1989; Lipsey & Wilson, 2001) includes systematic identification of relevant studies, statistical techniques for estimating an average effect size (either a magnitude of difference between various experimental conditions or degree of association between experimental variables). No less importantly, meta-analysis employs special procedures aimed to explain variability surrounding the mean effect size by systematically accounting for the influence of factors that determine the study-specific characteristics (research design, reliability of assessment tools used, participants' age, gender, abilities and personal characteristics, particular aspects of experimental treatment, etc.).

The method of meta-analysis is the most suitable for the purposes of the present research when it comes to the question "Under what circumstances is the RAN task association with reading the most salient?" Not only does it show whether a general effect (the above chance correlation between variables in question) exists consistently across numerous relevant studies and what its overall magnitude is, but met-analysis also allows for exploring sources of variability in the effect sizes through analyses of methodological and substantive study features as they mediate and/or moderate the strength of association between RAN and reading. Given that there is a great deal of controversy surrounding research findings concerning the RAN task, a meta-analysis also appears to be the most potent tool to use in an attempt to meaningfully reconcile such data.

What is known from previous meta-analytical research?

Recently, two meta-analyses investigated the literature that addressed correlates of reading (including the RAN task). Hopkins (2002) reported significant low-to-moderate correlations between the reading and RAN. Swanson et al. (2003) meta-analyzed over two thousands correlation coefficients from forty-nine independent samples and found RAN task performance to be correlated on average with the measure of real word reading at $r+ = .49$, with the measures of reading comprehension at $r+ = .53$, and with measures of pseudo-word reading at $r+ = .42$. As variability in effect sizes requires explanation, a subsequent set of so-called moderator analyses then explores how much moderator variables (individual study features) influence the direction and the magnitude of the effects. Moderator variables in this meta-analysis did not influence the strength of these associations much, though the authors reported that correlations between either RAN task performance or measures of phonological awareness and reading outcomes tended to be higher in skilled readers compare to troubled ones. The latter came out as rather a surprising finding since many researchers see the RAN task to be a more effective diagnostic tool for children at risk of developing reading disorders (for the references see Chapter 2 and a short review of study features below).

Later, Hammill (2004) reported findings of another, larger scale meta-analysis (a second-level meta-analysis that combined results from three preceding meta-analyses – Hammill & McNutt, 1981; Scarborough, 1998a; Swanson et al., 2003), also involving measures of RAN task performance and reading abilities. His analysis of over eleven thousand correlation coefficients from about four hundred fifty individual studies revealed that the RAN task, given the observed magnitude of the correlations, belongs to the cluster of moderate predictors of reading. Emerging second in this cluster at $r+ = .44$, the RAN task seemed to slightly overshadow indices of phonological awareness ($r+ = .40$) in importance. Two aspects of the author's interpretation of these findings are especially worth considering here.

First, in an attempt to explore different possibilities of causal relationships among variables in this meta-analysis, Hammill noticed that the variables most highly correlated with reading could also be classified in so-called "print clusters" (e.g., alphabet knowledge, single phoneme-letter recognition, print awareness, etc.) as they are very much related to the English writing system. What they all also have in common is that they are typically acquired through special instructional interventions (more or less formalized education). The other "non-print clusters" (with RAN and phonological awareness being among them alongside with memory, spoken language, perceptual and motor skills) combines more general cognitive abilities that are less strongly correlated with reading. These cognitive abilities are often measured on the corresponding subscales of various IQ tests. According to Hammill, only the print cluster could possibly provide a causal link to overall reading abilities, whereas the skills subsumed under the non-print cluster "…are simply measuring different aspects of general intelligence or aptitude" (Hammill, 2004, p. 464).

Second, from an applied perspective, Hammill concluded that despite their significant correlation with reading, variables in the non-print cluster might actually be overemphasized in the research literature. In his opinion, the regular educational practice should refocus (if not abandon entirely) attention from the skills represented in this cluster onto more trainable and closer connected to reading abilities in written language – those involving printed text processing. The last suggestion, as practical as it may seem, neither helps much in understanding the cognitive nature of RAN association with reading nor addresses the needs of those (3-5%) children who tend to fail in formal reading instruction, presumably because of some deeper (rooted in cognitive development) shortcomings.

In a sense, both the meta-analyses just mentioned provide at least partial answers to questions about the overall magnitude of RAN task performance correlations with reading abilities. However, there are several important limitations in these meta-analyses that render some of the answers incomplete. Even without getting too much into details with regard to moderator variables (or study features) they explored or did not explore, both meta-analyses lack specificity in defining the RAN measure itself. In them it appears as a single construct, as if the differences between symbolic and non-symbolic RAN sub-tasks were negligible for the major purposes of the analyses, but they should not be overlooked in the meta-analyses to come.

Other limitations of the Swanson et al. (2003) and Hammill (2004) meta-analyses, at least from the perspectives of the current research, include, as was mentioned previously, their choices of moderator variables. Some of the study features that they did not consider could, among other things, shed light on several issues about the cognitive nature of RAN-to-reading association, as well as advance our knowledge about under what conditions this association manifests itself most strongly.

For one, none of the meta-analyses above treated the language on which participants performed either RAN or reading tasks as a substantive study features, leaving no opportunity to verify Wolf et al's (2000) claim that in more transparent (in terms of grapheme-to-phoneme correspondence) the RAN task outperforms measures of phonological awareness as a predictor of reading outcomes. There are other factors that definitely deserve special attention, including a type of the RAN and reading sub-tasks, participants' age and reading abilities, etc., some of which were addressed in the previous meta-analyses. Unfortunately, the exclusion from them of all but English-speaking samples make potential generalization of their results to a bigger population problematic, as best.

Controversial issues surrounding the RAN task performance that could be, at least partially, resolved by means of a large-scale meta-analysis, were depicted in detail in the corresponding section of Chapter 2. Nevertheless, before turning to the methodology and major findings of the current meta-analysis, let's briefly consider some of them again.

Brief review encompassing selection of the study features for the current meta-analysis

One of the biggest unresolved problems with the RAN task is the difference in predictive power for reading between its symbolic and non-symbolic subtasks, not just in general, but more importantly, as it applies to different aspects of reading expertise. Here are just a few examples from some already mentioned sources:

- Badian (1993) described letter naming as more strongly associated with a measure of word recognition and object naming as rather related to reading comprehension.
- Van den Bos et al. (2003) emphasized the prominent role of letter and digit naming in predicting, single word reading speed in particular.
- Young and Bowers (1995) named both symbolic RAN subtypes as best predictors of success in word identification tasks (both – speed and accuracy), which seems to mediate their connection (if any) to reading comprehension (as suggested in Spring & Davis, 1988; Wolf, 1991).

- According to Wolf and Obregon (1992), object naming is linked to comprehension more than other RAN subtasks, whereas in a study by Wolf et al. (2002) the correlation between letter naming and a word identification task was just marginally higher than between the former and a passage comprehension measure.

The next example of the difference between symbolic and non-symbolic RAN subtasks brings up another very important issue, namely, *the optimal timeframe for administering the RAN task.* Denckla and Cutting (1999) suggested that symbolic subtasks better work as concurrent discriminators among participants with different reading abilities, whereas non-symbolic subtasks – as predictors of further reading outcomes. This issue – whether the cross-sectional (i.e., where administration of the RAN task and reading measures was contemporaneous) or the longitudinal (i.e., where administration of the RAN task and reading measures was separated by time) studies reveal stronger RAN-to-reading association – will also be addressed in the meta-analysis that follows.

Another important group of questions to consider is *how the strength of association between RAN and reading changes with age.* Conceptually, a possible answer to it would very much depend on how the cognitive nature of the RAN task is understood. If RAN, as a cognitive skill, is nearly identical to reading, what would happen to its predictive power as one moves from kindergarten to adulthood? Most logically, the correlation between them would grow stronger. Practice in one or both would go in self-reinforcing circles leading to better expertise in all underlying cognitive processes and, since these are shared by both tasks, strengthening their interconnection. What does empirical research tell us in this regard? There are several reviews that summarize, among other, data from longitudinal studies, focusing either on universality of the RAN-to-reading association across age groups, as well as, languages, cultural background, SES clusters, etc. (for example, Wolf et al. 2000, Wolf et al., 2002) or on relative failures to demonstrate RAN's utility for reading prognosis in older children (for example, Savage, 2004, Savage et al., 2005). According to some results (e.g., Meyer et al., 1998), the older the population in question, the less predictive of reading RAN tends to become. One possible explanation to it is some kind of a "ceiling effect"– whereby after some particular level of fluency is achieved, extra naming speed cannot result in additional gains in reading performance. Van Den Boss et al. (2002) found this point (of the highest RAN-to-reading correlation, or asymptote) to be reached by age of sixteen for symbolic subtasks, whereas single word reading speed and naming of non-symbolic stimuli, according to them, continued to increase in chorus up to mature adulthood. Also there are indications that naming speed could be among best cognitive predictors of long-term educational outcome in general (Wood & Felton, 1994). Finally, in the present research (see Chapters 3-5, as well as, the reports of preliminary findings in Borokhovski et al. 2004, 2005) the correlation between RAN performance on symbolic RAN subtasks and silent reading rate in normal adult readers was moderate, but significant, whereas reading correlation with non-symbolic RAN subtasks in most cases was noticeably weaker.

What is even more important here, perhaps, is that how strongly RAN task performance and reading are related also depends on such imperative characteristic of the sample in question as the level of reading expertise (on the continuum of skilled – impaired readers). Indeed, is there a difference between dyslexics and normal readers in the degree of correlation between the measures of RAN task performance and reading?

Though intended and primarily used for early diagnosis of reading disabilities (i.e., to detect difference between potentially successful and "at risk of a failure" readers), the RAN task is not equally sensitive across groups representing different levels of reading abilities – there are variations on this regard in empirical findings (see Chapter 2 for details). However, it would seem that RAN works better with those whose reading skills are underdeveloped or at risk of becoming impaired. For example, in a longitudinal study of average and severely impaired readers of age five through eight Wolf et al. (1986) observed that impaired readers were significantly slower than average readers in their performance on all naming tasks. Similarly, Savage et al. (2005) reported that: "...RAN discriminated only the below-average group from average performers [on several reading tasks]" (p. 12). Such findings are largely consistent with the major rational for the double-deficit hypothesis – impairment in both phonological and naming speed domains result in most severe cases of developmental dyslexia (Wolf & Bowers, 1999; Wolf et al., 2000). If so, it has another important implication – namely, that the RAN task taps into some basic cognitive mechanisms necessary for proper development of reading skills, but not completely overlaps with cognitive mechanisms of reading itself.

Addressing all these and related issues in a systematic manner, to allow for more conclusive summary of conditions affecting the degree of association between RAN task performance and reading abilities, seems as a proper task for the meta-analyses which methodology and major findings are reported below.

Method

Search strategy

An extensive literature search was designed and conducted to locate primary studies suitable for the purposes of the current meta-analysis. The search strategy (formulated as a statement with Boolean operators) targeted studies containing in their abstracts or descriptive key words any of the following terms: "RAN", "rapid naming", "automatized naming", "serial naming", "naming speed" in conjunction with any of the other set of terms: "literacy", "read*", "dyslex*". The timeframe for searches was set from 1976 – the year the RAN task was first reported (Denckla & Rudel, 1976) – with no upper limit.

Only four electronic databases were consulted because of their expected highest relevancy to the research question: (1) PSYCInfo, (2) PubMed, (3) ERIC, and (4) ProQuest Dissertations and Theses. These searches resulted in a total of 1503 hits. After all duplicates were identified and removed, the number of studies for potential inclusion was reduced to 714. In addition, the bibliographies of review articles, previous meta-analyses, and major empirical studies in the field were scanned resulting in an addition of 21 research articles. Thus, 735 studies in total emerged on the stage of literature searches.

Inclusion/Exclusion criteria and the review procedures

Each study identified through literature searches was first reviewed at the abstract level by two coders working independently. They then met to discuss their judgments and to document the agreement rate. One of the reviewers was the author of this research and the other was one of two research assistants (psychology Honours students) at the laboratory of Human Performance (Concordia University, Montreal). The decision at this stage was whether to retrieve the full text of the article or to exclude it from further analysis as unsuitable for its purposes.

Full-text document retrieval was considered warranted if the study abstract contained the following information (inclusion criteria):

- the study reports any of the "naming speed" measures using any version of the RAN tasks – original or modified;
- the study reports any measure of participants' reading performance;
- the study belongs to a broad category of primary empirical research employing cross-sectional (contemporaneous) or longitudinal design – with or without any instructional (remedial) intervention – and reporting correlational data relating performance on RAN and reading task.

Subsequently, if any of these criteria were clearly not met, the retrieval of the full-text document was not necessary. In such cases, reviewers were asked to indicate and document the particular reason for rejecting the study (the exclusion criteria) as follows:

- N-NSM – The study contained no naming speed measure.
- N-RPM – The study reported no measure of reading performance.
- N-PER – The study was not a primary empirical research study. In this case, the study was to be classified and marked accordingly as representing one of the following categories: REV – a review paper, MA – a meta-analysis, or TDO – theoretical, description or opinion article.

At the stage of the abstract review, the most liberal (inclusive) approach was implemented. In other words, whenever the abstract under review provided insufficient information to make a clear decision about whether any of the exclusion (rejection) criteria applies, the reviewer was instructed to mark the study for retrieval.

The procedure for the review of full-text documents followed a similar approach. At this stage more information was available, especially with regard to the most important inclusion criterion, namely, whether a measure of degree of association between RAN task and reading performance was reported in the study. If this additional criterion was not met, the study was rejected and was documented with a code N-MDA to indicate that no measures of degree of association were reported. All other inclusion/exclusion criteria for the abstract and full-text review were the same.

At each stage, reviewers used a numerical rating system to formalize the procedures of making decisions and properly documenting an agreement rate. Individual ratings were specified to range from 1 (the study is definitely unsuitable for the purposes of the project) to 5 (the study is definitely suitable for the purposes of the project). The midpoint of 3 (doubtful but possibly suitable) was designated as a vote in favor of including the study. In other words, ratings from 3 to 5 suggested either the retrieval of the full-text document (at the abstract review stage) or inclusion of the study in further analyses (at the full-text review stage), whereas ratings of 1 or 2 meant the elimination of the study from further consideration. Inter-rater agreement rate at these two stages of the review was calculated and reported in two different ways: (1) as a coefficient of correlation between ratings given by independent coders across all reviewed papers, and (2) as a percentage of studies, with respect to which both coders agreed whether to reject the study or to continue analyzing it.

The extent of uniformity between coders on the subsequent stages of effect size extraction and study features coding was also documented. For effect sizes, a number between 50 and 100 (in percentages) was assigned to each study to reflect the degree of consensus between the raters with regard to how many effect sizes should be extracted from each study, and this number was averaged across studies. As for the coding of study features, each study was assigned a rating according to the percentage of the features upon which the raters initially agreed; all disagreements were discussed until a final accord was negotiated. All agreement rates were averaged across studies, and the average rates are presented in the Results section below.

Effect size extraction

There are two options for estimating the extent to which RAN task performance and measures of reading abilities are interconnected, and these two approaches result in two corresponding types of metrics. One is to rely on explicitly reported coefficients of correlation between measures of RAN performance and different aspects reading abilities as estimates of the degree of their association. The second one is the usage of Cohen's *d*, converted to Hedges' *g* (Hedges et al., 1989) as representations of the studentized difference in RAN performance between pre-established groups of participants with notably disproportionate (uneven) reading skills. The current meta-analysis only utilized the former approach, as it is the more direct and easily interpreted representation of the degree of association between the RAN task and reading (Rosenthal, 1994). It automatically excluded studies that reported data in a format only suitable for measuring the magnitude of group differences. As a result, Pearson product-moment correlation coefficients (r) between the measures of RAN and reading performance, weighted by the corresponding sample sizes were analyzed using Comprehensive Meta-Analyses 2.0 software package (Borenstein, Hedges, Higgins, & Rothstein, 2005) and SPSS, Version 12 (Field, 2005). This produced an average point estimate separately for cross-sectional and longitudinal studies, and these estimates were further investigated in a subsequent series of moderator analyses based on coded study features.

The Q_T statistic was used to test for homogeneity of effect sizes (Hedges & Olkin, 1985). This homogeneity statistic is most commonly used in assessing a collection of effect sizes or correlation coefficients. When all findings share the same population value, Q_T has an approximate χ^2 distribution with $k - 1$ degrees of freedom, where k is the number of effect sizes or correlations. If the obtained Q_T value is larger than the critical value, the findings are determined to be significantly heterogeneous, meaning that there is more variability in the effect sizes or correlations than chance fluctuation would allow around a single population parameter.

Recently, Higgins and Thompson (2002), and then Huedo-Medina, Sánchez-Meca, Marin-Martinez, and Botella (2006), recommended the use of I^2 as a complement to the interpretation of Q_T. I^2 represents heterogeneity in proportional terms as the percentage of variability in the point estimates that is due to heterogeneity rather than to sampling error. Higgins and Thompson tentatively suggest the following interpretations of I^2: "… mild heterogeneity might account for less than 30 per cent of the variability in point estimates, and notable heterogeneity substantially more than 50 per cent" (p. 1553).

Study feature coding

Finally, in order to explain variability in effect sizes, coded study features were individually assessed in a series of moderator analyses. These study feature analyses were of the utmost interest for the project as they addressed the second major research question about factors affecting the degree of association between naming speed and different measures of reading. The following study features were coded as follows and analyzed.

(1) Type of the RAN task:

- Symbolic subtasks – i.e., those using letters or digits as stimuli to be named;
- Non-symbolic subtasks – i.e., those using colors, pictures, or any other non-symbolic stimuli;
- Mixed RAN subtasks – i.e., those that either used a mixture of different types of stimuli or, most often, used symbolic and non-symbolic subtasks separately, but only reported a composite naming speed index correlated with different measures of reading performance.

(2) Type of the reading measure:

- any assessment tool (standardized or otherwise) measuring participants' most closely related to phonological processing decoding skills (e.g., pseudo-word or nonsense word reading tasks, such as Woodcock Reading Mastery (WRMT) word-attack subtest – Woodcock, 1998, etc.);
- any assessment tool (standardized or otherwise) measuring participants' abilities of sight recognition or reading individual words, also called real-word reading abilities (e.g., recognition of regular or exceptional word as in the word identification subtest of the Woodcock-Johnson Psycho-educational Test Battery-

Revised – Woodcock & Johnson, 1989, or the Test of Word Reading Efficiency – Torgesen, Wagner, & Rashotte, 1999, etc.);

- any assessment tool (standardized or otherwise) measuring participants' reading rate, also called reading speed or fluency (e.g., the reading speed subtests of the Gray Oral Reading Test (GORT) – Wiederholt & Bryant, 2001, or the reading rate section of the Nelson-Denny Reading Test (NDRT) – Brown et al. 1993, etc.);
- any assessment tool (standardized or otherwise) measuring participants' abilities in reading comprehension (e.g., the passage comprehension subtest of the Woodcock-Johnson Psycho-educational Test Battery-Revised – Woodcock & Johnson, 1989, the comprehension section of the Nelson-Denny Reading Test (NDRT) – Brown et al., 1993, or the Test of Reading Comprehension (TORC) – Brown, Hammill, & Wiederholt, 1995, etc.);
- any assessment tool (standardized or otherwise) measuring participants' vocabulary knowledge (e.g., the vocabulary section of the Nelson-Denny Reading Test (NDRT) – Brown et al., 1993, or the Peabody Vocabulary Test (PPVT) – Dunn & Dunn, 1998, etc.);
- any assessment tool (standardized or otherwise) measuring participants' performance on spelling tasks – i.e., their ability to successfully discriminate between correct and simply plausible spellings – (e.g., the Test of Written Spelling (TWS) – Larsen, Hammill, & Moats, 1999, or the spelling and writing fluency subtest of the Woodcock-Johnson Test of Achievement (WJ-A), Woodcock, McGrew, & Mather, 2001, etc.);

- any assessment tool (standardized or otherwise) measuring participants' orthographic skills – different from the spelling skills, as mentioned in Swanson et al. (2003), only as they do nor require handwriting – (e.g., different orthographic choice and word matching tasks, such as in Siegel, Share & Geva, 1995, Stanovich & Siegel, 1994, or Berninger, Yates, & Lester, 1991);
- a composite measure of reading abilities (without specifying scores on individual reading subtasks (e.g., Lafrance & Gottardo, 2005).

(3) A combination of a particular RAN sub-task with an individual measure of reading in the order they appear under two previous categories of study features, so that the association between any symbolic RAN and any measure of decoding is considered first, followed by combinations of symbolic RAN and measures of word reading, etc. It is exactly how these combinations are labeled in the tables of the *Result* section that follow (e.g., Symbolic RAN x Decoding Skills).

(4) Participants' age. This category included the following options:

- kindergarteners,
- elementary school children,
- secondary school students,
- teenagers,
- adult readers,
- participants representing several age groups (without specifying results for each of them).

(5) Participants' dominant language. There were four major options within this category:

- English native speakers,
- participants' dominant language was other than English member of the Romance-Germanic family of languages, with more transparent grapheme-phoneme correspondence (e.g., Dutch, Spanish, German, etc.),
- participants' dominant language belonged to a very distant from English group, most often, not based on an alphabetical system (e.g., Korean, Japanese, etc.),
- participants were fluently bilingual.

(6) This study feature category described each effect size sample from the perspective of reading, as well as, more general learning abilities and included the following options:

- participants represented a large variety of impaired readers, including severe cases of developmental dyslexia,
- participants were normal readers, but suffered other forms of learning disabilities,
- participants were age-adequate (normal) readers,
- correlational data were collapsed across subgroups of participants representing different levels of reading abilities.

(7) The last study feature in this meta-analysis applied only to the subset of effect sizes from longitudinal studies. This category specified the amount of time that passed between the administration of the RAN task and the reading abilities assessment, and had two options:

- RAN task and a subsequent reading assessment happened within one calendar year,

- RAN task administration and reading assessment were separated in time by a period exceeding a calendar year.

Effect size extraction and study features coding were accomplished predominantly by the author of this research. However, to assure reliability compatible with that obtained at the stages of either abstract or full-text review, a second coder (one of the two research assistants mentioned above) worked on a representative sample of 15 studies as well (about 12% of the total set or 23% of the 65 documents included in the final report).

Results

Literature searches of PSYCInfo, PubMed, ERIC, and ProQuest Dissertations and Theses electronic databases and branching bibliographies from major review articles revealed 735 individual documents that were potentially suitable for further examination. Judging from the review of abstracts, 348 studies were marked for retrieval, of which 124 studies were retained after the full text review.

As reflecting a stage two meta-analysis or a work in progress, this report only includes data from a representative sample of 65 empirical studies (roughly a half of the total number of documents selected for inclusion). Inter-rater agreement rates at all stages of the review were:

☐ Abstract review – 92.65 % ($r = 0.852, p < 0.01$)

☐ Full-text review – 93.33 % ($r = 0.846, p < 0.01$)

☐ Agreement rate on the number and selection of the effect sizes (on a selected sample) – 93.18 %

☐ Agreement rate on study features coding (on a selected sample) – 89.09 %.

The 65 studies yielded 422 independent effect sizes (correlation coefficients between measures of the RAN task and reading performance) in the category of studies that used cross-sectional design, and 108 independent effect sizes in the category of the longitudinal design. The results of analyses of these two sets will be addressed in turn in two sections below.

Effect sizes obtained from cross-sectional designs

The findings of these analyses are generally in accord with what is already known about the overall strength of the connection between naming speed, as measured by performance on different RAN tasks, and various aspects of reading abilities. As shown in Table 6.1a, the average effect size is positive ($r+ = 0.345$), significantly different from the point of orthogonality (no connection) and belongs to a category many describe as moderate in magnitude.

However, the distribution is highly heterogeneous ($Q_T = 890.713, p < .001$). I^2 estimate here is 52.735, that is, almost 53 % of the variability is associated with heterogeneity in the findings and cannot be explained in terms of a sampling error (Table 6.1b). This fact weakens substantially any claim that the average effect size is representative of population parameters. Significant heterogeneity, on the other hand, both requires and opens up the possibility of further exploring effect size variability in terms of study features.

Table 6.1a. Effect size (*r*+) for the overall RAN-to-reading association (cross-sectional design)

Model:	*k*	Effect size	95% confidence interval		Test of null
		r+	Lower limit	Upper limit	Z-value
Fixed	422	0.345	0.334	0.355	58.861***
Random	422	0.350	0.334	0.367	38.210***

*** $p < .001$

Table 6.1b. Heterogeneity analysis (Q and I^2) for the overall RAN-to-reading association (cross-sectional design)

RAN – reading *r*	*k*	Heterogeneity			
		Q-value	Df (Q)	*p*	I-squared
Total:	422	890.713	421	< 0.001	52.735

Tables 6.2a through 6.7b below report results of the series of moderator analyses addressing how and to what extent various factors (study features described in detail in the *Method* section above) influence the strength of the RAN-to-reading association. Attention will be paid here to the findings proven to be fairly homogenous.

Type of the RAN task. The purpose of this analysis was to see whether and to what extent the degree of association between RAN task performance and reading abilities depends on the type of stimuli used. Table 6.2a show the effect sizes representing different types of the RAN subtasks, and Table 6.2b contains the results of the homogeneity analyses for these effect sizes. Only effect size for non-symbolic RAN subtasks reached the level of homogeneity ($Q(118) = 141.283, p = 0.071$) indicating the extreme likelihood that in this case the point estimate of $r+ = 0.292$ is truly representative of the corresponding population parameters. In other words, non-symbolic RAN appears to be fairly consistent across conditions, though its strength of association with reading is noticeably lower than the overall average effect size linking RAN in general to reading. As largely expected, symbolic RAN subtasks demonstrated a much higher degree of association with reading abilities ($r+ = 0.371$), though this association was extremely heterogeneous ($Q(278) = 664.162, p < 0.001$), warranting further exploration through the analyses of other study features.

Type of the reading measure. The next question addressed by this series of moderator analyses was whether different components of reading expertise vary in their connection with RAN task performance.

Table 6.2a. Effect size ($r+$) of RAN-to-reading association for each type of RAN (cross-sectional design)

Type of RAN:	*K*	Effect size	95% confidence interval		Test of null
		r+	Lower limit	Upper limit	Z-value
Symbolic RAN	279	0.371	0.358	0.385	49.174***
Non-symbolic RAN	**119**	**0.292**	**0.272**	**0.313**	**26.585*****
Mixed measures	24	0.335	0.304	0.366	19.522***
Overall	422	0.345	0.334	0.355	58.861***

*** $p < .001$

Table 6.2b. Heterogeneity analysis (Q and I^2) for each type of RAN (cross-sectional design)

Type of RAN	*K*	Heterogeneity			
		Q-value	df (Q)	*p*	I-squared
Symbolic RAN	279	664.162	278	< 0.001	58.143
Non-symbolic RAN	**119**	**141.283**	**118**	**0.071**	**16.480**
Mixed measures	24	32.377	23	0.005	47.580
Total within		849.322	419	< 0.001	
Total between		45.100	2	< 0.001	
Overall	422	890.713	421	< 0.001	52.735

Table 6.3a reports effect-sizes for each category of the reading measures, whereas Table 6.3b provides results of the analysis of their heterogeneity. The latter indicated that three reading measures in particular could be viewed as consistently connected to RAN task performance, as their average effect sizes were homogeneous ($Q(34) = 43.386, p = 0.130$; $Q(65) = 80.414, p = 0.094$; $Q(19) = 26.645, p = 0.113$, for the measures of reading rate, reading comprehension and spelling skills, respectively). Their corresponding effect sizes were $r+ = 0.419$, $r+ = 0.367$, and $r+ = 0.357$, among the highest in this category, suggesting that these particular reading skills have reliably strong associations with whatever cognitive processes are involved in RAN task performance. The weakest connection to RAN task performance, and significantly heterogeneous, was not surprisingly exhibited by the measure of vocabulary knowledge ($r+ = 0.172$; $Q(38) = 82.987, p < 0.001$).

Combinations of RAN and reading subtasks. Probably, one of the most interesting and important questions addressed in the present meta-analysis dealt with more specific relationships between different types of the RAN task and individual components of the reading ability. Here the question is what particular combinations of RAN subtasks and individual measures of reading consistently produce stronger correlations. Tables 6.4a and 6.4b report the results of such an analysis. Several effect sizes emerged as meeting criteria for homogeneity. Not all of them, however, were based on a sufficient number of cases. Only the effect sizes for which the *k*-statistics exceeds 10 will be briefly considered below. Nearly all of them were relatively strong. The one exception was the non-symbolic RAN correlation with the measure of vocabulary knowledge, where $r+ = 0.244$; $Q(10) = 13.426, p = 0.201$, which is still higher than for non-symbolic RAN.

Table 6.3a. Effect size (*r*+) of RAN-to-reading association for each type of reading measures (cross-sectional design)

Type of reading measure:	*k*	Effect size	95% confidence interval		Test of null
		r+	Lower limit	Upper limit	Z-value
Decoding skills	93	0.347	0.325	0.368	29.024***
Word reading fluency	136	0.407	0.388	0.425	37.758***
Reading rate	**35**	**0.419**	**0.374**	**0.462**	**16.493*****
Reading comprehension	**66**	**0.367**	**0.339**	**0.394**	**24.106*****
Vocabulary knowledge	39	0.172	0.136	0.208	9.237***
Orthographic skills	23	0.335	0.235	0.303	14.755***
Spelling accuracy	**20**	**0.357**	**0.307**	**0.406**	**12.903*****
Composite measure	10	0.279	0.202	0.353	13.435***
Overall	422	0.345	0.334	0.355	58.861***

*** $p < .001$

Table 6.3b. Heterogeneity analysis (Q and I^2) for each type of reading measures (cross-sectional design)

Type of reading measure:	*k*	Heterogeneity			
		Q-value	df (Q)	*p*	I-squared
Decoding skills	93	126.261	92	0.010	27.342
Word reading fluency	136	276.625	135	<0.001	51.197
Reading rate	**35**	**43.386**	**34**	**0.130**	**21.633**
Reading comprehension	**66**	**80.414**	**65**	**0.094**	**19.169**
Vocabulary knowledge	39	82.987	38	<0.001	54.209
Orthographic skills	23	67.514	22	<0.001	67.414
Spelling accuracy	**20**	**26.645**	**19**	**0.113**	**28.693**
Composite measure	10	13.435	9	0.144	33.009
Total within		717.626	414	< 0.001	
Total between		173.087	7	< 0.001	
Overall	422	890.713	421	< 0.001	52.735

Table 6.4a. Effect size (*r*+) of RAN-to-reading association for RAN type / reading measure type interactions (cross-sectional design)

RAN type X	*k*	Effect size	95% confidence interval		Test of null
Type of reading measure:		*r*+	Lower limit	Upper limit	Z-value
Symbolic RAN X Decoding skills	**65**	**0.384**	**0.357**	**0.410**	**25.377*****
Symbolic RAN X Word reading	95	0.438	0.416	0.461	33.164***
Symbolic RAN X Reading rate	**20**	**0.438**	**0.380**	**0.492**	**13.272*****
Symbolic RAN X Comprehension	**44**	**0.396**	**0.362**	**0.429**	**20.505*****
Symbolic RAN X Vocabulary	25	0.091	0.038	0.142	3.399**
Symbolic RAN X Orthography	**11**	**0.407**	**0.320**	**0.487**	**8.411*****
Symbolic RAN X Spelling	18	0.270	0.228	0.311	12.085***
Non-symbolic RAN X Decoding	**24**	**0.302**	**0.261**	**0.342**	**13.680*****
Non-symbolic RAN X Word reading	37	0.321	0.282	0.358	15.404***
Non-symbolic RAN X Reading rate	10	0.319	0.216	0.415	5.814***
Non-symbolic RAN X Comprehension	**18**	**0.341**	**0.285**	**0.396**	**11.070*****
Non-symbolic RAN X Vocabulary	**11**	**0.244**	**0.188**	**0.299**	**8.249*****
Overall[a]	422[a]	0.345	0.334	0.355	58.861***

** $p < .01$ & *** $p < .001$

[a] *Note: only interactions with* $k \geq 10$ *are included into the table*

Table 6.4b. Heterogeneity analysis (Q and I^2) for RAN type / reading measure type interactions (cross-sectional design)

Type of reading measure:	k	Heterogeneity			
		Q-value	df (Q)	p	I-squared
Symbolic RAN X Decoding skills	**65**	**78.959**	**64**	**0.099**	**18.945**
Symbolic RAN X Word reading	95	188.517	94	<0.001	50.137
Symbolic RAN X Reading rate	**20**	**22.182**	**19**	**0.275**	**14.343**
Symbolic RAN X Comprehension	**44**	**55.267**	**43**	**0.099**	**22.196**
Symbolic RAN X Vocabulary	25	47.342	24	0.003	49.305
Symbolic RAN X Orthography	**11**	**12.937**	**10**	**0.227**	**22.702**
Symbolic RAN X Spelling	18	62.831	17	<0.001	72.943
Non-symbolic RAN X Decoding	**24**	**33.211**	**23**	**0.077**	**30.745**
Non-symbolic RAN X Word reading	37	51.604	36	0.044	30.238
Non-symbolic RAN X Reading rate	10	6.262	9	0.713	0.000
Non-symbolic RAN X Comprehension	**18**	**15.319**	**17**	**0.573**	**0.000**
Non-symbolic RAN X Vocabulary	**11**	**13.426**	**10**	**0.201**	**25.517**
Total within[a]		634.623	398	< 0.001	
Total between[a]		256.091	23	< 0.001	
Overall[a]	422[a]	890.713	421	< 0.001	52.735

[a]*Note: only interactions with* $k \geq 10$ *are included into the table*

Among reading skills showing sound correlations with symbolic RAN subtasks these were, in descending order as in Table 6.4a, the following: reading rate ($r+ = 0.438$), orthographic skills ($r+ = 0.407$, though the number of cases was relatively small, k=11), reading comprehension ($r+ = 0.396$), and decoding skills ($r+ = 0.384$). All these effect sizes were homogeneous ($Q(19) = 22.182, p = 0.272$; $Q(10) = 12.937, p = 0.227$; $Q(43) = 55.267, p = 0.099$; $Q(64) = 78.959, p = 0.099$ – respectively). The tasks that measure these skills either require expertise with printed text or depend on processing speed, or both. Perhaps, this is why their connection to symbolic RAN appears to be the strongest (e.g., the reading rate measure). Surprisingly, individual word recognition correlation and symbolic RAN subtask performance was equal in magnitude with the correlation between speed-sensitive reading rate and symbolic RAN subtasks ($r+ = 0.438$), but was not homogeneous enough to be considered representative of such regularities in the entire population ($Q(94) = 188.517, p < 0.001$).

With respect to correlations between various reading measures and non-symbolic RAN subtasks, three of the effect sizes met the homogeneity criteria, namely, for decoding skills ($Q(23) = 33.211, p = 0.077$), reading comprehension ($Q(17) = 15.319, p= 0.573$), and vocabulary knowledge ($Q(10) = 13.426, p = 0.201$), although this final one was based on a relatively small number of cases (k=11). On average, these correlations were smaller in magnitude compared to the set described above. The effect size for the non-symbolic RAN subtask and vocabulary knowledge was small ($r+ = 0.244$), suggesting that these two measures had very little in common, though it should be viewed cautiously as the number of cases was limited. The other two effect sizes were $r+$=0.341

for the measures of reading comprehension and $r+ = 0.302$ for the measures of decoding skills.

Still smaller than the average effect size for symbolic RAN subtasks, these correlation coefficients could be categorized as moderate and deserve some extra consideration. Compared to the homogeneous correlations observed in analyses of symbolic RAN subtasks, decoding and comprehension skills appear to be more dependent on applying rules and building associations, skills necessarily involving attentional resources.

Age. This analysis addressed the question whether the degree of association between RAN task performance and reading outcomes depends on the age of those participating in the studies. Table 6.5a reports the results of this analysis. The overall pattern emerging from the table suggests that the correlation between naming speed and reading ability tends to increase with the age, presumably reflecting expanding practice in reading. However, as indicated in Table 6.5b, only two of the effect sizes in this category are homogeneous: for the kindergarteners ($r+ = 0.329$; $Q(40) = 45.363, p = 0.258$) and for children in secondary school ($r+ = 0.359$; $Q(21) = 32.624, p = 0.051$). Both effect sizes are moderate and based on relatively high number of cases.

Language. One of the focal points of interest for the present meta-analysis was whether the transparency of grapheme-to-phoneme mapping in different languages affects the magnitude of correlation between measures of the RAN task and reading performance. The results of moderator and heterogeneity analysis for this particular category of study feature are given below in Tables 6.6a and 6.6b, respectively.

Table 6.5a. Effect size ($r+$) of RAN-to-reading association by age groups (cross-sectional design)

Age group:	k	Effect size	95% confidence interval		Test of null
		$r+$	Lower limit	Upper limit	Z-value
Kindergarteners	**41**	**0.329**	**0.294**	**0.362**	**17.623*****
Elementary school students	244	0.325	0.309	0.341	37.691***
Secondary school students	**22**	**0.359**	**0.302**	**0.413**	**11.514*****
Teenagers	2	0.454	0.059	0.726	2.226*
Adults	43	0.409	0.376	0.441	21.915**
Mixed	70	0.357	0.338	0.376	33.754***
Overall	422	0.345	0.334	0.355	58.861***

* $p < .05$ & *** $p < .001$

Table 6.5b. Heterogeneity analysis (Q and I^2) by age groups (cross-sectional design)

Age group:	k	Heterogeneity			
		Q-value	df (Q)	p	I-squared
Kindergarteners	**41**	**45.363**	**40**	**0.258**	**11.823**
Elementary school students	244	597.223	243	<0.001	59.312
Secondary school students	**22**	**32.624**	**21**	**0.051**	**35.629**
Teenagers	2	0.221	1	0.638	0.000
Adults	43	74.701	42	0.001	43.776
Mixed	70	116.814	69	<0.001	40.932
Total within		866.946	416	< 0.001	
Total between		23.767	5	< 0.001	
Overall	422[a]	890.713	421	< 0.001	52.735

Table 6.6a. Effect size (*r*+) of RAN-to-reading association by languages (cross-sectional design)

Language:	*k*	Effect size	95% confidence interval		Test of null
		r+	Lower limit	Upper limit	Z-value
English	330	0.355	0.344	0.367	54.575***
Other (Romance-Germanic) with more transparent phonemic structure	**33**	**0.349**	**0.313**	**0.384**	**17.526*** **
Other languages (e.g., Japanese etc.)	**30**	**0.303**	**0.262**	**0.343**	**13.786*** **
Bilinguals	29	0.173	0.112	0.233	5.478*
Overall	422	0.345	0.334	0.355	58.861***

* $p < .05$ & *** $p < .001$

Table 6.6b. Heterogeneity analysis (Q and I^2) by language (cross-sectional design)

Language:	*k*	Heterogeneity			
		Q-value	df (Q)	*p*	I-squared
English	330	707.656	329	<0.001	53.508
Other (Romance-Germanic) with more transparent phonemic structure	**33**	**44.693**	**32**	**0.067**	**28.401**
Other languages (e.g., Japanese etc.)	**30**	**30.254**	**29**	**0.401**	**4.144**
Bilinguals	29	67.076	28	<0.001	58.256
Total within		849.679	418	< 0.001	
Total between		23.767	3	< 0.001	
Overall	422	890.713	421	< 0.001	52.735

They show correlations that are similar in magnitude for monolinguals across different languages, although only two effect sizes emerged as homogeneous. The group of languages from the Romance-Germanic family (more regular than English in their phonemic structure) demonstrated a somewhat higher effect size ($r+ = 0.349$ ($Q(32) = 44.693, p = 0.067$), compared to the point estimate for a large category subsuming languages like Japanese, Korean, Mandarin, etc., ($r+ = 0.303$; $Q(29) = 30.254, p = 0.401$). Unfortunately, the extremely heterogeneous findings in the studies in which English was the participants' dominant language ($Q(329) = 707.656, p < 0.001$) substantially impede conclusive interpretation. It is worth mentioning, however, that in the present analysis, contrary to numerous claims about superior RAN-to-reading associations in languages more transparent than English, the magnitude of the effect size for English was not lower ($r+ = 0.355$).

Reading abilities. The final set of study feature analyses for correlations from cross-sectional studies dealt with the issue of differences in participants' reading abilities. The results are presented in Tables 6.7a and 6.7b. There are two observations to make regarding the magnitude of the effect sizes. First, in agreement with one of the core premises of the double-deficit hypothesis, general learning disabilities seem to be relatively unconnected to RAN task performance ($r+ = 0.196$), although the number of cases this particular effect size was based upon was small ($k=10$). Second, those whose reading was impaired on average did not perform on the RAN task much more slowly than either normal readers or mixed-ability ("garden variety") readers ($r+ = 0.355$, $r+ = 0.349$, and $r+ = 0.336$ for each of these categories, respectively).

Table 6.7a. Effect size ($r+$) of RAN-to-reading association by population type (cross-sectional design)

Population type:	*k*	Effect size	95% confidence interval		Test of null
		$r+$	Lower limit	Upper limit	Z-value
Reading impaired (dyslexics)	140	0.355	0.338	0.371	39.408***
Normal (age adequate) readers	179	0.349	0.332	0.366	36.625***
Mixed (age adequate and impaired readers together)	93	0.336	0.310	0.361	23.690***
Readers with learning (but not reading) problems	10	0.196	0.129	0.261	5.690***
Overall	422	0.345	0.334	0.355	58.861***

*** $p < .001$

Table 6.7b. Heterogeneity analysis (Q and I^2) by population type (cross-sectional design)

Population type:	*k*	Heterogeneity			
		Q-value	df (Q)	*P*	I-squared
Reading impaired (dyslexics)	140	209.413	139	<0.001	33.624
Normal (age adequate) readers	179	444.145	178	<0.001	59.923
Mixed (age adequate and impaired readers together)	93	164.756	92	<0.001	44.160
Readers with learning (but not reading) problems	10	48.990	9	<0.001	81.629
Total within		867.304	418	< 0.001	
Total between		23.409	3	< 0.001	
Overall	422	890.713	421	< 0.001	52.735

It seems the RAN task performance is fairly uniform across different levels of reading abilities. However, once again, high heterogeneity of all these findings prevents us from generalizing them with respect to the entire population.

Effect sizes obtained from longitudinal designs

The findings from studies involving longitudinal designs resemble the results of the overall analysis of effect sizes derived from cross-sectional designs (Tables 6.8a & 6.8b). The average point estimate here is slightly higher ($r+ = 0.398$) and also heterogeneous ($Q(107) = 149.175, p = 0.004$).

Before addressing in turn the most interesting findings of the moderator (study features) analyses, there is something that needs to be said about the entire set of effect sizes based on studies using longitudinal designs. The number of cases is much smaller here than it was for cross-sectional designs, which means there are inevitably fewer number of effect sizes, especially when split by particular study features. Therefore, even if the criteria for homogeneity are met, reasonable caution is warranted when it comes to interpretation. As before, only effect sizes where the number of cases exceeds ten will be addressed below, with special attention paid to those that are homogeneous.

Type of the RAN task. Tables 6.9a and 6.9b report the results of the analysis that addressed the issue whether and to what extent the degree of association between RAN task performance and reading abilities depends on the type of stimuli used in the RAN task in longitudinal studies, symbolic and non-symbolic.

Table 6.8a. Effect size (*r*+) for the overall RAN-to-reading association (longitudinal design)

Model:	*k*	Effect size	95% confidence interval		Test of null
		r+	Lower limit	Upper limit	Z-value
Fixed	108	0.398	0.373	0.422	28.250***
Random	108	0.394	0.360	0.426	20.819***

*** $p < .001$

Table 6.8b. Heterogeneity analysis (Q and I^2) for the overall RAN-to-reading association (longitudinal design)

RAN – reading *r*+	*k*	Heterogeneity			
		Q-value	Df (Q)	*p*	I-squared
Total:	108	149.175	107	0.004	28.272

Table 6.9a. Effect size (*r*+) of RAN-to-reading association for each type of RAN (longitudinal design)

Type of RAN:	*k*	Effect size	95% confidence interval		Test of null
		r+	Lower limit	Upper limit	Z-value
Symbolic RAN	**70**	**0.481**	**0.446**	**0.514**	**23.292*****
Non-symbolic RAN	**35**	**0.318**	**0.281**	**0.353**	**16.131*****
Mixed measures	3	0.511	0.369	0.630	6.256***
Overall	108	0.398	0.373	0.422	28.250***

*** $p < .001$

Table 6.9b. Heterogeneity analysis (Q and I^2) for each type of RAN (longitudinal design)

Type of RAN	*k*	Heterogeneity			
		Q-value	df (Q)	*p*	I-squared
Symbolic RAN	**70**	**65.311**	**69**	**0.604**	**0.000**
Non-symbolic RAN	**35**	**39.134**	**34**	**0.250**	**13.119**
Mixed measures	3	0.924	2	0.630	0.000
Total within		105.370	105	0.471	
Total between		45.100	2	< 0.001	
Overall	108	149.175	107	0.004	28.272

As expected, the same pattern was obtained as was seen in the analysis of cross-sectional data. Symbolic RAN task performance was correlated with reading abilities to a much higher degree than non-symbolic ($r+ = 0.481$ and $r+ = 0.318$, respectively). Both were homogeneous: $Q(69) = 65.311, p = 0.604$ and $Q(34) = 39.134, p = 0.250$.

Type of the reading measure. Analyzing the strength of connection between the RAN task and reading depends on which category of reading measure is selected. The following patterns were observed (See Tables 6.10a and 6.10b below). Only four sets of the effect sizes had a sufficient number of cases to consider. Three of them turned out to be homogeneous. These were RAN correlations with different measures of decoding skills ($r+ = 0.346$, $Q(23) = 37.811, p = 0.027$), with tests of reading comprehension ($r+ = 0.335$, $Q(28) = 13.567, p = 0.990$), and with reading rate indices ($r+ = 0.389$, $Q(21) = 7.564, p = 0.997$). Also, reading rate and reading comprehension showed significant and homogeneous correlations with most RAN tasks.

Combinations of RAN and reading subtasks. Another important question is what particular combinations of RAN subtasks and individual measures of reading consistently produce stronger correlations. This question was of a high priority in the analyses of cross-sectional data and is now addressed in the longitudinal analyses. Tables 6.11a and 6.11b show the findings.

Unfortunately, all results concerning the strength of association between reading abilities and non-symbolic RAN subtasks cannot be conclusively interpreted due to the low number of cases associated with each type of effect size. The only effect size that was marginally suitable (k=10) for the single word reading/recognition measure is moderate in magnitude ($r+ = 0.343$) and homogeneous ($Q(9) = 10.395, p = 0.319$).

Table 6.10a. Effect size (*r*+) of RAN-to-reading association) for each type of reading measures (longitudinal design)

Type of reading measure:	*k*	Effect size	95% confidence interval		Test of null
		r+	Lower limit	Upper limit	Z-value
Decoding skills	**24**	**0.346**	**0.287**	**0.403**	**10.672*****
Word reading fluency	24	0.471	0.435	0.506	21.821***
Reading rate	**22**	**0.389**	**0.283**	**0.485**	**6.742*****
Reading comprehension	**29**	**0.335**	**0.282**	**0.387**	**11.544*****
Vocabulary knowledge	1	0.020	-0.302	0.338	0.118
Spelling accuracy	6	0.350	0.258	0.437	7.008***
Composite measure	2	0.473	0.208	0.674	3.321**
Overall	108	0.398	0.373	0.422	28.250***

** $p < .01$ *** $p < .001$

Table 6.10b. Heterogeneity analysis (*Q* and I^2) for each type of reading measures (longitudinal design)

Type of reading measure:	*k*	Heterogeneity			
		Q-value	df (Q)	*p*	I-squared
Decoding skills	**24**	**37.811**	**23**	**0.027**	**39.171**
Word reading fluency	24	53.518	23	<0.001	57.024
Reading rate	**22**	**7.564**	**21**	**0.997**	**0.000**
Reading comprehension	**29**	**13.567**	**28**	**0.990**	**0.000**
Vocabulary knowledge	1	0.000	0	1.000	0.000
Spelling accuracy	6	5.098	5	0.404	1.921
Composite measure	2	0.764	1	0.382	0.000
Total within		118.322	101	0.115	
Total between		30.853	6	< 0.001	
Overall	108	149.175	107	0.004	28.272

Table 6.11a. Effect size (*r*+) of RAN-to-reading association for RAN type / reading measure type interactions (longitudinal design)

RAN type X	*k*	Effect size	95% confidence interval		Test of null
Type of reading measure:		*r*+	Lower limit	Upper limit	Z-value
Symbolic RAN X Decoding skills	**14**	**0.445**	**0.344**	**0.537**	**7.781*****
Symbolic RAN X Word reading	14	0.537	0.495	0.577	20.391***
Symbolic RAN X Reading rate	**18**	**0.470**	**0.273**	**0.629**	**4.349*****
Symbolic RAN X Comprehension	**21**	**0.355**	**0.266**	**0.438**	**7.392*****
Symbolic RAN X Vocabulary knowledge	1	0.020	-0.302	0.388	0.118
Symbolic RAN X Orthographic skills	2	0.523	0.303	0.690	4.256***
Non-symbolic RAN X Decoding	9	0.261	0.180	0.338	6.136***
Non-symbolic RAN X Word reading	10	0.343	0.274	0.408	9.229***
Non-symbolic RAN X Reading rate	4	0.357	0.230	0.472	5.247***
Non-symbolic RAN X Comprehension	8	0.324	0.256	0.389	8.884***
Non-symbolic RAN X Orthography	4	0.318	0.215	0.413	5.823***
Mixed RAN X Decoding skills	1	0.530	0.356	0.668	5.317***
Mixed RAN X Composite index	2	0.473	0.208	0.674	3.321**
Overall^a	108	0.398	0.373	0.422	28.250***

** $p < .01$ & *** $p < .001$

Table 6.11b. Heterogeneity analysis (*Q* and I^2) for RAN type / reading measure type interactions (longitudinal design)

Type of reading measure:	*k*	Heterogeneity			
		Q-value	df (Q)	*p*	I-squared
Symbolic RAN X Decoding skills	**14**	**9.343**	**13**	**0.747**	**0.000**
Symbolic RAN X Word reading	14	18.273	13	0.147	28.859
Symbolic RAN X Reading rate	**18**	**6.054**	**17**	**0.993**	**0.000**
Symbolic RAN X Comprehension	**21**	**6.086**	**20**	**0.999**	**0.000**
Symbolic RAN X Vocabulary knowledge	1	0.000	0	1.000	0.000
Symbolic RAN X Orthographic skills	2	0.023	1	0.881	0.000
Non-symbolic RAN X Decoding	9	15.882	8	0.044	49.630
Non-symbolic RAN X Word reading	10	10.395	9	0.319	13.422
Non-symbolic RAN X Reading rate	4	0.520	3	0.915	0.000
Non-symbolic RAN X Comprehension	8	7.166	7	0.412	2.323
Non-symbolic RAN X Orthography	4	2.170	3	0.538	0.000
Mixed RAN X Decoding skills	1	0.000	0	1.000	0.000
Mixed RAN X Composite index	2	0.764	1	0.382	0.000
Total within[a]		76.678	95	0.916	
Total between[a]		72.498	12	< 0.001	
Overall	108	149.175	107	0.004	28.272

On the other hand, there were four effect sizes with symbolic RAN subtasks that included a sufficient number of cases and that were homogeneous.

Once again, similar to what was observed in the cross-sectional analyses, speed-sensitive measures of individual word reading and text reading fluency were noticeably higher than the others, with $r+ = 0.537$ and $r+ = 0.470$, respectively ($Q(31) = 18.273$, $p = 0.147$ and $Q(17) = 6.054$, $p = 0.993$).

Age. Only two age groups were represented in longitudinal studies – kindergarteners and elementary school students. As Tables 6.12a and 6.12b show, both average effect sizes emerged homogeneous ($Q(45) = 53.157$, $p = 0.189$ and $Q(61) = 69.296$, $p = 0.218$, respectively for each category). The magnitude of the RAN-to-reading association, however, was substantially higher in children in elementary school ($r+ = 0.480$ compared to $r+ = 0.348$ in preschoolers), i.e., in those, whose practice in reading and reading-related instruction (or at least exposure to printed text) presumably was more prolonged.

Language. This analysis addressed the moderation impact of the transparency of the language phonemic structure on the strength of correlation between measures of RAN and reading. None of the results were interpretable under the pre-established criteria. In three categories effect sizes did not have enough number of cases associated with them and in one – English as participants' dominant language – the assumption of homogeneity was obviously violated ($Q(95) = 141.549$, $p = 0.001$), although the magnitude of the effect size was moderate ($r+ = 0.403$) and compatible either with others within this category or with that in cross-sectional analyses ($r+ = 0.355$, also highly heterogeneous). See Tables 6.13a and 6.13b, for more details.

Table 6.12a. Effect size (*r*+) of RAN-to-reading association by age groups (longitudinal design)

Age group:	*k*	Effect size	95% confidence interval		Test of null
		r+	Lower limit	Upper limit	Z-value
Kindergarteners	**46**	**0.348**	**0.315**	**0.380**	**19.452*****
Elementary school students	**62**	**0.480**	**0.373**	**0.422**	**21.127*****
Overall	108	0.398	0.373	0.422	28.250***

*** $p < .001$

Table 6.12b. Heterogeneity analysis (Q and I^2) by age groups (longitudinal design)

Age group:	*k*	Heterogeneity			
		Q-value	df (Q)	*p*	I-squared
Kindergarteners	**62**	**69.296**	**61**	**0.218**	**11.971**
Elementary school students	**46**	**53.157**	**45**	**0.189**	**15.345**
Total within		122.453	106	0.131	
Total between		26.722	1	< 0.001	
Overall	108	149.175	107	0.004	28.272

Table 6.13a. Effect size ($r+$) of RAN-to-reading association by languages (longitudinal design)

Language:	k	Effect size	95% confidence interval		Test of null
		$r+$	Lower limit	Upper limit	Z-value
English	96	0.403	0.375	0.431	25.142***
Other from Romance-Germanic group with more transparent phonemic structure	8	0.368	0.303	0.429	10.328***
Other languages (e.g., Japanese etc.)	2	0.395	0.292	0.488	7.043***
Bilinguals	2	0.473	0.208	0.674	3.321**
Overall	108	0.398	0.373	0.422	28.250***

** $p < .01$ & *** $p < .001$

Table 6.13b. Heterogeneity analysis (Q and I^2) by language (longitudinal design)

Language:	k	Heterogeneity			
		Q-value	df (Q)	p	I-squared
English	96	141.549	95	0.001	32.885
Other from Romance-Germanic group with more transparent phonemic structure	8	5.377	7	0.614	0.000
Other languages (e.g., Japanese etc.)	2	0.090	1	0.764	0.000
Bilinguals	2	0.764	1	0.382	0.000
Total within		147.780	104	0.003	
Total between		1.395	3	0.707	
Overall	108	149.175	107	0.004	28.272

Reading abilities. Tables 6.14a and 6.14b report results of the analysis of moderation effects of participants' reading abilities on the strength of association between measures of RAN task performance and reading outcomes. The data for normal readers are not easily interpreted due to their very high heterogeneity ($Q(52) = 113.238$, $p < 0.001$). The average effect size for the samples of participants with mixed reading abilities was slightly below the average point estimate for the overall analysis of the longitudinal data ($r+ = 0.358$) and homogeneous ($Q(11) = 16.549, p = 0.122$), although these were based on a relatively small number of cases (k=12). By contrast, the results for participants representing the reading impaired population were much stronger. These were extremely homogeneous ($Q(42) = 16.227, p = 1.00$), with the average effect size in the top moderate area ($r+ = 0.423$). These results are truly indicative of the high level of association between the RAN task and reading abilities in those affected by developmental dyslexia, in longitudinal studies in particular.

Time lag in administering the RAN task and reading measures. Finally, but no less importantly than the rest of the moderator analyses, one more study feature was considered applicable uniquely to effects sizes deriving from longitudinal studies. This study feature dealt with the issue of how much time separated the administration of the RAN task and the assessment of reading performance. All data were sorted to fit a nominal scale with two values: "within a year" and "longer than a year". The findings for this set of analyses are given in Tables 6.15a and 6.15b below. Homogeneous results were observed only for the effect sizes associated with the longer time lag ($Q(87) = 58.704, p = 0.991$), though their average magnitude was relatively modest ($r+ = 0.359$),

Table 6.14a. Effect size (*r*+) of RAN-to-reading association by population type (longitudinal design)

Population type:	*k*	Effect size	95% confidence interval		Test of null
		r+	Lower limit	Upper limit	Z-value
Reading impaired (dyslexics)	**43**	**0.423**	**0.347**	**0.493**	**9.967*****
Normal (age adequate) readers	53	0.408	0.377	0.438	23.430***
Mixed (age adequate and impaired readers together)	**12**	**0.358**	**0.306**	**0.409**	**16.549*****
Overall	108	0.398	0.373	0.422	28.250***

*** $p < .001$

Table 6.14b. Heterogeneity analysis (Q and I^2) by population type (longitudinal design)

Population type:	*k*	Heterogeneity			
		Q-value	df (Q)	*p*	I-squared
Reading impaired (dyslexics)	**43**	**16.227**	**42**	**1.000**	**0.000**
Normal (age adequate) readers	53	113.238	52	<0.001	54.079
Mixed (age adequate and impaired readers together)	**12**	**16.549**	**11**	**0.122**	**33.531**
Total within		146.015	105	0.005	
Total between		3.161	2	0.206	
Overall	108	149.175	107	0.004	28.272

Table 6.15a. Effect size (*r*+) of RAN-to-reading association by the time lag (longitudinal design)

Time lag (between administering RAN and reading measures):	*k*	Effect size	95% confidence interval		Test of null
		r+	Lower limit	Upper limit	Z-value
No more than a year	20	0.464	0.425	0.502	20.074***
Longer than a year	**88**	**0.359**	**0.327**	**0.391**	**20.286*** **
Overall	108	0.398	0.373	0.422	28.250***

*** $p < .001$

Table 6.15b. Heterogeneity analysis (Q and I^2) by the time lag (longitudinal design)

Time lag (between administering RAN and reading measures):	*k*	Heterogeneity			
		Q-value	df (Q)	*p*	I-squared
No more than a year	20	74.037	19	<0.001	74.337
Longer than a year	**88**	**58.704**	**87**	**0.991**	**0.000**
Total within		132.741	106	0.040	
Total between		16.434	1	<0.001	
Overall	108	149.175	107	0.004	28.272

whereas the average effect size for shorter time lags was substantially higher (r+ = 0.464).Unfortunately the latter dataset was extremely heterogeneous ($Q(19) = 74.037$, $p < 0.001$), preventing definite conclusions about this specific pattern in results.

Discussion

The present stage two meta-analysis was designed and conducted to address the following set of questions: (1) What is the point estimate (an average effect size) of the degree of association between the RAN task and reading? (2) What factors (methodological and substantive study features) affect (increase or reduce) the strength of this association and to what extent?

The discussion below is organized in two general parts, one looking at the results from the cross-sectional studies and the other from the longitudinal studies. Although the pattern effect sizes in the cross-sectional and longitudinal studies were similar, the average point estimates for longitudinal data were slightly higher. Both overall *r+* were heterogeneous, which prevents drawing any definitive conclusions about the strength of the RAN-to-reading association in the general population. However, a series of subsequent moderator (study features) analyses revealed some interesting patterns in the results that were homogeneous and, thus, generalizable more reliably.

Cross-sectional data

The most interesting findings for the cross-sectional design were the following. There was a low-to-moderate correlation between non-symbolic RAN subtasks and reading, and this was fairly consistent across all reviewed studies. Reading rate and comprehension and spelling accuracy were strongly and homogeneously associated with

RAN task performance. In the moderator analysis of particular combinations of different types of RAN subtasks with individual measures of reading abilities, the following pairs showed strong and homogeneous correlations, and were based on sufficient number of cases to permit interpretation. Symbolic RAN subtasks were correlated with reading rate, reading comprehension, and decoding skills (listed in the descending order of the corresponding $r+$ magnitude). As was mentioned before, all tasks that measure these skills (including orthographic processing, for which the number of cases was not large enough for conclusive interpretation) either require expertise with printed text or depend on processing speed, or both. In light of this, the obtained higher and more consistent connection to symbolic RAN is only logical.

Non-symbolic RAN subtasks showed consistent correlations with reading comprehension and participants' decoding skills. Unlike the homogeneous correlations from the subset involving symbolic RAN subtasks (speed-sensitive and printed characters oriented), decoding and comprehension skills largely depend on applying rules and building associations. As such, their consistent (though moderate) association with non-symbolic RAN subtasks is suggestive of the involvement of attention-based mechanisms.

Whereas these results do largely correspond to the patterns reported in research literature (see Chapter 2), some other moderator analyses resulted in rather surprising findings. With regard to participants' age, the general regularity observed was that there were stronger correlations for older samples. Although most of the results were heterogeneous, this particular pattern should not be easily dismissed. It could indicate that with age, and for most people this means with increased practice in reading, the strength of the RAN-to-reading association tends to grow. Also, and somewhat contrary to literature-based expectations, no substantial difference in the correlation between RAN and reading was observed between English and other languages with more transparent phonemes-to-graphemes correspondence. Data for groups of participants different in their reading abilities were inconclusive due to the high degree of heterogeneity.

To briefly summarize the findings from the cross-sectional studies, the most important finding appears to be that the non-symbolic RAN task is homogeneously connected to those aspects of reading that are driven by rules and require attention (i.e., decoding and comprehension), and the symbolic RAN is more highly correlated with speed-sensitive measures of reading (such as reading rate or fluency). Practically none of the other study features explored, except perhaps for age of participants) made any substantial difference in moderating the RAN-to-reading association. These findings are generally in accord with the observations made throughout the experimental portion of the present research.

Longitudinal data

In the analyses of longitudinal data, results for both symbolic and non-symbolic RAN subtasks turned out to be homogeneous (and higher in magnitude for symbolic subtasks). Strictly speaking, given this outcome, further moderator analyses are not necessary. Nevertheless, the findings (especially in comparison with the cross-sectional data) could provide some extra insight to the specifics of the correlations between RAN task performance and measures of reading abilities. These findings mirror to a great extent the results of the study feature analyses for the cross-sectional data with regard to measures of reading rate, reading comprehension and decoding skills, especially when correlated with symbolic RAN tasks, although the longitudinal results were overall slightly higher in magnitude. Very importantly, in both types of research designs there were two reading measures consistently correlated with overall RAN performance – reading rate and reading comprehension. Their relative associations with different individual RAN subtasks are especially interesting. There was no noticeable difference in the strength of the RAN-to-reading association as a function of the category of participants' dominant languages. No longitudinal data were available for participants in older age groups, whereas correlations for kindergarteners and elementary school students emerged strong and homogeneous. The magnitude of the RAN-to-reading association was higher in children in elementary school, once again implicating the reading practice factor in influencing the predictive power of the RAN task. Interestingly, the analysis of the time lag factor (the interval between the times of administering RAN task and taking measures of reading performance) showed stronger RAN-to-reading association for longer delays in longitudinal studies. In other words, what strengthens this association, most likely could also be attributed to the practice (instruction) in reading, whereas it looks like the RAN task per se possesses capabilities of predicting reading outcomes at any time. Finally, those reading impaired or at risk of developing reading disabilities demonstrated stronger homogeneous correlations between RAN task performance and reading measures.

To conclude the discussion of the moderator analyses of the longitudinal data, there are several points that deserve mentioning in particular. First of all, the magnitude of the average effect size in this subset of the studies appears to be somewhat higher than in cross-sectional ones, though no direct comparison is methodologically possible. Secondly, longitudinal effects across practically all individual study features analyses also tend to be more homogeneous, indicating that the RAN task, as a correlate of reading abilities, is more consistent (if not necessarily stronger), when it is used to anticipate (predict) further reading outcomes.

Brief summary

With respect to the major research questions posed here, this stage two meta-analysis of correlational patterns between the RAN task and reading abilities found moderate average effect sizes of $r+ = 0.345$ and $r+ = 0.398$ for cross-sectional and longitudinal data, respectively. Both were highly heterogeneous, but the subsequent moderator analyses revealed some homogeneous effects for correlation coefficients grouped by the selected study features. Once again, substantial differences were observed in the patterns of correlations with reading measures between symbolic and non-symbolic RAN subtasks. In particular, the symbolic RAN subtasks were consistently associated, most of all, with measures of reading skills that are speed-sensitive and that benefit from exposure to printed text. In contrast, the non-symbolic RAN subtasks were primarily associated with reading comprehension, which may indicate substantial involvement of attention-based processing in such associations.

These findings reflect the mainstream regularities reported in the literature and are also highly consistent with the major patterns of results of experimental studies reported here in the present research.

CHAPTER 7: CONCLUSION

The present research, in a series of experimental studies, has made an attempt to explore the cognitive nature of the RAN task – the test well known to be related to reading skills. In particular, research concentrated on automaticity and attention as two major factors thought to underlie RAN task performance. Here are the highlights of the results that were obtained.

Study 1 addressed three research questions. First, it tested one of the major assumptions of the double-deficit hypothesis (Wolf & Bowers, 1999) about whether individual differences in degree of automatic information processing (in this case stimulus recognition) – operationalized either as ballistic or as stable and efficient processing – underlie individual differences in RAN task performance. Second, it considered whether a viable alternative to an automaticity-based account could be one that focuses on individual differences in the degree of attention control – operationalized as a shift cost – as underlying individual differences in RAN task performance. Third, Study 1 looked at whether automatic and attention-based aspects of RAN task performance were linked to reading equally and what their links were to symbolic and non-symbolic RAN subtasks.

Study 1 found that neither ballistic nor efficiency-based measures of automaticity in stimulus recognition manifested significantly strong associations with participants' performance on non-symbolic RAN performance. Their connection to symbolic (letter naming) was also weak, although the association reached statistical significance. In contrast, the measure of attention was found to be strongly associated with RAN task performance across different subtasks. However, only performance on symbolic RAN subtasks was correlated to the measure of silent reading speed. Nevertheless, the result demonstrated that the connection between RAN task performance and reading skills, consistently observed in children, extends beyond childhood and exists in adults whose reading abilities have presumably been fully developed through extensive practice in reading. The basic patterns just described were found to be very similar with respect to the participants' second language, but no second-language specific correlations were obtained.

One of the major observations of Study 1 was the substantial difference between performance on symbolic and non-symbolic RAN subtasks on all levels – in performance time, in underlying cognitive mechanisms, and in degree of association with reading outcomes. Exploring possible explanations for these differences was among major purposes for the studies that followed.

The attention factor in Study 1 not only substantially outperformed both indices of automaticity as a predictor of RAN task performance, regardless of whether symbolic or non-symbolic stimuli were used, but it showed even greater success as a predictor when conceptualized in a broader sense. Form B of the Trial Making test, taken as an index of general attention, was a better predictor of RAN task performance than the initially employed index of attention shift, implicating other aspects of attention-based processing in rapid naming. This finding became the focus of interest for further research. In other words, the strongest findings of Study 1 then guided the research in two subsequent studies, as described below.

Study 2 explored the following major issues. First, it experimentally tested how dependent on the degree of attentional demand RAN task performance is. It did this by explicitly manipulating attention demands in a series of modified RAN subtasks. Second, Study 2 looked whether a factor such as the source set size of the stimuli used in the different RAN subtasks plays role in RAN task performance time. Third, the potential contribution to naming speed of the factor of stimulus familiarity, as a function of relative frequency of bigrams in printed text, was explored using another set of modified RAN subtasks.

With respect to the set of variables shared by Study 1 and Study 2, the findings were highly similar, especially in terms of demonstrating differences between symbolic and non-symbolic RAN subtasks. In particular, the superior contribution to RAN task performance of attention over automaticity was very clearly replicated.

In terms of the major research questions, the Study 2 findings were the following. Modified RAN subtasks showed high sensitivity to the experimental manipulation of the attentional demand. Those subtasks that required extra resources at all levels of task performance – remembering, searching for, recognizing, and responding to the target stimulus before shifting back to the speeded naming – were performed significantly slower across stimulus type (symbolic, non-symbolic) and source set size conditions. Performance on these subtasks was also better predicted by the index of general attention – the participants' performance on Form B of the Trail Making test – than on their attentionally less demanding counterparts. The manipulation of stimulus source set size, however, had little impact on RAN task performance in the various modified subtasks. Only non-symbolic naming was somewhat slowed down when stimuli were drawn from a substantially larger source set, e.g., naming pictures of unrelated objects compared to naming pictures of animals. The influence of the familiarity factor on RAN task performance, on the other hand, appeared to be beyond doubt. More frequent bigrams were named significantly faster than less frequent ones, indicating that practice in reading may play an important role in RAN task performance. Similarly to the patterns of results observed for the original RAN subtasks, multiple regression analyses with performance on the modified RAN subtasks as criterion variables revealed that attention was a much stronger predictor of naming speed than either of automaticity-related factors. Moreover, the percent of variance explained by the index of general attention typically tended to increase in subtasks with heavy attentional demand compared to attention-wise less demanding and in the subtask with the relatively less frequent bigrams compared to the subtask with the more frequent ones. In addition, Study 2 found that performance on the RAN subtask based on less frequent bigrams showed the highest degree of inter-correlation with performance on the other RAN subtasks. Presumably, this particular subtasks reflects importance of both major components previously implicated in RAN task performance: (1) more automatic recognition of highly practiced symbols (through reading experience, as indirectly indicated by difference in naming speed of more versus less familiar combinations of characters), and (2) more efficient attention control to manage performance when these stimuli are presented in less familiar combinations. Finally, it is particularly interesting to note that the attentionally more challenging modified RAN subtasks demonstrated overall stronger connection to the measure of reading performance. It was true even for the bigram-based modified RAN subtasks. Performance on those that utilized the less frequent and hence less familiar bigrams was correlated with reading rate somewhat more strongly than did naming speed for more frequent bigrams. This particular pattern in the correlational data may well indicate that the tasks associated with greater processing challenges better differentiate stronger and relatively weaker readers.

With respect to the focal area of the research interest – the cognitive nature of the RAN tasks – both Study 1 and Study 2 established that attention and not automaticity-based factors most likely underlie RAN task performance.

Study 3 was designed as a follow-up of the first two studies and addressed the next set of research questions. First, Study 3 made another attempt to find a link between RAN task performance and automaticity of stimulus recognition when the latter was operationalized in a different way. Second, Study 3 tried to identify what particular aspects of attention control were associated with successful RAN task performance. Third, it also explored the possibility that some other, previously unaddressed factors such as efficiency of lexical access and working memory capacity, might be among the cognitive mechanisms underlying RAN task performance.

For the set of variables common across all three experimental studies, the pattern of results was practically the same for all three. Similar findings emerged in the analysis of variance with respect to all modified RAN subtasks – a significant main effect for the attention manipulation and significant differences between symbolic and non-symbolic stimulus type, with faster RAN task performance under the condition of light attention demand and on symbolic stimuli. Similarly, more frequent bigrams were named significantly faster than relatively less frequent bigrams. Going beyond the most obvious explanation that the less frequent bigrams are less practiced and hence are named more slowly, the result could also suggest that stimuli in RAN are not processed individually but in short sequences, thereby implicating attention management as a factor.

The correlational analysis in Study 3 supported the findings of the first two studies. It revealed a close association among all RAN subtasks and a stronger connection to reading rate of those subtasks that (1) utilized symbolic stimuli and (2) within the same by the stimulus type category, associated with higher attention demand. Additionally, in Study 3 a standardized measure of reading comprehension was also available, and so it was subjected to correlational analysis. This analysis showed that comprehension was also associated with attention-demanding RAN subtasks, especially non-symbolic ones. The index of working memory not only was significantly correlated with practically all RAN subtasks, but also with both measures of reading ability, possibly implicating working memory as a potential link between RAN and reading performance.

The series of multiple regression analyses with the RAN subtask performance time as criterion variable and different sets of predictors revealed that measures of automaticity and efficiency of lexical access contributed very little to explaining variability in RAN task performance, fully in accord with previous findings, whereas the contribution of the index of general attention was substantial and statistically significant. Furthermore, the contribution of attention only increased when the index of general attention was replaced by three component measures that correlated highly with it and presumed to reflect such specific cognitive subcomponents of attention as spatial search, working memory, and attention shift cost. This particular combination of predictors explained up to 29% of variability in RAN task performance (M-RAN-Non-Symbolic-Large-Heavy), although it did not yield such a strong result for all types of the RAN task.

To briefly summarize the outcomes of all three experimental studies, their major findings include the emergence of two sets of factors underlying RAN task performance:

(1) factors that could be indirectly related to practice in reading and (2) much more influential factors responsible for efficient management of attention resources. An attempt to strike a balance between these two will be in the focus of the subsection that follows.

Finally, the stage two meta-analysis reviewed a representative sample (65 studies) of empirical evidence of RAN-to-reading association in two types of research design. The meta analysis involved 422 coefficients of correlation based on a total sample of 6495 participants in investigations that employed cross-sectional design resulted in the average effect size of $r+ = 0.345$, indicating a low-to-moderate association between naming speed and measures of reading performance. In the moderator analyses of these data the following particular pattern was observed. Symbolic RAN subtasks tended to be most strongly correlated with reading rate, reading comprehension, and decoding skills, whereas non-symbolic RAN subtasks showed consistent (though somewhat lower) correlations with reading comprehension and participants' decoding skills. These findings are quite consistent with the results of the three experimental studies reported above. Indeed, reading skills associated with symbolic RAN subtasks – rate, decoding, and to some extent, comprehension – either require expertise with printed text or depend on processing speed, or both, and as such could be traced to practice-based cognitive components earlier discovered in the three experimental studies. Also, decoding and comprehension skills largely depend on applying rules and building associations. In this respect, their consistent association with non-symbolic RAN subtasks is suggestive of the involvement of attention-based mechanisms, which already was demonstrated in this research. With respect to participants' age, correlations between RAN task performance and reading were relatively stronger for older samples.

The average effect size was, if anything, somewhat stronger for 108 coefficients of correlation (total sample size of 2060 participants) based on longitudinal data: $r+ = 0.398$. The patterns of results in the moderator analyses, in large part, mirrored that of the cross-sectional data. Two reading measures in particular – reading rate and reading comprehension – were correlated with overall RAN performance, more consistently with symbolic RAN subtasks. The magnitude of correlations between naming speed and reading was higher in children in elementary school, as well as for longer delays (time lag between administration of the RAN task and measure of reading performance) in longitudinal studies. Interestingly enough, longitudinal effects across practically all individual moderator analyses tended to be more homogeneous compared to cross-sectional data, possibly indicating that the RAN task, as a correlate of reading abilities, is more consistent when it is used for prognosis of further reading outcomes. These were the major findings of the three experimental studies and the meta-analyses designed to explore the cognitive nature of the association between RAN task performance and reading abilities.

General discussion

In the light of these research findings, it seems that the answer to the major question – why is the RAN task successful in predicting reading abilities? – could be relatively simple. It could be due to the fact that the RAN task very much resembles reading itself, in a sense that it, most likely, requires many of the skills of reading, including among others, stimulus recognition, attention control, etc. Yet the RAN task is sufficiently different from a reading task (it nowhere near predicts 100% of the variance of reading skill) to be thought of as a test of the cognitive prerequisites for reading (that is a simplified reading task called upon exactly the critical cognitive resources for full-scale reading).

This is in no way a new idea. To start with, both reading and RAN are extremely complex activities that include a variety of interdependent components. Some of them, such as stimulus recognition and extracting their meanings from memory, for example, are virtually identical for RAN task performance and for reading, at least from the procedural point of view. The resemblance is no less impressive if we look at these two skills from the perspective of their functional (production) structure – to recognize diverse stimuli presented in various combinations, to attribute to them appropriate labels and to progress through the entire sequence maintaining optimal speed and avoiding mistakes. There are differences, of course. The major one is, obviously, the fact that the sequences of characters in the RAN task do not carry any (conventionally) meaningful message. On the other hand, pseudo-word reading or the reading of nonsense sentences are still reading tasks, insofar as they follow the basic rules of combining letters into words, and as such could be perceive to be somewhat closer to the RAN task. The other difference is the fact that the RAN task requires out-loud naming, whereas normal reading typically is silent or only involves articulation that is enormously reduced.

These differences aside, the question, however, is whether similarities or overlap with reading provide enough reason to perceive the RAN task as a close-to-complete analogue of reading. The research literature seems to generally provide a rather positive answer. For example, Wolf et al. (2000) provide the following description: "…naming speed (particularly serial naming speed) provides an early, simpler approximation of the reading process (see Blachman, 1984), with reading's similar combination of rapid, serial processing and integration of attentional, perceptual, contextual, lexical, and motoric sub-processes…" (p. 393). They continue then with the acknowledgement of differences: "The demands in reading for high-level comprehension processes go far beyond those in naming speed…" (Wolf et al., 2000, p. 393). This last remark not only recognizes the importance of processes responsible for achieving comprehension in reading, but, by contrasting them to naming speed, the authors emphasize (perhaps, even overemphasize) the role of rapid automatic processing in RAN. The correctness of emphasizing automaticity is, in light of the results reported here, somewhat debatable. The present research could not find any consistent link between measures of automaticity and RAN task performance. The role of speed-related mechanisms in RAN has been questioned by others, as well. Consider, for example, among others, Chiappe et al. (1997), who openly questioned the role of temporal processing in RAN task performance a decade ago. The issue of automaticity aside, striking similarities between the RAN task and reading exist and continue to receive acknowledgement. Some researchers are quite unequivocal: "…RAN is an apparent analogue of the reading process" (Stringer, et al., 2004, p. 892). Needless to say, this is especially true for young children whose exposure to actual (full-scale) reading is only beginning and who are more likely to be screened by the RAN task.

From the perspective of the present research, similarities between RAN and reading, in large part, could be described in terms of two major factors – sensitivity to factors presumably related to practice and efficient management of attention resources. Of course, reading is not just a combination of practice and attention, and that is why the RAN task is not the only (and not necessarily the strongest) predictor of reading skills. To name just a few other factors, knowledge of letter-sound correspondence, phonological awareness, vocabulary build-up, increase in the associative networking among various language components – words that represent concrete, abstract, and functional concepts, all are crucial for reading, but hardly relevant to RAN task performance. However, it appears that the present research observed the core similarities between reading and RAN – presumed contribution of practice and efficient management of attention.

What is really important with respect to RAN task performance is that automaticity and attention are not necessarily the opposing constructs here. In general, theory does not contrast the two. True, at any given moment the lack of automaticity is assumed to be associated with a corresponding extra burden placed on the attention system. However, from a developmental or skills acquisition perspective, efficient management of attentional resources can be seen as a pre-condition (pre-requisite) for successful gains in automatic processing, regardless of how automaticity is understood and operationalized in different theoretical accounts. Properly directed, efficiently maintained, and focused in a timely manner, attention helps to optimally restructure underlying processes to enable more stable and efficient performance (Segalowitz & Segalowitz, 1993), to protect processing from interference (Neely, 1977), or to promote transition from serial to parallel processing (Schneider & Shiffrin, 1977). There are reasons to believe that something like that happens with the RAN task. At the time of the first exposure to the RAN task, individual differences in naming speed are most likely attributable to individual differences in attention management. With time, however, as practice in reading progresses, familiarity with alphabetical characters may come to play a stronger role in performance on symbolic RAN subtasks. In non-symbolic RAN tasks, however, practice cannot compensate for weak attention control in those individuals with this problem, and so individual differences in attention now make a more noticeable difference in naming speed, as was observed in Studies 1, 2 and 3.

The relationships between attention-based and automatic processes with respect to RAN task performance may even work in a self-reinforcing manner, so that those, whose attentional control is more efficient, gain in automaticity of alphabetical stimulus recognition sooner and are able to allocate more attentional resources to the management of new challenges that come with more complex reading tasks. This function, obviously, cannot be linear because of the influence of other factors and because of the enormous variability in reading experience that different people have, but the key role of attention remains and manifests itself in determining naming speed, regardless of the kind of RAN task and the age of the person the task is administered to. From this standpoint, using an adult sample (as in the present research) is not a limitation, but rather an opportunity to generalize findings across age groups.

As major similarities between RAN task performance and reading are acknowledged, the findings of the present research should not come as a surprise. The role attention – including its working memory component – plays in any complex activity and in reading in particular, cannot be underestimated. Regardless how fluent a person's ability to read is, if it is reading for understanding, then attention involvement to deal with the novelty of each emerging message is crucial. The RAN task, though it does not require the same fullness of understanding as reading, is nevertheless complex and variable in presenting unpredictable combinations of individual stimuli, and this complexity puts critical demands on attention control, especially in young children (novice readers).

Implications

To briefly summarize, the results of the present research emphasized the role of attention in RAN task performance, and this may have the following implications.

Despite some reservations expressed in other meta-analyses (e.g., Hammill, 2004; Swanson et al., 2003) about the RAN task as a predictor of reading abilities, its connection to reading should not be considered inferior to other predictors (e.g., letter-sound correspondence or phonological awareness). Even if the degree of association with reading is stronger in the case of other predictors, the RAN task still deserves special attention as an assessment tool for prognosis in development of literacy across age groups, and in particular for the population of learners with special needs, who may be less responsive to regular instruction in reading.

The particular reason for this is that understanding the cognitive mechanisms underlying RAN task performance and the RAN-to-reading association has the potential to guide literacy interventions effectively. Reading for comprehension, vocabulary enrichment, fluency in complex pattern recognition, even second language learning may well benefit from the recognition of the role played by attention in naming speed and reading. Some special tools and practices directed towards achieving a better management of attentional resources may be developed and used in education. It appears that reading training oriented toward achieving higher fluency should be complemented by techniques that target efficient management of attention resources, including the attention-directing elements of the language itself.

Finally, reading-specific findings may very well hold the key to better understanding of a variety of complex activities – how efficient management of attentional resources precedes (and sets the conditions for) successful automatization (fluency development) in a variety of cognitively complex skills, whether the sequence of development is reversed (automaticity precedes attentional development), or whether attention and automaticity develop in tandem and are mutually supportive.

References

Aarnoutse, C., van Leeuwe, J., & Verhoeven, L. (2005). Early literacy from a longitudinal perspective. *Educational Research and Evaluation, 11*(3), 253-275.

Ackerman, P. L. (1987). Individual differences in skill learning: An integration of psychometric and information processing perspectives. *Psychological Bulletin, 102*(1), 3-27.

Ackerman, P. T., & Dykman, R. A. (1993). Phonological processes, confrontational naming, and immediate memory in dyslexia. *Journal of Learning Disabilities, 26*(9), 597-609.

Ackerman, P. T., Holloway, C. A., Youngdahl, P. L., & Dykman, R. A. (2001). The double-deficit theory of reading disability does not fit all. *Learning Disabilities Research & Practice 16* (3), 152–160.

American Psychiatric Association. (1994). *Diagnostic and statistical manual of mental disorders* (4th ed.). Washington, DC: Author.

Anderson, J. R. (1983). *The architecture of cognition.* Mahwah, NJ: Erlbaum.

Arbuthnott, K., & Frank, J. (2000). Trail making test, part B as a measure of executive control: Validation using a set-switching paradigm. *Journal of Clinical and Experimental Neuropsychology, 22*(4), 518-528.

*[4]Babur, F. N. (2003). Exploring the relationships among RAN, linguistic/cognitive variables and early reading skills in first- and second-grade students. (Doctoral dissertation, The University of Arizona, 2003). *Dissertation Abstracts*

---

[4]* Note: Marked with asterisks those primary research used in the meta-analysis as the source of correlational data.

International-A. Retrieved on July 25, 2006 from the ProQuest Digital Dissertation + Theses Fulltext database.

Baddeley, A. D., & Della Sala, S. (1996). Working memory and executive control. *Philosophical Transactions of the Royal Society of London, 351*, 1397-1404.

Baddeley, A. D., & Hitch, G. (1974). Working memory. In G. H. Bower (Ed.), *The psychology of learning and motivation: Advances in research and theory* (Vol. 8, pp. 47-89). New York: Academic Press.

Badian, N. A. (1993). Phonemic awareness, naming, visual symbol processing, and reading. *Reading and Writing, 5*(1), 87-100.

Badian, N. A. (1994). Preschool prediction: Orthographic and phonological skills, and reading. *Annals of Dyslexia, 44*, 3-25.

Badian, N. A. (1997). Dyslexia and the double deficit hypothesis. *Annals of Dyslexia, 47,* 69-88.

*Badian, N. A. (1996). Dyslexia: A validation of the concept at two age levels. *Journal of Learning Disabilities, 29*(1), 102-112.

*Badian, N. A. (2005). Does a visual-orthographic deficit contribute to reading disability? *Annals of Dyslexia, 55*(1), 28-52.

*Bell, S. M., McCallum, R. S., & Cox, E. A. (2003). Toward a research-based assessment of dyslexia: Using cognitive measures to identify reading disabilities. *Journal of Learning Disabilities, 36*(6), 506-516.

Bernard, R. M., & Naidu, S. (1990). Integrating research into instructional practice: The use and abuse of meta-analysis. *Journal of Educational Communication, 19* (3), 171-198.

Berninger, V. W., Abbot, S. P., Greep, K., Reed, E., Hoover, C., & Abbot, R. D. (1995). *Single, double, and triple deficits in impaired readers at the end of the first grade: Individual differences in learner characteristics and response to intervention.* Paper presented at the Society for Research in Child Development. Indianapolis, IN.

*Berninger, V. W., Abbott, R. D., Thomson, J. B., & Raskind, W. H. (2001). Language phenotype for reading and writing disability: A family approach. *Scientific Studies of Reading, 15*(1), 59-106.

Berninger, V., Yates, C., & Lester. K. (1991). Multiple orthographic codes reading and writing acquisition, *Reading and Writing: An Interdisciplinary Journal, 3*(2), 115-149.

*Biddle, K. R. (1996). Timing deficits in impaired readers: An investigation of visual naming speed and verbal fluency. (Doctoral dissertation, Tufts University, 1996). *Dissertation Abstracts International-A.* Retrieved on July 25, 2006 from the ProQuest Digital Dissertation + Theses Fulltext database.

*Bishop, A. G. (2001). Prediction of first grade reading achievement using phonological processing skills and letter identification during fall and winter of kindergarten. (Doctoral dissertation, University of Florida, 2001). *Dissertation Abstracts International-A.* Retrieved on July 25, 2006 from the ProQuest Digital Dissertation + Theses Fulltext database.

Bishop, A. G. (2003). Prediction of first-grade reading achievement: A comparison of fall and winter kindergarten screenings. *Learning Disability Quarterly, 26*(3), 189-202.

Bishop, D. V. M. (1997) *Uncommon Understanding: Development and Disorders of Language Comprehension in Children.* Psychology Press.

Blachman, B. A. (1984). Relationship of rapid naming ability and language analysis skills to kindergarten and first-grade reading achievement. *Journal of Educational Psychology, 76*(4), 610-622.

Blachman, B. A. (1989). Phonological awareness and word recognition: Assessment and intervention. In A. G. Kamhi, & H. W. Catts (Eds.), *Reading disabilities: A developmental language perspective* (pp. 133-158). Boston: Little, Brown.

*Blumenthal, S. H. (1980). A study of the relationship between speed of retrieval of verbal information and patterns of oral reading errors. *Journal of Learning Disabilities, 13*(10), 568-570.

Bone, R. B., Cirino, P., Morris, R. D., & Morris, M. K. (2002). Reading and phonological awareness in reading disabled adults. *Developmental Neuropsychology, 21*(3), 305-320.

Borenstein M, Hedges L, Higgins J, Rothstein H. (2005). *Comprehensive Meta-analysis Version 2.* Biostat, Englewood NJ.

Borokhovski E., Segalowitz, N., & Lacroix, G.L. (2004). On a test for predicting success in reading skill development Anatomy of the RAN Task. *Proceedings of /Cognitio: Graduate Studen Conference on Cognitive Science, /Uneversite du Quebec at Montral (UQAM)*, Montreal, Canada April 2004, p. 18-32. URL: http://cognitio.uqam.ca/2004

Borokhovski E., Segalowitz, N., & Lacroix, G. L. (2005). The RAN (Rapid Automatized Naming) Task: Does it reflect automatic or attention-based naming? *10th Conference of the International Association for Cognitive Education and Psychology (IACEP)*, Hild-Bede College, Durham, United Kingdom, July 10th-14th, 2005, p. 27.

Borokhovski E., Segalowitz N., Sokolovskaya, A., & Tapler, C. (2006). Modifying factors that underlie Rapid Automatized Naming (RAN) task performance can clarify its association with reading. St-Petersburg, Russia, June 9th-13th

Bowers, P. G. (1989). Naming speed and phonological awareness: Independent contributors to reading disabilities. *National Reading Conference Yearbook, 38*, 165-172

*Bowers, P. G. (1995). Tracing symbol naming speed's unique contributions to reading disabilities over time. *Reading and Writing, 7*(2), 189-216.

Bowers, P. G., & Ishaik, G. (2003). RAN's contribution to understanding reading disabilities. In H. L. Swanson, (Ed.), *Handbook of learning disabilities* (pp. 140-158). New York, Guilford Press.

Bowers, P. G., & Kennedy, A. (1993). Effects of naming speed differences on fluency of reading after practice. *Annals of the New York Academy of Sciences, 682*(1), 318–320.

*Bowers, P. G., Steffy, R., & Tate, E. (1988). Comparison of the effects of IQ control methods on memory and naming speed predictors of reading disability. *Reading Research Quarterly, 23*(3), 304-319.

*Bowers, P. G., & Swanson, L. B. (1991). Naming speed deficits in reading disability: Multiple measures of a singular process. *Journal of Experimental Child Psychology, 51*(2), 195-219.

Bowers, P. G., & Wolf, M. (1993). Theoretical links among naming speed, precise timing mechanisms and orthographic skill in dyslexia. *Reading and Writing, 5*(1), 69-85.

*Bowey, J. A., Storey, T., & Ferguson, A. N. (2004). The association between continuous naming speed and word reading skill in fourth- to sixth-grade children. *Australian Journal of Psychology, 56*(3), 155-163.

Bradley, L., & Bryant, P. E. (1983). Categorizing sounds and learning to read – A causal connection. *Nature, 301*, 419-421.

Brady, S. A., & Shankweiler, D. P. (1991). *Phonological processes in literacy: A tribute to Isabelle Y. Liberman.* Lawrence Erlbaum Associates.

Breznitz, Z. (2005). Brain activity during performance of naming tasks: Comparison between dyslexic and regular readers. *Scientific Studies of Reading, 9*(1), 17-42.

Brock, S. E. (1995). The reading comprehension abilities of children with Attention-deficit/Hyperactivity disorder. (Doctoral dissertation, University of California, 1995). *Dissertation Abstracts International-A.* Retrieved on July 25, 2006 from the ProQuest Digital Dissertation + Theses Fulltext database.

Brown, J. I., Fishco, V. V., & Hanna, G. (1993). *Nelson-Denny reading test: Technical report forms G&H.* Chicago: Riverside.

Brown, V., Hammill, D. D., & Wiederholt, J. L., (1995). *Test of reading comprehension* (3^{rd} ed.). Austin, TX; PRO-ED.

Buehler, K. L. (2001). Standardized group achievement tests and the accommodation of additional time. (Doctoral dissertation, Indiana State University, 2001). *Dissertation Abstracts International-A.* Retrieved on July 25, 2006 from the ProQuest Digital Dissertation + Theses Fulltext database.

*Burgess, K. A. (2000). An exploration of the associations among continuous naming speed tasks, phonological tasks, reading ability, and orthographic knowledge. (Doctoral dissertation, University of Virginia, 2000). *Dissertation Abstracts International-A.* Retrieved on July 25, 2006 from the ProQuest Digital Dissertation + Theses Fulltext database.

*Burhanpurkar, A. (2002). Predictors of change in reading skill across grade one: A growth curve analysis. (Doctoral dissertation, University of Guelph, 2002). *Dissertation Abstracts International-A.* Retrieved on July 25, 2006 from the ProQuest Digital Dissertation + Theses Fulltext database.

*Cannon, J. J. A. (2002). A test of the double-deficit hypothesis for children with low reading achievement. (Doctoral dissertation, University of Northern Colorado, 2002). *Dissertation Abstracts International-A.* Retrieved on July 25, 2006 from the ProQuest Digital Dissertation + Theses Fulltext database.

*Cardoso-Martins, C., & Pennington, B. F. (2004). The relationship between phoneme awareness and rapid serial naming skills and literacy acquisition: The role of developmental period and reading ability. *Scientific Studies of Reading, 8*(1), 27-52.

*Carver, R. P., & David, A. H. (2001). Investigating reading achievement using a causal model. *Scientific Studies of Reading, 5*(2), 107-140.

Castles, A. & Coltheart, M. (2003). Is there a causal link from phonological awareness to success in learning to read? *Cognition, 91*(1), 77-111.

*Chandarina, A. S. (2003). Acquisition of reading skills in russian-speaking ESL children. (Doctoral dissertation, University of Toronto, 2003). *Dissertation Abstracts International-A.* Retrieved on July 25, 2006 from the ProQuest Digital Dissertation + Theses Fulltext database

*Chiappe, P. R. (1997). A multivariate investigation of the timing deficit hypothesis of reading disability. (Doctoral dissertation, University of Toronto, 1997). *Dissertation Abstracts International-A.* Retrieved on July 25, 2006 from the ProQuest Digital Dissertation + Theses Fulltext database.

Chiappe, P. (2005). How reading research can inform mathematics difficulties: The search for the core deficit. *Journal of Learning Disabilities, 38*(4), 313-317.

Chiappe, P., Stanovich, K. E., & Siegel, L. S. (1997, March). *A timely look at the timing hypothesis of reading disability.* Paper presented at the Annual Meeting of the Society for the Scientific Study of Reading, Chicago, IL.

*Chin, C. E. (2001). The relations of phonological awareness and visual naming speed to beginning reading skills in at-risk children. (Doctoral dissertation, Georgia State University, 2001). *Dissertation Abstracts International-A.* Retrieved on July 25, 2006 from the ProQuest Digital Dissertation + Theses Fulltext database.

Chincotta, D., Underwood, G., Ghani, K. A., Papadopoulou, E., & Wresinski, M. (1999). Memory span for Arabic numerals and digit words: Evidence for a limited-capacity, visuo-spatial storage system. *Quarterly Journal of Experimental Psychology A: Human Experimental Psychology, 52*(2), 325-351.

*Cho, J., & McBride-Chang, C. (2005). Correlates of Korean hangul acquisition among kindergartners and second graders. *Scientific Studies of Reading, 9*(1), 3-16.

*Chow, B. W., McBride-Chang, C., & Burgess, S. (2005). Phonological processing skills and early reading abilities in Hong Kong Chinese kindergarteners learning to read English as a second language. *Journal of Educational Psychology, 97*(1), 81-87.

*Clarke, P., Hulme, C., & Snowling, M. (2005). Individual differences in RAN and reading: A response timing analysis. *Journal of Research in Reading, 28*(2), 73-86.

*Clinton, A. B. (2001). Phonology, orthography, and naming as predictors of reading ability in the Spanish language. (Doctoral dissertation, University of Georgia, 2001). *Dissertation Abstracts International-A.* Retrieved on July 25, 2006 from the ProQuest Digital Dissertation + Theses Fulltext database.

*Cobbold, S., Passenger, T., & Terrell, C. (2003). Serial naming speed and the component elements of speech time and pause time: Relationships with the development of word-level reading in children aged four to five years. *Journal of Research in Reading, 26*(2), 165-176.

Cohen, J. D., MacWhinney, B., Flatt, M. R., & Provost, J. (1993). PsyScope: A new graphic interactive environment for designing psychology experiments. *Behavior Research Methods, Instruments, and Computers, 25*(2), 257–271.

Cohen, J. D., & Servan-Schreiber, D. (1992). Context, cortex, and dopamine: A connectionist approach to behavior and biology in schizophrenia. *Psychological Review, 99*, 45-77.

*Compton, D. L. (2003a). Modeling the relationship between growth in rapid naming speed and growth in decoding skill in first-grade children. *Journal of Educational Psychology, 95*(2), 225-239.

*Compton, D. L. (2003b). The influence of item composition on RAN letter performance in first-grade children. *Journal of Special Education, 37*(2), 81-94.

*Compton, D. L., DeFries, J. C., & Olson, R. K. (2001). Are RAN- and phonological awareness-deficits additive in children with reading disabilities? *Dyslexia, 7*(3), 125-149.

*Compton, D. L., Olson, R. K., DeFries, J. C., & Pennington, B. F. (2002). Comparing the relationships among two different versions of alphanumeric rapid automatized naming and word level reading skills. *Scientific Studies of Reading, 6*(4), 343-368.

Conrad, N. J. (2003). *Letter processing in children with naming speed deficits.* (Doctoral dissertation, McMaster University, 2003). *Dissertation Abstracts International-A.* Retrieved on July 25, 2006 from the ProQuest Digital Dissertation + Theses Fulltext database.

*Cornwall, A. (1992). The relationship of phonological awareness, rapid naming, and verbal memory to severe reading and spelling disability. *Journal of Learning Disabilities, 25*(8), 532-538.

*Coyne-Martinson, P. A. (1999). Assessing the prereading language development of kindergarten students: The reliability, validity, and sensitivity of basic language assessment story tasks as dynamic indicators of basic early literacy skills. (Doctoral dissertation, University of Oregon, 1999). *Dissertation Abstracts International-A.* Retrieved on July 25, 2006 from the ProQuest Digital Dissertation + Theses Fulltext database.

Critchley, M. (1970) *The dyslexic child. 2nd edition.* London: Heinemann Medical.

Cronin, V., & Carver, P. (1998). Phonological sensitivity, rapid naming, and beginning reading. *Applied Psycholinguistics, 19*(3), 447-461.

Cui, Y., & Chen, Y. (1998). Predictive inference in reading: The effects of semantic relations and their strength. *Acta Psychologica Sinica, 30*(1), 14-20.

*Cunningham, A. E., Perry, K. E., Stanovich, K. E., & Share, D. L. (2002). Orthographic learning during reading: Examining the role of self-teaching. *Journal of Experimental Child Psychology, 82*(3), 185-199.

*Cutting, L. E., & Denckla, M. B. (2001). The relationship of rapid serial naming and word reading in normally developing readers: An exploratory model. *Reading and Writing, 14*(7), 673-705.

Daneman, M., & Carpenter, P. A. (1980). Individual differences in working memory and reading. *Journal of Verbal Learning and Verbal Behaviour, 19*(4), 450-466.

*Davis, C. J. (2003). Localization of susceptibility genes for reading and rapid naming difficulties. (Doctoral dissertation, University of Colorado at Boulder, 2003). *Dissertation Abstracts International-A.* Retrieved on July 25, 2006 from the ProQuest Digital Dissertation + Theses Fulltext database.

Davy E., & Davy, K. (1992). *TOEFL reading and vocabulary workbook.* NY: Macmillan.

*de Jong, P. F., & van der Leij, A. (1999). Specific contributions of phonological abilities to early reading acquisition: Results from a Dutch latent variable longitudinal study. *Journal of Educational Psychology, 91*(3), 450-476.

*de Jong, P. F., & van der Leij, A. (2002). Effects of phonological abilities and linguistic comprehension on the development of reading. *Scientific Studies of Reading, 6*(1), 51-77.

de Jong, P. F., & van der Leij (2003). Developmental changes in the manifestation of a phonological deficit in dyslexic children learning to read a regular orthography. *Journal of Educational Psychology, 95*(1), 22-40.

*de Jong, P. F., & Vrielink, L. O. (2004). Rapid automatic naming: Easy to measure, hard to improve (quickly). *Annals of Dyslexia, 54*(1), 65-88.

Denckla, M. B. (1972). Color-naming defects in dyslexic boys. *Cortex, 8*(2), 164-176.

Denckla, M. B., & Cutting, L. E. (1999). History and significance of rapid automatized naming. *Annals of Dyslexia, 49*, 29-42.

Denckla, M. B., & Rudel, R. G. (1974). Relation of forward and backward digit repetition to neurological impairment in children with learning disabilities. *Neuropsychologia, 12*(1), 109-118.

Denckla, M. B., & Rudel, R. G. (1976a). Naming of object drawings by dyslexics and other learning disabled children. *Brain and Language, 3*, 1-15.

Denckla, M. B., & Rudel, R. G. (1976b). Rapid 'automatized' naming (R.A.N.): Dyslexia differentiated from other learning disabilities. *Neuropsychologia, 14*(4), 471-479.

*Denckla, M. B., Rudel, R. G., & Broman, M. (1981). Tests that discriminate between dyslexic and other learning-disabled boys. *Brain and Language, 13*(1), 118-129.

*Deutsch, G. K., Dougherty, R. F., Bammer, R., Siok, W. T., Gabrieli, J. D. E., & Wandell, B. (2005). Children's reading performance is correlated with white matter structure measured by tensor imaging. *Cortex, 41*(3), 354-363.

Doi, L. M. M. (1996). The significance of naming speed in reading development. (Doctoral dissertation, University of Southern California, 1996). *Dissertation Abstracts International-A.* Retrieved on July 25, 2006 from the ProQuest Digital Dissertation + Theses Fulltext database.

Dunn, L. M., & Dunn, L. M. (1998). *Peabody Picture Vocabulary Test* (3rd ed.). Circle Pines, MN: American Guidance Services.

Dyer, A., MacSweeny, M., Szczerbinski, M., Green, L., & Campbell, R. (2003). Predictors of reading delay in deaf adolescents: The relative contribution of rapid automatized naming speed and phonological awareness and decoding. *Journal of Deaf Studies and Deaf Education, 8* (3), 215-229.

*Ebaugh, J. C. (2000). The effects of fluency instruction on the literacy development of at-risk first graders. (Doctoral dissertation, University of Fordham University, 2000). *Dissertation Abstracts International-A.* Retrieved on July 25, 2006 from the ProQuest Digital Dissertation + Theses Fulltext database.

*Egert, A. (1998). A componential investigation of reading comprehension. (Doctoral dissertation, Columbia University Teachers College, 1998). *Dissertation Abstracts International-A.* Retrieved on July 25, 2006 from the ProQuest Digital Dissertation + Theses Fulltext database.

Engle, R. W. (2002). Working memory capacity as executive attention. *Current Directions in Psychological Science 11*(1), 19-23

Engle, R.W., Cantor, J., & Carullo, J. J. (1992). Individual differences in working memory and comprehension: a test of four hypotheses. *Journal of Experimental Psychology, Learning, Memory, and Cognition 18*(5), 972-992.

*Etmanskie, J. M. (1999). Reading, spelling, and phonological processing in children with phonological or surface reading problems. (Doctoral dissertation, Queen's University at Kingston, 1999). *Dissertation Abstracts International-A.* Retrieved on July 25, 2006 from the ProQuest Digital Dissertation + Theses Fulltext database.

*Evans, M. A., Shaw, D., & Bell, M. (2000). Home literacy activities and their influence on early literacy skills. *Canadian Journal of Experimental Psychology, 54*(2), 65-75.

Fastenau, P. S., Shen, J., Dunn, D. W., Perkins, S. M., Hermann, B. P., & Austin, J. K. (2004). Neuropsychological predictors of academic underachievement in pediatric epilepsy: Moderating roles of demographic, seizure, and psychosocial variables. *Epilepsia, 45*(10), 1261-1272.

Favreau, M., & Segalowitz, N. (1983) Automatic and controlled processes in the first and second language reading of fluent bilinguals. *Memory & Cognition, 11*, 565-574.

Fawcett, A. (Ed.) (2001). *Dyslexia, theory and good practice*. London: Whurr.

Fawcett, A. J., & Nicolson, R. I. (1992). Automatisation deficits in balance for dyslexic children. *Perceptual and Motor Skills, 75*(2), 507-529

Fawcett, A., & Nicolson, R. (1994 a). *Dyslexia in children: multidisciplinary perspectives.* Englewood Cliffs, NJ: Prentice Hall

Fawcett, A. J., & Nicolson, R. I. (1994 b). Naming speed in children with dyslexia. *Journal of Learning Disabilities, 27*(10), 641-646.

Fawcett, A. J., & Nicolson, R. I. (1995). Persistence of phonological awareness deficits in older children with dyslexia. *Reading and Writing, 7*(4), 361-376

*Felton, R. H. (1992). Early identification of children at risk for reading disabilities. *Topics in Early Childhood Special Education, 12*(2), 212-229.

Felton, R. H., Naylor, C. E., & Wood, F. B. (1990). Neuropsychological profile of adult dyslexics. *Brain and Language, 39*, 485-497.

Field, A. (2005). *Discovering statistics using SPSS.* SAGE Publications.

Fleming, K. M. (1999). The effect of instruction, rapid automatized naming, intellectual functioning, initial phonological awareness skill, and age on phonological awareness growth trajectories. (Doctoral dissertation, University of Oregon, 1999). *Dissertation Abstracts International-A.* Retrieved on August 14, 2006 from the ProQuest Digital Dissertation + Theses Fulltext database.

Fletcher, J. M.. Morris, R., Lyon, G. R., Stuebing, K. K., Shaywitz, S. E., Shankweiler, D. P., Katz, L., & Shaywitz, B. A. (1997). Subtypes of dyslexia: An old problem revisited. In B. A. Blachman (Ed.), *Foundations of reading acquisition and dyslexia: Implications for early intervention.* (pp. 95-114) Lawrence Erlbaum Associates, Publishers.

Foy, J. G., & Mann, V. (2003). Home literacy environment and phonological awareness in preschool children: Differential effects for rhyme and phoneme awareness. *Applied Psycholinguistics, 24*(1), 59-88.

Frederickson, N., Frith, U., & Reason, R. (1997). *Phonological assessment battery.* Windsor, UK: NREF.

Gallagher, A., & Frederickson, N. (1995). The phonological assessment battery (PhAB): An initial assessment of its theoretical and practical utility. *Educational and Child Psychology, 12*(1), 53-67.

*Georgiou, G. K. (2004). Rapid naming speed components and early reading acquisition. (Doctoral dissertation, University of Alberta, 2004). *Dissertation Abstracts International-A.* Retrieved on August 14, 2006 from the ProQuest Digital Dissertation + Theses Fulltext database.

Geschwind, N. (1965). Disconnection syndrome in animals and man (Parts I, II). *Brain, 88*, 237-294, 585-644.

*Gholamain, M. (1992). The role of orthography and cognitive factors in the concurrent development of basic reading skills in bilingual Persian English speaking children. (Doctoral dissertation, University of Toronto, 1992). *Dissertation Abstracts International-A.* Retrieved on August 14, 2006 from the ProQuest Digital Dissertation + Theses Fulltext database.

Glass, G. V., McGaw, B., & Smith, M. L. (1981). *Meta-analysis in social research.* Beverly Hills, CA: Sage.

*Golden, J. O. (1997). Analysis of orthographic knowledge and its relationship to naming speed, phonological awareness, and single word identification. (Doctoral dissertation, University of Waterloo, 1997). *Dissertation Abstracts International-A.* Retrieved on August 14, 2006 from the ProQuest Digital Dissertation + Theses Fulltext database.

Gottardo, A., Stanovich, K. E., & Siegel, L. S. (1996). The relationships between phonological sensitivity, syntactic processing, and verbal working memory in the reading performance of third-grade children. *Journal of Experimental Child Psychology, 63*, 563-582.

*Griffiths, Y. M., & Snowling, M. J. (2001). Auditory word identification and phonological skills in dyslexic and average readers. *Applied Psycholinguistics, 22*(3), 419-439.

*Grigorenko, E. L., Wood, F. B., Meyer, M. S., & Pauls, D. L. (2000). Chromosome 6p influences on different dyslexia-related cognitive processes: Further confirmation. *American Journal of Human Genetics, 66*(2), 715-723.

Harn, E. A. (2000). Examining and predicting response to instruction based on kindergarten children's early literacy profiles. (Doctoral dissertation, University of Oregon, 2000). *Dissertation Abstracts International-A.* Retrieved on August 14, 2006 from the ProQuest Digital Dissertation + Theses Fulltext database.

Hammill, D. D. (2004). What we know about correlates of reading; Corrected tables. *Exceptional Children, 71*(1), 122-124.

Hammill, D. D., & McNutt, G. (1981). *The correlates of reading: The consensus of thirty years of correlational research.* Austin, TX: PRO-ED.

*Hann, P. L. (1999). A comparison of two methods of teaching word recognition to kindergarten students. (Doctoral dissertation, Memorial University of Newfoundland, 1999). *Dissertation Abstracts International-A.* Retrieved on August 14, 2006 from the ProQuest Digital Dissertation + Theses Fulltext database.

Harn, E. A. (2000). Examining and predicting response to instruction based on kindergarten children's early literacy profiles. (Doctoral dissertation, University of Oregon, 2000). *Dissertation Abstracts International-A.* Retrieved on August 14, 2006 from the ProQuest Digital Dissertation + Theses Fulltext database.

*Harty, K. R. (2003). Subtypes of reading disabilities: Examining the relationships among measures. (Doctoral dissertation, University at Pittsburgh, 2003). *Dissertation Abstracts International-A.* Retrieved on August 14, 2006 from the ProQuest Digital Dissertation + Theses Fulltext database.

*Havey, J. M., Story, N., & Buker, K. (2002). Convergent and concurrent validity of two measures of phonological processing. *Psychology in the Schools, 39*(5), 507-514.

Heath, S. M., & Hogben, J. H. (2004). Cost-effective prediction of reading difficulties. *Journal of Speech, Language, and Hearing Research, 47*(4), 751-765.

Hedges, L. V., & Olkin, I. (1985). *Statistical Methods for Meta-analysis*. Boston, Mass: Academic Press.

Hedges, L., Shymansky, J., & Woodworth, G. (1989). *A practical guide tomodern methods of meta-analysis*. Washington, DC: National Science Teachers Association.

Higgins, J. P. T., & Thompson, S. G. (2002). Quantifying heterogeneity in a meta-analysis. *Statistics in Medicine,* 21, 1539-1558.

Ho, C. S., Chan, D. W., Leung, P. W. L., Lee, S., & Tsang, S. (2005). Reading-related cognitive deficits in developmental dyslexia, attention-deficit/hyperactivity disorder, and developmental coordination disorder among Chinese children. *Reading Research Quarterly, 40*(3), 318-337.

*Ho, C. S., & Lai, D. N. (1999). Naming-speed deficits and phonological memory deficits in Chinese developmental dyslexia. *Learning and Individual Differences, 11*(2), 173-186.

Holland, J., McIntosh, D., & Huffman, L. (2004). The role of phonological awareness, rapid automatized naming, and orthographic processing in word reading. *Journal of Psychoeducational Assessment, 22*(3), 233-260.

*Holopainen, L., Ahonen, T., & Lyytinen, H. (2001). Predicting delay in reading achievement in a highly transparent language. *Journal of Learning Disabilities, 34*(5), 401-413.

Hopkins, W. G. (2002). *A scale of magnitudes for the effect statistics*. A new view of statistics. http://www.sportsci.org/resource/stats.effect-mag.html

*Howe, A. E., Arnell, K. M., Klein, R. M., Joanisse, M. F., & Tannock, R. (2006). The ABCs of computerized naming: Equivalency, reliability, and predictive validity of a computerized rapid automatized naming (RAN) task. *Journal of Neuroscience Methods, 151*(1), 30-37.

Huedo-Medina, T. B., Sánchez-Meca, J., Marin-Martınez, F., & Botella, J. (2006). Assessing Heterogeneity in Meta-Analysis: *Q* Statistic or *I*2 Index? *Psychological Methods, 11*(2), 193–206

*Huff, E., Sorenson, J., & Dancer, J. (2002). Relation of reading rate and rapid automatic naming among third graders. *Perceptual and Motor Skills, 95*(3), 925-926.

Hultquist, A. M. (1996). Orthographic processing in reading-disabled students and reading age controls: Whole word and subword units. (Doctoral dissertation, American International College, 1996). *Dissertation Abstracts International-A*. Retrieved on August 14, 2006 from the ProQuest Digital Dissertation + Theses Fulltext database.

Hutchens, T. A. (1988). Automaticity, naming, and reading in learning disabled and normally achieving college students. (Doctoral dissertation, University of Georgia, 1998). *Dissertation Abstracts International-A*. Retrieved on July 25, 2006 from the ProQuest Digital Dissertation + Theses Fulltext database.

Hynd, G. W., Lorys, A. R., Semrud-Clikeman, M., & Nieves, N. (1991). Attention deficit disorder without hyperactivity: A distinct behavioral and neurocognitive syndrome. *Journal of Child Neurology, 6,* s37-s43.

James, J. S. (1996). Phonological processing in early reading and invented spelling. (Doctoral dissertation, Queen's University at Kingston, 1996). *Dissertation Abstracts International-A.* Retrieved on August 14, 2006 from the ProQuest Digital Dissertation + Theses Fulltext database.

Johnson-Davis, C. (1993). The determinants of response to phonological awareness training. (Doctoral dissertation, The Florida State University, 1993). *Dissertation Abstracts International-A.* Retrieved on August 14, 2006 from the ProQuest Digital Dissertation + Theses Fulltext database.

Jones, M. N., & Mewhort, D. J. K. (2004). Case-sensitive letter and bigram frequency counts from large scale English corpora. *Behavior research Methods, Instruments, & Computers, 36*(3), 388-396.

Joy, R. M. (2003). The concurrent development of basic reading skills in French and English in early French immersion. (Doctoral dissertation, University of Toronto, 2003). *Dissertation Abstracts International-A.* Retrieved on August 14, 2006 from the ProQuest Digital Dissertation + Theses Fulltext database.

*Kail, R., Hall, L. K., & Caskey, B. J. (1999). Processing speed, exposure to print, and naming speed. *Applied Psycholinguistics, 20*(2), 303-314.

Kahneman, D. (1973). *Attention and effort.* Englewood Cliffs, NJ: Prentice Hall.

*Katz, W. F., Curtiss, S., & Tallal, P. (1992). Rapid automatized naming and gesture by normal and language-impaired children. *Brain and Language, 43*(4), 623-641.

Kaufman, A. S., & Lichtenberger, E. O. (1999). *Essentials of WAIS-III assessment.* New York: John Wiley & Sons, Inc.

Kelly, J. W. (1998). The alternative conformations of amyloidogenic proteins and their multi-step assembly pathways. *Current Opinion in Structural Biology, 8*(1), 101-106.

Kirby, J. R., Martinussen, R., & Beggs, P. (1996). *Causal path analysis of processes affecting early reading.* Canada; Ontario, American Psychological Association, Toronto, 11 August 1996.

Kirby, J. R., & Parrila, R. K. (1999). Theory-based prediction of early reading. *Alberta Journal of Educational Research, 45*(4), 428-447.

Kobayashi, M. S. (2001). Cognitive-linguistic factors in Japanese children's reading. (Doctoral dissertation, MGH Institute of Health Professions, 2001). *Dissertation Abstracts International-A.* Retrieved on August 14, 2006 from the ProQuest Digital Dissertation + Theses Fulltext database.

*Kobayashi, M. S., Haynes, C. W., Macaruso, P., Hook, P. E., & Kato, J. (2005). Effects of Mora deletion, nonword repetition, rapid naming, and visual search performance on beginning reading in Japanese. *Annals of Dyslexia, 55*(1), 105-128.

Korhonen, T. (1995). The persistence of rapid naming problems in children with reading disabilities: A nine-year follow-up. *Journal of Learning Disabilities, 28,* 232-239.

Krug, C. H. (1996). The diagnostic implications of the double-deficit hypothesis: An investigation of fifth-grade readers classified by phonological awareness and visual naming speed. (Doctoral dissertation, Tufts University, 1996). *Dissertation Abstracts International-A.* Retrieved on August 14, 2006 from the ProQuest Digital Dissertation + Theses Fulltext database.

Kuhara-Kojima, K., Hatano, G., Saito, H., & Haebara, T. (1996). Vocalization latencies of skilled and less skilled comprehenders for words written in Hiragana and Kanji. *Reading Research Quarterly, 31*(2), 158-171.

Laberge, D. & Samuels, J. (1974). Toward a theory of automatic information processing in reading. *Cognitive Psychology, 6*, 293-323.

Lacroix, G. L., Constantinescu, I., Cousineau, D., de Almeida, R. G., Segalowitz, N., & von Grünau, M. (2005). Attentional blink differences between adolescent dyslexic and normal readers. *Brain & Cognition, 57,* 115-119.

*Lafrance, A., & Gottardo, A. (2005). A longitudinal study of phonological processing skills and reading in bilingual children. *Applied Psycholinguistics, 26*(4), 559-578.

*Landerl, K. (2001). Word recognition deficits in German: More evidence from a representative sample. *Dyslexia,* 7(4), 183-196.

Landerl, K. (2003). Dyslexia in German-speaking children. In N. Goulandris (Ed.), *Dyslexia in different languages: Cross-linguistic comparisons.* (pp. 15-32). Whurr Publishers, Ltd.

Larsen, S. C., Hammill, D. D., & Moats (1999). *Test of Written Spelling* (4th ed.). Austin, TX: PRO-ED.

Lepola, J., Poskiparta, E., Laakkonen, E., & Niemi, P. (2005). Development of and relationship between phonological and motivational processes and naming speed in predicting word recognition in grade 1. *Scientific Studies of Reading* 9(4), 367-399

*Levy, Y., Smith, J., & Tager-Flusberg, H. (2003). Word reading and reading-related skills in adolescents with Williams syndrome. *Journal of Child Psychology and Psychiatry, 44*(4), 576-587.

Lipsey, M., & Wilson, D. (2001). *Practical Meta-analysis* (vol. 49).Thousand Oaks,CA: Sage Publications. 185-204.

*Lovett, M. W. (1987). A developmental approach to reading disability: Accuracy and speed criteria of normal and deficient reading skill. *Child Development, 58*(1), 234-260.

Lovett, M. W., Steinbach, K. A., & Frijters, J. C. (2000). Remediating the core deficits of developmental reading disability: A double-deficit perspective. *Journal of Learning Disabilities, 33*(4), 334-358.

Lu, T. (2004). The relationship of phonological processing (phonological awareness, verbal short-term memory, and rapid naming) and visual short-term memory to reading disabilities in Chinese children. (Doctoral dissertation, University Iowa, 2004). *Dissertation Abstracts International-A.* Retrieved on August 14, 2006 from the ProQuest Digital Dissertation + Theses Fulltext database.

Manis, F. R., & Doi, L. M. (1995). *Word naming speed, phonological coding and orthographic knowledge in dyslexic and normal readers.* Symposium paper presented at the Society for Research in Child Development. Indianapolis, IN.

*Manis, F. R., Doi, L. M., & Bhadha, B. (2000). Naming speed, phonological awareness, and orthographic knowledge in second graders. *Journal of Learning Disabilities, 33*(4), 325.

*Manis, F. R., Lindsey, K. A., & Bailey, C. E. (2004). Development of reading in grades K-2 in Spanish-speaking English-language learners. *Learning Disabilities Research & Practice, 19*(4), 214-224.

Manley, J. (1993). A comparison of the phonological processing abilities of two groups of disabled readers. (Doctoral dissertation, University of Nevada, 1993). *Dissertation Abstracts International-A.* Retrieved on August 14, 2006 from the ProQuest Digital Dissertation + Theses Fulltext database.

Mann, V. & Wimmer, H. (2002). Phoneme awareness and pathways into literacy: A comparison of German and American children. *Reading and Writing. 15*(7-8), 653-682.

Marshall, C. M., Snowling, M. J., & Bailey, P. (2001). Rapid auditory processing and phonological ability in normal readers and readers with dyslexia. *Journal of Speech, Language and Hearing Research, 44*, 925-940.

Martinussen, R., Frijters, J., & Tannock, R. (1998). *Naming speed and stimulant effects in inattention-deficit/hyperactivity disorder.* Paper presented at American Academy of Child and Adolescent Psychiatry. Anaheim, CA.

Mayringer, H. & Wimmer, H. (2000). Pseudoname learning by German-speaking children with dyslexia: Evidence for a phonological learning deficit. *Journal of Experimental Child Psychology, 75*(2), 116-133.

Mazzocco, M. M., & Thompson, R. E. (2005). Kindergarten predictors of math learning disability. *Learning Disabilities Research & Practice, 20*(3), 142-155.

McBride-Chang, C., & Ho, C. S. (2000). Naming speed and phonological awareness in Chinese children: Relations to reading skills. *Journal of Psychology in Chinese Societies, 1*(1), 93-108.

McBride-Chang, C., & Manis, F. R. (1996). Structural invariance in the associations of naming speed, phonological awareness, and verbal reasoning in good and poor readers: A test of the double deficit hypothesis. *Reading and Writing, 8*(4), 323-339.

McBride-Chang, C., Shu, H., Zhou, A., Wat, C. P., & Wagner, R. K. (2003). Morphological awareness uniquely predicts young children's Chinese character recognition. *Journal of Educational Psychology, 95*(4), 743-751.

McCrory, E. J., Mechelli, A., Frith, U., & Price, C. J. (2005). More than words: A common neural basis for reading and naming deficits in developmental dyslexia? *Brain: A Journal of Neurology, 128*(2), 261-267.

Meyer, M. S., Wood, F. B., Hart, L. A., & Felton, R. H. (1998). Selective predictive value of rapid automatized naming in poor readers. *Journal of learning disabilities, 31*(2), 106-117.

Misra, M., Katzir, T., Wolf, M., & Poldrack, R. A. (2004). Neural systems for rapid automatized naming in skilled readers: Unraveling the RAN-reading relationship. *Scientific Studies of Reading, 8*(3), 241-256.

Mitchell, J. (2001). Comprehensive test of phonological processing. *Assessment for Effective Intervention, 26*(3), 57-63.

Moores, E., Nicolson, R. I., & Fawcett, A. J. (2003). Attention deficits in dyslexia: Evidence for an automatisation deficit? *European Journal of Cognitive Psychology, 15*(3), 321-348.

Moors, A. & De Houwer, J. (2006). Automaticity: A theoretical and conceptual analysis. *Psychological Bulletin, 132*(2), 297-326.

Morris, B. (2002). Overcoming dyslexia. *Fortune, 145*(10), 55-70.

Morris, R. D., Stuebing, K. K., Fletcher, J. M., Shaywitz, S. E., Lyon, G. R., & Shankweiler, D. P., et al. (1998). Subtypes of reading disability: Variability around a phonological core. *Journal of Educational Psychology, 90*(3), 347-373.

Naglieri, J. A. (1999). Traditional IQ is irrelevant to learning disabilities – intelligence is not. *School Psychology Review, 28*(1), 145-62.

Nagliery, J. A. (2005). The myth of IQ: 100 years of misconception. *10th Conference of the International Association for Cognitive Education and Psychology (IACEP)*, Hild-Bede College, Durham, United Kingdom, July 10th-14th, 2005, p. 90.

Närhi, V. (2002). The use of clinical neuropsychological data in learning disability research. (Doctoral dissertation, Jyvaskylan Yliopisto, Finland, 2002). *Dissertation Abstracts International-A.* Retrieved on August 14, 2006 from the ProQuest Digital Dissertation + Theses Fulltext database.

Närhi, V., & Ahonen, T. (1995). Reading disability with or without attention deficit hyperactivity disorder: Do attentional problems make a difference? *Developmental Neuropsychology, 11*(3), 337-349.

Naslund, J.C., & Schneider, W. (1991). Longitudinal effects of verbal ability, memory capa-city and phonological awareness on reading performance, *The European Journal of Psychology of Education 6*, 375–392.

Neely, J. (1977). Semantic priming and retrieval from lexical memory: Roles of inhibitionless spreading activation and limited capacity attention. *Journal of Experimental Psychology: General 106*, 226-254.

Neuhaus, G. F. (2000). An investigation of phonological awareness, orthographic recognition, and attention as predictors of rapid automatized naming (RAN) and reading. (Doctoral dissertation, University of Houston, 2000). *Dissertation Abstracts International-A.* Retrieved on August 14, 2006 from the ProQuest Digital Dissertation + Theses Fulltext database

Neuhaus, G. F., & Swank, P. R. (2002). Understanding the relations between RAN letter subtest components and word reading in first-grade students. *Journal of Learning Disabilities, 35*(2), 158-174.

Nicolson, R. I. & Fawcett, A. J. (1996). *Dyslexia screening test.* London: The Psychological Corporation.

Nicolson, R. I. & Fawcett, A. J. (2000). Long-term memory in dyslexic children. *European Journal of Cognitive Psychology 12*(3), 357–393.

Nigg, J. T., Hinshaw, S. P., Carte, E. T. & Treuting, J. L. (1998). Neuropsychological correlates of childhood attention-deficit/hyperactivity disorder: Explainable by comorbid disruptive behavior or reading problems? *Journal of Abnormal Psychology, 107* (3), 468-480.

Nopola-Hemmi, J., Myllyluoma, B., Voutilainen, A., Leinonen, S., Kere, J., & Ahonen, T. (2002). Familial dyslexia: Neurocognitive and genetic correlation in a large finnish family. *Developmental Medicine & Child Neurology, 44*(9), 580-586.

Novoa, L. (1988). Word-retrieval process and reading acquisition and development in bilingual and monolingual children. Unpublished doctoral dissertation, Harvard University, Cambridge, M.

Patel, T. K., Snowling, M. J., & de Jong, P. F. (2004). A Cross-Linguistic Comparison of Children Learning to Read in English and Dutch. *Journal of Educational Psychology, 96*(4), 785-797.

Pennington, B. F., Cardoso-Martins, C., Green, P. A., & Lefly, D. L. (2001). Comparing the phonological and double deficit hypotheses for developmental dyslexia. *Reading and Writing, 14*(7), 707-755.

Petterson, S. M. (2001). The double-deficit hypothesis: An investigation of isolated word fluency by students classified as single visual naming speed deficit or phonological deficit. (Doctoral dissertation, Wayne State University, 2001). *Dissertation Abstracts International-A.* Retrieved on August 14, 2006 from the ProQuest Digital Dissertation + Theses Fulltext database.

Pommerening, K. (2000). Relative bigram frequencies in English. Retrieved from http://www.unimainz.de/~pommeren/Kryptologie99/klassisch/6_Transpos/Bigramme.html on May 20, 2005.

Raberger, T., & Wimmer, H. (2003). On the automaticity/cerebellar deficit hypothesis of dyslexia: Balancing and continuous rapid naming in dyslexic and ADHD children. *Neuropsychologia, 41*(11), 1493-1497.

Ransby, M. J., & Swanson, H. L. (2003). Reading comprehension skills of young adults with childhood diagnoses of dyslexia. *Journal of Learning Disabilities, 36*(6), 538-555.

Raymond J. E., Shapiro K. L., & Arnell K. M., (1992). Temporary suppression of visual processing in an RSVP task: an attentional blink? *Journal of Experimental Psychology: Human Perception and Performance. 18*(3), 849-860.

Rayner, K., Foorman, B. R., Perfetti, C. A., Pesetsky, D., & Seidenberg, M. S. (2001). How psychological science informs the teaching of reading. *Psychological Science in the Public Interests (Special Issue), 2*(2), 31-74.

Reitan, R. M. (1955). The relation of the Trail Making Test to organic brain damage. *Journal of Consulting Psychology, 19*(5), 485-494.

Reitan, R. M. (1958). Validity of the Trail Making Test as an indicator of organic brain damage. *Perceptual and Motor Skills, 8*, 271-276.

Reitan, R. & Wolfson, D. (1993). *The Halstead-Reitan Neuropsychological Test Battery: Theory and clinical interpretation.* Tucson, AZ: Neuropsychology Press.

Roditi, B. N. (1988). Automaticity, cognitive flexibility, and mathematics: A longitudinal study of children with and without learning disabilities. (Doctoral dissertation, Tufts University, 1988). *Dissertation Abstracts International-A.* Retrieved on August 14, 2006 from the ProQuest Digital Dissertation + Theses Fulltext database

Rosenthal, R. (1994). Parametric measures of effect size. In H. Cooper & L. V. Hedges (Eds.), *Handbook of research synthesis* (pp. 231-244). New York: Russell Sage Foundation.

Rucklidge, J. J., & Tannock, R. (2002). Neuropsychological profiles of adolescents with ADHD: Effects of reading difficulties and gender. *Journal of Child Psychology and Psychiatry, 43*(8), 988-1003.

Ruff, R. M., Niemann, H., Allen, C. C., Farrow, C. E., & Wylie, T. (1992). The Ruff 2 and 7 Selective Attention Test: A neuropsychological application. *Perceptual and Motor Skills 75*, 1311–1319.

Russell, E. D. (2002). An examination of the nature of reading fluency. (Doctoral dissertation, University of Rhode Island, 2002). *Dissertation Abstracts International-A.* Retrieved on August 14, 2006 from the ProQuest Digital Dissertation + Theses Fulltext database.

Savage, R. (2004). Motor skills, automaticity and developmental dyslexia: A review of the research literature. *Reading and Writing: An Interdisciplinary Journal, 17,* 301-324.

Savage, R. S., Blair, R., & Rvashiew, S. (in press, 2006). Rimes are not necessarily favored by pre-readers: Evidence from epi- and meta-linguistic phonological tasks. *Journal of Experimental Child Psychology.*

Savage, R. S., & Frederickson, N. (2004) Do we need more than nonsense words to explain the performance of poor readers? (Paper submitted).

Savage, R., Frederickson, N., Goodwin, R., Patni, U., Smith, N., & Tuersley, L. (2005a). Evaluating current deficit theories of poor reading: Role of phonological processing, naming speed, balance automaticity, rapid verbal perception and working memory. *Perceptual and Motor Skills, 101*(2), 345-361.

Savage, R. S., Frederickson, N., Goodwin, R., Patni, U., Smith, N., & Tuersley, L. (2005b). Relationships among rapid digit naming, phonological processing, motor automaticity, and speech perception in poor, average, and good readers and spellers. *Journal of Learning Disabilities, 38*(1), 12-28.

Scarborough, H. S. (1998a). Early identification of children at risk for reading disabilities. In B. K. Shapiro, P. J. Accardo, & A. J. Capute (Eds.), *Specific reading disability* (pp. 75-119). Timonium, MD: York Press.

Scarborough, H. S. (1998b). Predicting the future achievement of second graders with reading disabilities: Contributions of phonemic awareness, verbal memory, rapid naming, and IQ. *Annals of Dyslexia, 48*, 115-136

Schatschneider, C., Carlson, C. D., Francis, D. J., Foorman, B. R., & Fletcher, J. M. (2002). Relationship of rapid automatized naming and phonological awareness in early reading development: Implications for the double-deficit hypothesis. *Journal of Learning Disabilities, 35* (3), 245-256.

Schmidt, B. T. (2003). The relation between oral reading and silent reading comprehension skill. (Doctoral dissertation, City University of New York, 2003). *Dissertation Abstracts International-A.* Retrieved on September 28, 2006 from the ProQuest Digital Dissertation + Theses Fulltext database

Schneider, W., & Shiffrin, R. M. (1977). Controlled and automatic human information processing: I. Detection, search, and attention. *Psychological review, 84* (1), 1-66.

Segalowitz, N. & Frenkiel-Fishman, S. (2005). Attention control and ability level in a complex cognitive skill: attention-shifting and second language proficiency. *Memory & Cognition, 33(4)*, 644-653.

Segalowitz, N., & Hulstijn, J. (2005). Automaticity in bilingualism and second language learning. In J.F. Kroll & A.M.B. De Groot, (Eds.), *Handbook of bilingualism: Psycholinguistic approaches.* (pp. 371-388) Oxford, UK: Oxford University Press.

Segalowitz, N., Poulsen, C., & Segalowitz, S. (1999). RT coefficient of variation is differentially sensitive to executive control involvement in an attention switching task. *Brain and Cognition, 38,* 255-258

Segalowitz, N., & Segalowitz, S.J. (1993) Skilled performance, practice, and the differentiation of speed-up from automatization effects: Evidence from second language word recognition. *Applied Psycholinguistics, 14*, 369-385.

Segalowitz, S. J., Segalowitz, N. S., & Wood, A. G. (1998). Assessing the development of automaticity in second language word recognition. *Applied Psycholinguistics,* 19, 53-67.

Semrud, C. M., Guy, K., Griffin, J. D., & Hynd G. W. (2000). Rapid naming deficits in children and adolescents with reading disabilities and attention deficit hyperactivity disorder. *Brain and Language, 74* (1), 70-83.

Shapiro, K. L., Arnell, K. M., & Raymond, J. E. (1997). The attentional blink. *Trends in Cognitive Sciences, 1*(8), 291-296.

Share, D. L., Jorm, A. F., Maclean, R., & Matthews, R. (2002). Temporal processing and reading ability. *Reading and Writing: An Interdisciplinary Journal, 15*(1-2), 151-178.

Shiffler, M. D. (2004). The effects of a fluency-based intervention program on the reading achievement of two students with double-deficit reading disabilities. (Doctoral dissertation, Cardinal Stritch University, 2004). *Dissertation Abstracts International-A.* Retrieved on September 28, 2006 from the ProQuest Digital Dissertation + Theses Fulltext database.

Sidhu, R. (2001). An examination of phonological and surface subtypes of readers and their relationship to subtypes of the double deficit hypothesis. (Doctoral dissertation, University of Toronto 2001). *Dissertation Abstracts International-A.* Retrieved on September 28, 2006 from the ProQuest Digital Dissertation + Theses Fulltext database

Siegel, L. S., Share, D., & Geva, E. (1995). Evidence for superior orthographic skills in dyslexics. *Psychological Science, 6,* 250-254.

Snowling, M. J. (2000). *Dyslexia.* Oxford, UK: Blackwell Publishers Ltd.

Spreen, O., & Strauss, E. (1991). *A compendium of neuropsychological tests. Administration, norms, and commentary.* New York: Oxford University Press.

Spring, C., & Davis, J. M. (1988). Relations of digit naming speed with three components of reading. *Applied Psycholinguistics, 9*(4), 315-334.

Sprugevica, I. (2003). The impact of enabling skills on early reading acquisition. (Doctoral dissertation, Universitetet I Bergen 2003). *Dissertation Abstracts International-A.* Retrieved on September 28, 2006 from the ProQuest Digital Dissertation + Theses Fulltext database

Sprugevica, I., & Hoien, T. (2004). Relations between enabling skills and reading comprehension: A follow-up study of Latvian students from first to second grade. *Scandinavian journal of psychology, 45*(2), 115-122.

Stanovich, K. E. (1981). Relationships between word decoding speed, general name-retrieval ability, and reading progress in first-grade children. *Journal of Educational Psychology, 73*(6), 809-815.

Stanovich, K. E. (2000). Progress in Understanding Reading: Scientific Foundations and New Frontiers. Guilford Press.

Stanovich, K. E., Cunningham, A. E., & Feeman, D. J. (1984). Intelligence, cognitive skills, and early reading progress. *Reading Research Quarterly, 19*(3), 278-303.

Stanovich, K. E., & Siegel, L. S. (1994). Phenotypic performance profile of children with reading disabilities: A regression-based test of the phonological-core variable-difference model. *Journal of Educational Psychology, 86*(1), 24-53.

Sternberg, R. J. (1999). The theory of successful intelligence. *Review of General Psychology, 3*, 292-316.

Sternberg, R. J. (2005). Culture, instruction, and assessment. *10th Conference of the International Association for Cognitive Education and Psychology (IACEP)*, Hild-Bede College, Durham, United Kingdom, July 10th-14th, 2005, p. 114.

Strattman, K. I. H. (2001). Predictors of second graders' reading and spelling scores. (Doctoral dissertation, Wichita State Univeristy, 2001). *Dissertation Abstracts International-A.* Retrieved on September 28, 2006 from the ProQuest Digital Dissertation + Theses Fulltext database

Stringer, R. W., Toplak, M. E., & Stanovich, K. (2004). Differential relationships between RAN performance, behavioral ratings, and executive function measures: Searching for a double dissociation. Reading and Writing: An Interdisciplinary Journal, 17, 891-914.

Sunseth, K., & Bowers, P. G. (2002). Rapid naming and phonemic awareness: Contributions to reading, spelling, and orthographic knowledge. *Scientific Studies of Reading, 6*(4), 401-429.

Swanson, H. L. (2004). Working memory and phonological processing as predictors of children's mathematical problem solving at different ages. *Memory & Cognition. 32*(4), 648-661.

Swanson, H. L. (2006). Cognitive processes that underlie mathematical precociousness in young children. *Journal of Experimental Child Psychology, 93*(3), 239-264.

Swanson, H. L., Trainin, G., Necoechea, D. M., & Hammill, D. D. (2003). Rapid naming, phonological awareness, and reading: A meta-analysis of the correlation evidence. *Review of Educational Research, 73*(4), 407-440.

Swanson, L. B. (1989). Analyzing naming speed - reading relationships in children. (Doctoral dissertation, University of Waterloo, 1989). *Dissertation Abstracts International-A.* Retrieved on September 28, 2006 from the ProQuest Digital Dissertation + Theses Fulltext database.

Tabachnick, B. G. & Fidell, L. S. (2001). *Using multivariate statistics.* Needham Heights, MA: A Pearson Education Company.

Tallal, P., Miller, S. L., Jenkins, W. M., & Merzenich, M. M. (1997). The role of temporal processing in developmental language-based learning disorders: Research and clinical implications. In B. A. Blachman (Ed.), *Foundations of reading acquisition and dyslexia: Implications for early interventions* (pp. 49-66). Mahwah, New Jersey: Lawrence Erlbaum Associates.

Tannock, R., Martinussen, R., & Frijters, J. (2000). Naming speed performance and stimulant effects indicate effortful, semantic processing deficits in attention-deficit/hyperactivity disorder. *Journal of Abnormal Child Psychology, 28*(3), 237-252.

Taube-Schiff, M., & Segalowitz, (2005). Linguistic attention control: attention shifting governed by grammaticized elements of language. *Journal of Experimental Psychology:Learning, Memory, and Cognition, 31*(3), 508–519.

Tiu, R. D. J., Wadsworth, S. J., Olson, R. K., & DeFries, J. C. (2004). Causal models of reading disability: A twin study. *Twin Research, 7*(3), 275-283.

Torgesen, J.K., & Burgess, S.R. (1998). Consistency of reading-related phonological processes throughout early childhood: Evidence from longitudinal, correlational and instructional studies. In: J. Metsala & L. Ehri (eds.), *Word processing in beginning literacy* (pp. 161-188). Mahwah, NJ: Erlbaum.

Torgesen, J. K., Wagner, R. K., & Rashotte, C. A. (1999). *TOWRE: Test of word reading efficiency*. Austin: PRO-ED.

Torgeson, J. K., Wagner, R. K., Rashotte, C. A., Burgess, C., & Hecht, S. (1997). Contributions of phonological awareness and rapid automatic naming ability to the growth of word-reading skills in second-t0fifth grade children. *Scientific Studies of Reading, 1,* 161-185.

Tulsky, D. S., & Price, L. R. (2003). The joint WAIS-III and WMS-III factor structure: Development and cross-validation of a six-factor model of cognitive functioning. *Psychological Assessment, 15,* 149–162.

Uhry, J. K. (2002). Kindergarten phonological awareness and rapid serial naming as predictors of grade 2 reading and spelling. In E. Witruk, A. D. Friederici & T. Lachmann (Eds.), *Basic functions of language, reading and reading disability.* (pp. 299-313) Kluwer Academic Publishers.

van Daal, V., & van der Leij, A. (1999). Developmental dyslexia: Related to specific or general deficits? *Annals of Dyslexia, 49,* 71-104.

van den Bos, K. (1998). IQ, phonological awareness, and continuous-naming speed related to Dutch children's performance on two word identification tests. *Dyslexia, 4,* 73-89.

van den Bos K. P., Zijlstra, B. J. H., & Spelberg, H. C. (2002). Life-span data on continuous-naming speeds of numbers, letters, colors, and pictured objects, and word-reading speed. *Scientific Studies of Reading, 6*(1), 25-49.

van den Bos K. P., Zijlstra, B. J. H., & van den Broeck, W. (2003). Specific relations between alphanumeric-naming speed and reading speeds of monosyllabic and multisyllabic words. *Applied Psycholinguistics, 24*(3), 407-430.

van der Leij, A., & Morfidi, E. (2006). Core deficits and variable differences in Dutch poor readers learning English. *Journal of Learning Disabilities, 39*(1), 74-90.

van der Sluis, S., de Jong, P. F., & van der Leij, A. (2004). Inhibition and shifting in children with learning deficits in arithmetic and reading. *Journal of Experimental Child Psychology, 87*(3), 239-266.

Veii, K. & Everatt, J. (2005). Predictors of reading among Herero–English bilingual Namibian school children. Bilingualism: Language and Cognition, 8, 239-254

Vellutino, F.R., Scallon, D. et Sipay, E.R. (1997). Toward distinguishing between cognitive and experiential deficits as primary sources of difficulty in learning to read : The importance of early intervention in diagnosing specific reading disability. In B.A. Blachman (dir.), Foundations of reading acquisition and dyslexia : Implications for early intervention (p. 145-162). Hillsdale, NJ : Lawrence Erlbaum.

Vukovic, R. K., Wilson, A. M., & Nash, K. K. (2004). Naming speed deficits in adults with reading disabilities: A test of the double-deficit hypothesis. *Journal of Learning Disabilities, 37*(5), 440-450.

Waber, D., Wolff, P. H., Forbes, P. W., & Weiler, M. D. (2000). Rapid automatized naming in children referred for evaluation of heterogeneous learning problems: How specific are naming speed deficits to reading disability? *Child Neuropsychology, 6*(4), 251-261.

Wagenmakers, E.J., & Brown, S. (in press). On the linear relation between the mean and the standard deviation of a response time distribution. *Psychological Review.*

Wagner, R.K., & Torgessen, J.K. (1987). The nature of phonological processing and its causal role in the acquisition of reading skills. *Psychological Bulletin, 101*(2), 192-212.

Wagner, R. K., Torgesen, J. K., & Rashotte, C. A. (1994). Development of reading-related phonological processing abilities: New evidence of bidirectional causality from a latent variable longitudinal study. *Developmental psychology, 30*(1), 73-87.

Walker, M. M. (2002). Visual and lexical factors in naming speed by children with reading disorders. *Perceptual and Motor Skills, 95*(3), 1196-1198.

Watkins, M. W., Kush, J., & Glutting, J. J. (1997). Discriminant and predictive validity of the WISC-III ACID profile among children with learning disabilities. *Psychology in the School, 34*(4), 309-319.

Wechsler, D. (2003). *Wechsler Intelligence Scale for Children* (4th ed.). San-Antonio, TX: Psychological Corporation.

Wiederholt, J. L. & Bryant, B. R. (2001). *Gray Oral Reading Test* (4th ed.). Austin, TX; PROED.

Williams, G. J. (2001). The clinical significance of visual-verbal processing in evaluating children with potential learning-related visual problems. *Journal of Optometric Vision Development, 32*(2), 107-110.

Wilson, J., & Frederickson, N. (1995). Phonological awareness training: An evaluation. *Educational and Child Psychology, 12*(1), 68-79.

Wimmer, H. (1993). Characteristics of developmental dyslexia in regular writing system. *Applied Psycholinguistics, 14,* 1-34.

Wimmer, H., Mayringer, H., & Landerl, K. (1998). Poor reading: A deficit in skill-automatization or a phonological deficit? *Scientific Studies of Reading, 2*(4), 321-340.

Wimmer, H., Mayringer, H., & Landerl, K. (2000). The double-deficit hypothesis and difficulties in learning to read a regular orthography. *Journal of Educational Psychology, 92,* 668–680

Witt, D. G. (2004). Investigation of the neurophysiological substrates of rapid automatic naming with quantitative electroencephalography. (Doctoral dissertation, Temple University, 2004). *Dissertation Abstracts International-A.* Retrieved on September 28, 2006 from the ProQuest Digital Dissertation + Theses Fulltext database

Wolf, M. (1986). Rapid alternating stimulus naming in the developmental dyslexias. *Brain and Language, 27*(2), 360-379.

Wolf, M. (1999). What time may tell: Towards a new conceptualization of developmental dyslexia. *Annals of Dyslexia, 49*, 3-28.

Wolf, M. (1991). Naming speed and reading: The contribution of the cognitive neurosciences. *Reading Research Quarterly*, *26*(2), 123-141.

Wolf, M., Bally, H., & Morris, R. (1986). Automaticity, retrieval processes, and reading: A longitudinal study in average and impaired readers. *Child Development, 57*(4), 988-1000.

Wolf, M., & Bowers, P. G. (1999). The double-deficit hypothesis for the developmental dyslexia. *Journal of Educational Psychology, 91*(3), 415-438.

Wolf, M., Bowers, P., & Biddle, K. (2000). Naming-speed processes, timing, and reading: A conceptual review. *Journal of Learning Disabilities, 33,* 387-407.

Wolf, M., & Obregon, M. (1992). Early naming deficits, developmental dyslexia, and a specific deficit hypothesis. *Brain and Language, 42*(3), 219-247.

Wolf, M., O'Rourke, A. G., Gidney, C., Lovett, M., Cirino, P., & Morris, R. (2002). The second deficit: An investigation of the independence of phonological and naming –speed deficits in developmental dyslexia. *Reading and Writing: An Interdisciplinary Journal, 15,* 43-72.

Wolf, M., Pfeil, C., Lotz, R., & Biddle, K. (1994). Towards a more universal understanding of the developmental dyslexia: The contribution of orthographic factors. In V. W. Berninger (Ed.), *The varieties of orthographic knowledge, 1: Theoretical and developmental issues.* (pp. 137-171) Kluwer Academic/Plenum Publishers.

Wolff, P. H., Michel, G. F., & Ovrut, M. (1990). Rate variables and automatized naming in developmental dyslexia. *Brain and Language, 39*(4), 556-575.

Wood, F. B., & Felton, R. H. (1994). Separate linguistic and attentional factors in the development of reading. *Topics in Language Disorders, 14*(4), 42-57.

Woodcock, R. W. (1998). *Woodcock Reading Mastery Revised.* Circle Pines, MN: American Guidance Services.

Woodcock, R. W. & Johnson M. B. (1989). *Woodcock-Johnson psycho-educational battery-Revised.* Allen, TX: DLM Teaching Resources.

Woodcock, R. W., McGrew, K., & Mather, N. (2001). *Woodcock-Johnson Test of Cognitive Ability,* Itasca, IL: Riverside

Xiangzhi, M., Shuying, S., & Xiaolin, Z. (2004). Phonological awareness, naming speed and Chinese reading. *Psychological Science (China), 27*(6), 1326-1329.

Young, A. R. (1993). Determinants of oral reading fluency and expressiveness in poor and average readers. (Doctoral dissertation, University of Waterloo, 1993). *Dissertation Abstracts International-A.* Retrieved on September 28, 2006 from the ProQuest Digital Dissertation + Theses Fulltext database.

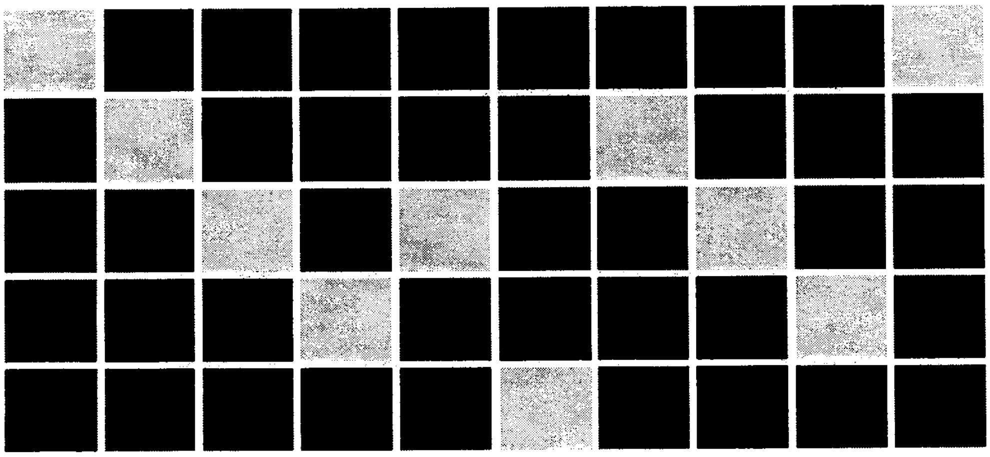
Young, A., & Bowers, P. G. (1995). Individual difference and text difficulty determinants of reading fluency and expressiveness. *Journal of Experimental Child Psychology, 60*(3), 428-454.

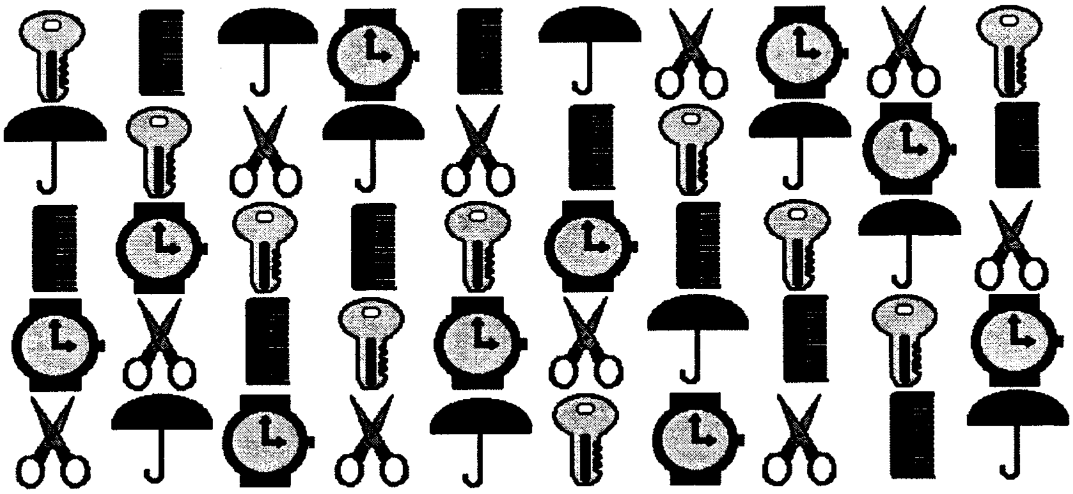
APPENDIX A

Rapid Automatized Naming (RAN) Task: Screen samples of the four subtasks – (1) Naming letters, (2) Naming digits, (3) Naming colors, and (4) Naming objects

a o s p o s d p d a
s a d s d o a s p o
o p a o a p o a s d
p d o a p d s o a p
d s p d s a p d o s

2 4 6 9 4 6 7 9 7 2
6 2 7 6 7 4 2 6 9 4
4 9 2 4 2 9 4 2 6 7
9 7 4 2 9 7 6 4 2 9
7 6 9 7 6 2 9 7 4 6





APPENDIX B

Primed decision making experimental paradigm (Neely, 1977):
Task instructions and an illustration of the sequence of events in the experiment

XR

INSTRUCTION

(Part 1)

Thank you for agreeing to take part in this study. By participating in the following experiment, you will be making a contribution to our understanding of the brain mechanisms involved in reading.

You will be asked to respond to different stimuli — letters and numbers — by making decisions about the "target" that appears in the center of the screen in front of you. When you see a "letter-target" you must indicate whether it is a vowel or a consonant by pressing as fast as you can the "LEFT" key for vowels and the "RIGHT" key for consonants. Similarly, when you see a "digit-target" you must decide whether it is an even or an odd digit by pressing as fast as you can the "LEFT" key in response to odds and the "RIGHT" key in response to evens.

To help prepare you to decide as quickly as possible a signal will precede each target stimulus. Before each new target appears you will see one of the following:

"1 2 3 4 5"

or "A B C D E"

or "* * * * *"

You do not need to react to this signal – it is there to help you get ready by informing you what kind of stimulus to expect next. Please remember that ***"1 2 3 4 5"*** will usually be followed by a digit-target, and ***"A B C D E"*** will usually be followed by a letter-target. The signal **"* * * * *"** indicates that the next stimulus is about to appear, but it does not provide you with any specific information about what that stimulus will be.

We ask you to pay close attention to the preceding signal, since one of the major purposes for this experiment is to assess how fast your responses are when you know in advance what type of target to expect. Remember: when you see a string of digits *"1 2 3 4 5"* expect a digit-target to follow, and when you see a string of letters *"A B C D E"* expect a letter-target to follow.

There always will be a short interval between the signal and the target. Please respond to the target as quickly as you can while keeping errors as low as possible.

After each trial (the sequence ' signal – target – response ') there will be a 1 second delay with a small cross in the center of the screen. Please focus on this fixation point while waiting for the next trial to begin.

The experiment will consist of a training part to familiarize you with the procedure, a short resting interval, and then the main part where you will have to respond as described above.

During the resting interval you will be given some additional instructions as well as an opportunity to ask questions if necessary as you prepare yourself to the rest of the experiment.

If you have any questions now, please ask the experimenter.

Start whenever you are ready by pressing either the "LEFT" or the "RIGHT" key.

XR

INSTRUCTION

(Part 2)

You have just familiarized yourself with the experimental procedure and should now be ready to begin the second part of the experiment. Your task is the same. Press the “LEFT” key in response to vowel letters and odd numbers and the “RIGHT” key in response to consonant letters and even numbers as fast as you can (but still try not to make errors).

Remember that the signal ***“1 2 3 4 5”*** is usually followed by a digit-target and the signal ***“A B C D E”*** is usually followed by a letter-target. The signal***“* * * * *”*** does not provide any specific information about the following target but rather simply reminds you to stay focused and try to react quickly to the target.

We ask you to pay close attention to the preceding signal, since one of the major purposes for this experiment is to assess how fast your responses are when you know in advance what type of target to expect. Remember: when you see a string of digits *“1 2 3 4 5”* expect a digit-target to follow, and when you see a string of letters *“A B C D E”* expect a letter-target to follow.

On several occasions during the experiment, you will be given feedback on your performance. You will see on the screen information about how accurate (% errors) and fast (average response time) you were. Each time the information appears, please enter into the chart provided the corresponding numbers:

- % error;
- average response time.

This will help you keep track of your progress and achieve better results throughout the experiment.

Good luck and thank you for your help.

Start whenever you are ready by pressing either the “LEFT” or the “RIGHT” key.

XU

INSTRUCTION

(Part 1)

Thank you for agreeing to take part in this study. By participating in the following experiment, you will be making a contribution to our understanding of the brain mechanisms involved in reading.

You will be asked to respond to different stimuli — letters and numbers — by making decisions about the "target" that appears in the center of the screen in front of you. When you see a "letter-target" you must indicate whether it is a vowel or a consonant by pressing as fast as you can the "LEFT" key for vowels and the "RIGHT" key for consonants. Similarly, when you see a "digit-target" you must decide whether it is an even or an odd digit by pressing as fast as you can the "LEFT" key in response to odds and the "RIGHT" key in response to evens.

To help prepare you to decide as quickly as possible a signal will precede each target stimulus. Before each new target appears you will see one of the following:

"1 2 3 4 5"
or "A B C D E"
or *"* * * * *"*

You do not need to react to this signal – it is there to help you get ready by informing you what kind of stimulus to expect next. Please remember that ***"1 2 3 4 5"*** will usually be followed by a letter-target, and ***"A B C D E"*** will usually be followed by a digit-target.

The signal ***"* * * * *"*** indicates that the next stimulus is about to appear, but it does not provide you with any specific information about what that stimulus will be.

We ask you to pay close attention to the preceding signal, since one of the major purposes for this experiment is to assess how fast your responses are when you know in advance what type of target to expect. Remember: when you see a string of digits *"1 2 3 4 5"* expect a letter-target to follow, and when you see a string of letters *"A B C D E"* expect a digit-target to follow.

There always will be a short interval between the signal and the target. Please respond to the target as quickly as you can while keeping errors as low as possible.

After each trial (the sequence ‘ signal – target – response ‘) there will be a 1 second delay with a small cross in the center of the screen. Please focus on this fixation point while waiting for the next trial to begin.

The experiment will consist of a training part to familiarize you with the procedure, a short resting interval, and then the main part where you will have to respond as described above.

During the resting interval you will be given some additional instructions as well as an opportunity to ask questions if necessary as you prepare yourself to the rest of the experiment.

If you have any questions now, please ask the experimenter.

Start whenever you are ready by pressing either the “LEFT” or the“RIGHT” key.

XU

INSTRUCTION

(Part 2)

You have just familiarized yourself with the experimental procedure and should now be ready to begin the second part of the experiment. Your task is the same. Press the "LEFT" key in response to vowel letters and odd numbers and the "RIGHT" key in response to consonant letters and even numbers as fast as you can (but still try not to make errors).

Remember that the signal ***"1 2 3 4 5"*** is usually followed by a letter-target and the signal ***"A B C D E"*** is usually followed by a digit-target. The signal ***"* * * * *"*** does not provide any specific information about the following target but rather simply reminds you to stay focused and try to react quickly to the target.

We ask you to pay close attention to the preceding signal, since one of the major purposes for this experiment is to assess how fast your responses are when you know in advance what type of target to expect. Remember: when you see a string of digits *"1 2 3 4 5"* expect a letter-target to follow, and when you see a string of letters *"A B C D E"* expect a digit-target to follow.

On several occasions during the experiment, you will be given feedback on your performance. You will see on the screen information about how accurate (% errors) and fast (average response time) you were. Each time the information appears, please enter into the chart provided the corresponding numbers:

- % error;
- average response time.

This will help you keep track of your progress and achieve better results throughout the experiment.

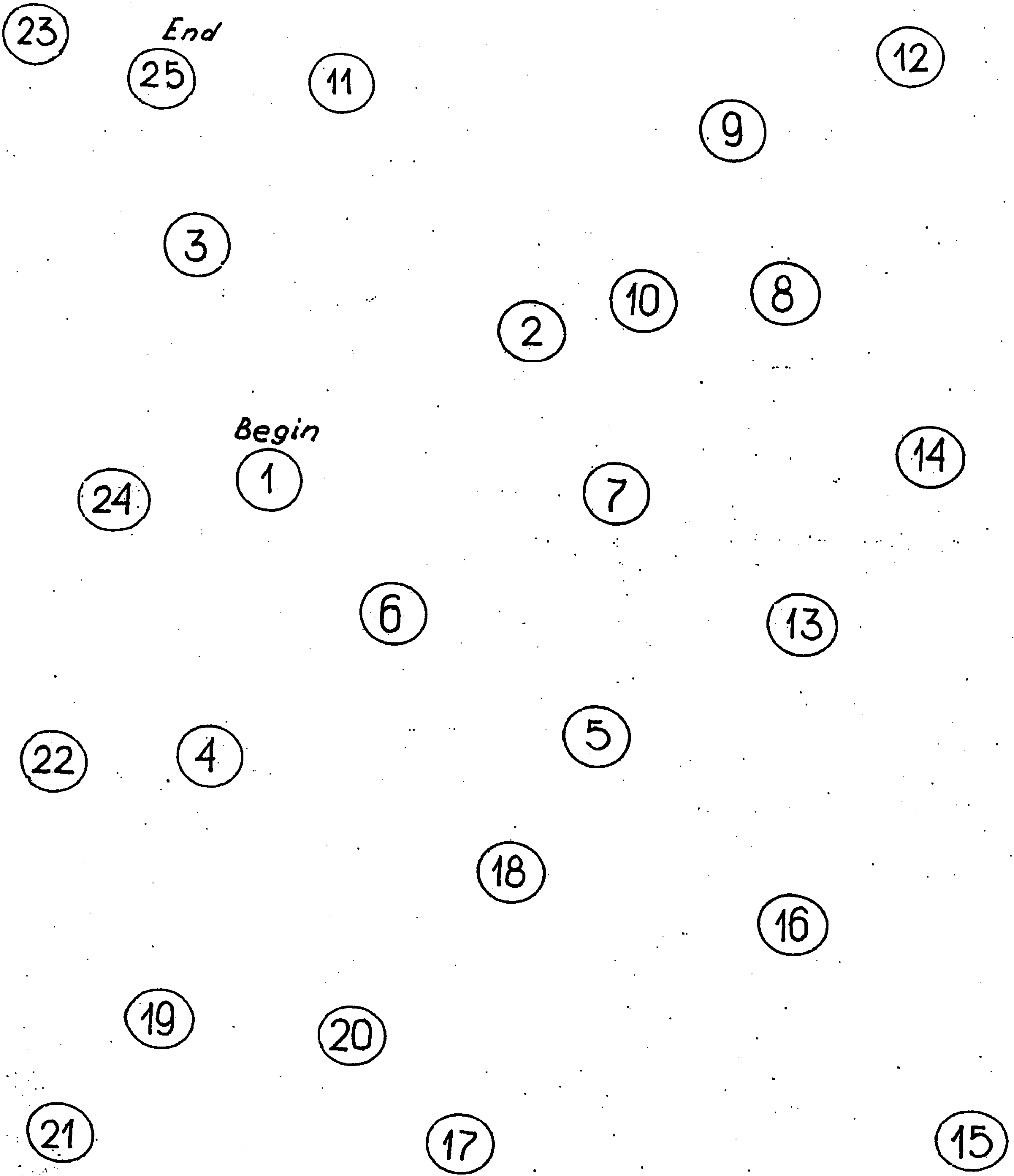
Good luck and thank you for your help.

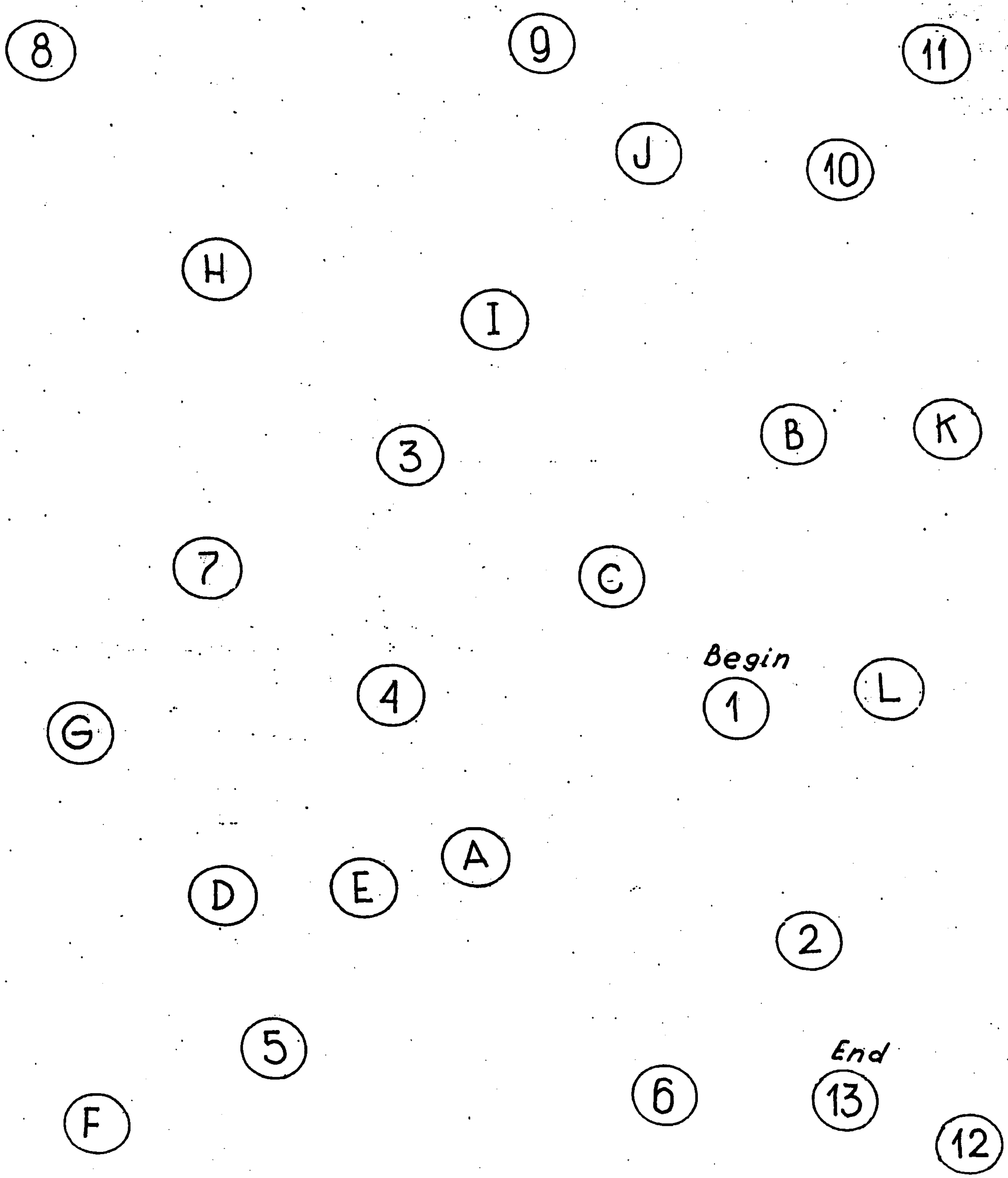
Start whenever you are ready by pressing either the "LEFT" or the "RIGHT" key.


INFORMATIVE
PRIME
12345
6
4
12345
3

APPENDIX C

Trail Making test: Forms A and B


23
End
25
11
12
9
3
10
8
2
Begin
1
14
24
7
6
13
22
4
5
18
16
19
20
21
17
15


8
9
11
J
10
H
I
B
K
3
7
C
Begin
1
L
4
G
A
E
D
2
5
End
13
6
F
12

APPENDIX D

Demographic questionnaire

PARTICIPANT QUESTIONNAIRE

Name: ____________________
Age: ____________________ Sex: M F
Field of Study: ____________________

1. Where were you born? (city, country) ____________
2. What do you consider to be your first language? English French Other______
3. What do you consider to be your second language? English French Other______
4. What language do you consider your dominant language? English French Other______
5. At what age did you learn your second language? ____________
6. What language do you speak at home now? ____________
7. What is the first language of your mother? ________ and father? ________
8. In what language did you attend school (Please circle the appropriate one):
   - Elementary school: English French Other__________
   - High school: English French Other__________
   - CEGEP: English French Other__________
   - University: English French Other__________
9. Do you have a known visual impairment that is NOT corrected by wearing glasses or contact lenses? Yes No
10. Do you have a known reading disability (e.g., dyslexia)? Yes No
11. Please rate your level of ability for each of the three skills listed below by using the following rating scheme and circling the appropriate number in the boxes below:

1 = no ability at all 2 = very little 3 = moderate 4 = very good 5 = native-like ability

Language	**Speaking**	**Reading**	**Writing**
English	1 2 3 4 5	1 2 3 4 5	1 2 3 4 5
French	1 2 3 4 5	1 2 3 4 5	1 2 3 4 5
Other	1 2 3 4 5	1 2 3 4 5	1 2 3 4 5
Other	1 2 3 4 5	1 2 3 4 5	1 2 3 4 5

12. Please fill out column 1 first. Then rate the time spent each week using each language. Use the following rating scheme and circle the appropriate number in the boxes:

1 = never/almost never 3 = four to six times/week 5 = main language used
2 = one to three times/week 4 = more than six times but less than my main language

Language	**Speaking**	**Reading**	**Writing**
First language:	1 2 3 4 5	1 2 3 4 5	1 2 3 4 5
Second language:	1 2 3 4 5	1 2 3 4 5	1 2 3 4 5
Other:	1 2 3 4 5	1 2 3 4 5	1 2 3 4 5
Other:	1 2 3 4 5	1 2 3 4 5	1 2 3 4 5

APPENDIX E

Consent form for participation in the experiment

CONSENT FORM TO PARTICIPATE IN RESEARCH

This is to state that I agree to participate in a program of research being conducted by Eugene Borokhovski of the Psychology Department at Concordia University as a requirement for completion of the Ph. D. degree, under the supervision of Professor Norman Segalowitz.

A. PURPOSE

I have been informed that the purpose of this research is to study cognitive processes underlying performance on Rapid Automatized Naming (RAN) task in its connection to reading.

B. PROCEDURES

I have been informed that this study will take place at Concordia University, in the laboratory of Dr. Segalowitz. I have been informed that the tasks I will be asked to accomplish consist of identifying stimuli, which will appear on a computer screen by responding on a keypad or orally. I will also be asked to perform several paper-and-pencil tasks. I am aware that my responses will be timed. The total testing time will be of approximately one hour.

C. CONDITIONS OF PARTICIPATION

- I understand that I may decline to participate in the experiment without negative consequences.
- I understand that I am free to withdraw my consent and discontinue my participation at any time without negative consequences.
- I understand that my participation in this study is confidential (i.e., the researcher will know but will not disclose my identity).
- I understand that the data from this study may be published or presented at a scientific conference; data will be reported in a way that protects each participant's identity
- I understand the purpose of this study and know that there is no hidden motive of which I have not been informed.
- I will be paid $20.00 upon completion of my participation.
- I understand that I may receive a copy of the final research report when the study has been completed (please allow several months) by writing to Professor Segalowitz at <norman.segalowitz@concordia.ca>.
- I may have a copy of this agreement.

I HAVE CAREFULLY STUDIED THE ABOVE AND UNDERSTAND THE AGREEMENT.
I FREELY CONSENT AND AGREE TO PARTICIPATE IN THIS STUDY.

Participant's name: (please print): ______________________
Participant's signature: ______________________
Researcher's signature: ______________________
Date: ______________, 2005.

For inquiries about this research please contact Prof. Norman Segalowitz at 514.848.2424, Psychology Department, Concordia University, Montréal (Québec) H4B 1R6. If you have any questions about your rights as a research participant you may contact Michelle Hoffman, Compliance Officer, Concordia University, at <michelle.hoffman@concordia.ca> or by calling 514.848.2424, extension 7481.

APPENDIX F

Debriefing form

DEBRIEFING

Naming speed and reading: Cognitive factors underlying performance

The "Human Performance" laboratory thanks you for your participation in this experiment on the cognitive processes that underlie naming speed in its connection to reading.

There is consistent empirical evidence that a strong reliable predictor of reading outcomes in different age groups is the ability to name aloud as fast as possible a large sequence of either symbolic (letters and numbers) or non-symbolic (colors and pictures) stimuli. This naming task is known as Rapid Automatized Naming (RAN) task. Poor readers (including those who suffer from developmental dyslexia of different types and degrees of severity) usually perform worse on the RAN task. This phenomenon is known as the "naming-speed deficit" (Wolf & Bowers, 2000). Many researchers believe that what causes the naming-speed deficit is the lack of automaticity in the underlying cognitive processes. A somewhat alternative explanation has emphasized the role of attention control in RAN performance.

The experiment you just participated in was designed to address both these hypotheses by obtaining quantitative measures of different aspects of automaticity, as well as several measures of attention. You also received a reading fluency test and several modifications of the RAN task. All these measures will be analyzed, allowing us to determine to what extent various aspects of automaticity and attention are related to RAN performance and the extent to which the RAN task relates to reading performance because of cognitive mechanisms it taps into.

Your participation in the experiment helped us to collect valuable information and it is greatly appreciated.

APPENDIX G

Bigram-based modified RAN subtasks

{12.2} {11.4} {10.8} …

p o s a s o p p a s
d a p o d s a d s s
d s a d o d a s o o
p p a s o d s a p p
d a p o d a d o o p

$\sum = 353.7$

{0.2} {1.9} {3.6} …

a o d p s p d a a p
o a d d p s s d p s
a o o a p s d o a o
s d p s d o o a p s
o s p s d p a a o d

$\sum = 114.1$

APPENDIX H

Other modified RAN subtasks:
Screen samples and an illustration of expected participants responses

a e i o u

In this part of the test you will see the letters shown above presented in several rows.

Start with the top row and name the letters starting at the left, saying the name aloud. When you reach the end of the row, press the space bar, and then continue immediately on the next row, starting again at the left. Press the space bar at the end of each row, including the last row. Do this as quickly as possible. If you make a mistake saying the name of a letter, then correct yourself immediately and continue. The experimenter will record your time as well as uncorrected mistakes.

If you have any questions, please ask them now.

Try it now with the sample presented above and press the space bar to continue.

a o e i o u e i e a
u a i u e o a u i o
o i a o a i o a u e
i e o a i e u o a i
e u i e u a i e o u

d n p s v

In this part of the test you will see the letters shown above presented in several rows.

Start with the top row and name the letters starting at the left, saying the name aloud. When you reach the end of the row, press the space bar, and then continue immediately on the next row, starting again at the left. Press the space bar at the end of each row, including the last row. Do this as quickly as possible. If you make a mistake saying the name of a letter, then correct yourself immediately and continue. The experimenter will record your time as well as uncorrected mistakes.

If you have any questions, please ask them now.

Try it now with the sample presented above and press the space bar to continue.

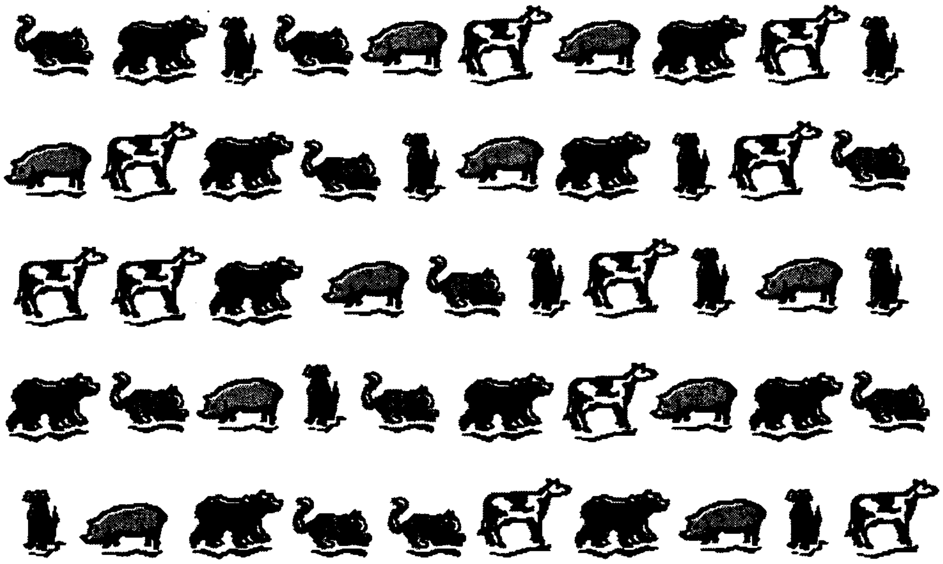
n v s p v s d p d n
s n d s d v n s p v
v p n v n p v n s d
p d v n p d s v n p
d s p d s n p d v s

In this part of the test, you will see the animals shown above presented in several rows.

Start with the top row and name the animals starting at the left, saying the name aloud. When you reach the end of the row, press the space bar, and then continue immediately on the next row, starting again at the left. Press the space bar at the end of each row, including the last row. Do this as quickly as possible. If you make a mistake saying the name of an animal, then correct yourself immediately and continue. The experimenter will record your time as well as uncorrected mistakes.

If you have any questions, please ask them now.

Try it now with the sample presented above and press the space bar to continue.

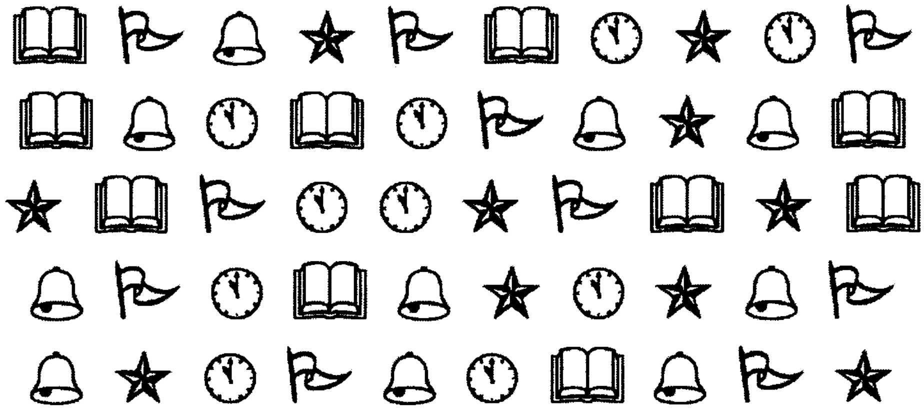


In this part of the test, you will see the objects shown above presented in several rows.

Start with the top row and name the objects starting at the left, saying the name aloud. When you reach the end of the row, press the space bar, and then continue immediately on the next row, starting again at the left. Press the space bar at the end of each row, including the last row. Do this as quickly as possible. If you make a mistake saying the name of an object, then correct yourself immediately and continue. The experimenter will record your time as well as uncorrected mistakes.

If you have any questions, please ask them now.

Try it now with the sample presented above and press the space bar to continue.



(ei) (ou) (i:) (ai) (ou) (ju:) (i:) (ai) (i:) (ei)
a o e i o u e i e a

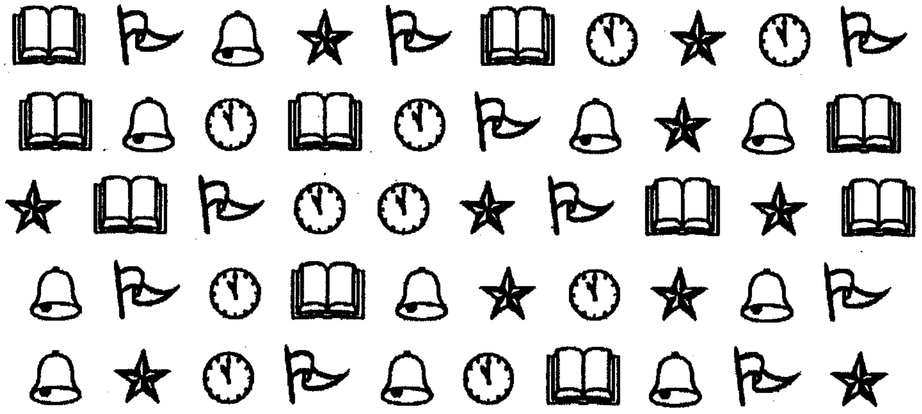
u a i u e o a u i o

o i a o a i o a u e

i e o a i e u o a i

e u i e u a i e o u

[book] [flag] [bell] [star] [flag] [book] clock star



APPENDIX I

Study 2 ANOVA summary table

Study 2. Performance on modified RAN subtasks – 2x2x2 ANOVA summary table (N=16)

Source	*df*	*F*	*MS*	η^2	*p*
Attention:					
Effect	1	62.124	1711095750	.806	< .001
Error	15		27543164.1		
Stimulus type:					
Effect	1	131.216	9288504253	.897	< .001
Error	15		70787953.4		
Source set size:					
Effect	1	1.063	22266132.8	.066	.319
Error	15		20950585.3		
Attention x Type:					
Effect	1	3.923	57467240.3	.207	.066
Error	15		4648836.6		
Attention x Size:					
Effect	1	.079	164164.5	.005	.782
Error	15		2078085.1		
Type x Size:					
Effect	1	18.973	71628480.5	.558	.001
Error	15		3775251.3		
Attention x Type x Size:					
Effect	1	3.558	52790826.5	.192	.079
Error	15		9214886.4		

APPENDIX J

Nelson-Denny test materials

COMPREHENSION TEST

PASSAGE ONE

On Christmas Eve in 1795, the horses stabled at the Swan and Hoop in London crunched their holiday oats and rubbed their noses on the worn mangers, while in the rooms above a mother held her first-born child, John Keats, to the lamplight and called the boy's father to see him smile—"smiling at seven weeks!" But little John Keats soon grew into a hot-tempered, irrepressible, and wilful child. Perhaps he was spoiled, for his mother, whom he greatly resembled, adored him. She was passionate, gay, and vivacious, and John inherited her disposition, but in a finer way.

Thomas Keats was head hostler of the Swan and Hoop. He was ambitious to get along in the world, and his common sense and competence were so noteworthy that Mr. Jennings, his father-in-law, left the business to him. The new owner prospered. John was packed off to school at Enfield, a little town about ten miles from London.

Thomas Keats came to a sudden end, falling from his horse and fracturing his skull. Mrs. Keats found herself helpless. Within a year she married a Mr. Rawlings. The marriage was unhappy, and Mrs. Rawlings left both the new husband and the livery stable, and with her children, who were now four—George, Tom, and Fanny had been born by that time—went to her mother's home.

At school, John was no prodigy in his studies, but he was a terror with his fists. His schoolfellows declared that "fighting was meat and drink to him" and that he had "a terrier-like resoluteness." He seemed destined to be anything but a poet. He would keep the boys pop-eyed with tall tales of a soldier-uncle on his mother's side of the family who was his hero. Or he would go for the usher who had boxed his brother Tom's ears. Of a keenly affectionate and morbidly sensitive disposition, he would often work himself sick with unfounded suspicions of his companions. They have testified that he was "always in extremes," now violent, now generous, "in passions of tears or outrageous fits of laughter." They liked the lad and admired his fiery pluck.

As for his mother, she idolized him, as he did her. When he came home for the holidays, she fell under the spell of his alternating moods of poetic depression and prankish merriment. And once, we hear, when Mrs. Keats was ill and quiet had been ordered, John found an old sword and, mounting guard in front of her door, would permit no one to pass!

Imagine, then, how a boy of fifteen, passionate in all things, susceptible beyond most to suffering, afflicted, in his own words, with "a horrid morbidity of temperament"—imagine how such a boy would recoil from the shock of death. We can understand what happened to Keats when, in 1810, his mother died. If he became more moody than ever, if he sulked and was inconsolable, hiding in a corner under the teacher's desk and spurning all comfort from teacher or friend, we can understand. And we can understand all the more why, having suddenly and passionately discovered literature two years before, he should now turn in his despair ~~to the~~ glory and the forgetfulness that books could give. He read as intensely as he had fought and brooded. He translated Virgil's Aeneid. He dipped into Shakespeare. Most important of all, he found out a way to the golden myths of Greece through certain anthologies in the school library. Gods, nymphs, and heroes took fire in him! If ever anybody was doomed to be a poet and all poet, it was John Keats.

END OF READING SELECTION ONE. NOW ANSWER QUESTIONS 1 THROUGH 8.

1. How old was Keats when his mother died?
   - A. twelve
   - B. thirteen
   - C. fourteen
   - D. fifteen
   - E. sixteen

2. At school Keats was said to be
   - F. average.
   - G. a good student.
   - H. a daydreamer.
   - I. at the bottom of his class.
   - J. no prodigy.

3. Keats was said to have had a terrier-like
   - A. stubbornness.
   - B. resoluteness.
   - C. resistance.
   - D. toughness.
   - E. courage.

4. As a youth, John Keats translated
   - F. Virgil.
   - G. Homer.
   - H. Aristotle.
   - I. Plato.
   - J. Horace.

5. Apparently Keats's most influential reading was in
   - A. Latin literature.
   - B. English literature.
   - C. Greek literature.
   - D. fiction.
   - E. poetry.

6. What word best describes Keats's character?
   - F. intense
   - G. earnest
   - H. merry
   - I. depressed
   - J. sulky

7. On what basis is the material in this passage arranged?
   - A. from general to specific
   - B. from most to least important
   - C. in cause-effect order
   - D. in time sequence order
   - E. from the ordinary to the unusual

8. After his mother's death, Keats read largely for
   - F. guidance.
   - G. inspiration.
   - H. information.
   - I. escape.
   - J. practical help.

GO ON▼

PASSAGE ONE

We know very little of the person who was said to have written the Iliad and the Odyssey. 009
His name was Homer. The Greeks tell us that he was blind and that, as he got old, he 027
wandered about reciting his verses and getting food and shelter where he could. After he was 044
dead, those who had paid little attention to him realized the power and beauty of what he had 062
written. 072

The Iliad and the Odyssey were very important in the life of the Greeks. They were more 080
to the Greeks than any poems we know are to us. They were recited by people trained to recite 100
them, and audiences listened to them as they would to plays or music today. Often the 116
rhapsodists, as the reciters of Homer were called, performed before twenty thousand people 132
or more. 139

To some extent, these poems were like the Bible. In the Iliad and the Odyssey, written a 147
little while before the Jews were beginning to set down the Bible, Homer had described how 164
brave and wise people behaved. He had written beautiful prayers to the gods of the Greeks. 180
He had described how courteous men and women treated their friends and the strangers who 196
came to them. 206

Also he showed, in the way he wrote the poems, how to say things simply, yet with words 216
that clashed like shields or flowed like slow music. His poems seldom waste language. They 233
say directly what they have to say. Yet they manage to say it so well that we cannot forget it. 249
Some poets get started making poetry and make too much of it. Homer rarely did this. He 267
knew when to say little and when to say much. The Greeks saw how fine a thing it was to do 286
this. "Measure [moderation] is best in all things," was their idea of conduct. These are the 305
words Homer had put into the mouth of Menelaus, and if he was not the first to bring this 322
sense of proportion to the Greeks, he was foremost among those who helped them to praise 341
and to practice it. And we today, often dashing about with very little idea of moderation, still 357
pause to listen to Homer's words, to talk about them and try to follow them. 374

The Iliad and the Odyssey are called epics. An epic is a poem about great events in the life 388
of a people. The poets of many countries have written epics, but Homer's are generally 408
acknowledged to be the greatest of all. We still come from reading them full of their spirit of 423
bravery, their wisdom, their beauty. 437

More than that, we still use Homer. We write stories and poems better because of these 446
first great poetic stories, which have influenced the narrative poetry of the world ever since 460
they were made. Certainly we think and write about the people he made for us. Perhaps Helen 477
never lived until Homer put her into his verse, but ever since he did so poets have written 494
about her. The Greek ideal of beauty in women still lingers on today in the name Helen of 512
Troy. 522

Life now is not the life Homer knew. In Homer's time people brought water to the house 532
in skins and jars; when we want it we turn on a faucet. Homer's kings rode fierce horses, or 550
jolting chariots without springs; we go in soft-tired automobiles. Then people had only 566
torches for light; we use electricity. There were only rude fireplaces in Homer's time; we 579
have stoves and furnaces. Gods, clothes, speech, music—all are different. Yet we read the 593
poetry that Homer made for his world and find it still useful in ours. 610

END OF READING SELECTION ONE. NOW ANSWER QUESTIONS 1 THROUGH 8.

COMPREHENSION TEST (CONT.)

1. The audience size mentioned was
   - A. five thousand.
   - B. eight thousand.
   - C. twelve thousand.
   - D. sixteen thousand.
   - E. twenty thousand.

2. The reciters of Homer were called
   - F. narrators.
   - G. chanters.
   - H. minstrels.
   - I. rhapsodists.
   - J. interpreters.

3. Who said "Measure is best in all things"?
   - A. Paris
   - B. Menelaus
   - C. Priam
   - D. Odysseus
   - E. Hector

4. Homer was said to know how to say things
   - F. dramatically.
   - G. ironically.
   - H. simply.
   - I. graciously.
   - J. fancifully.

5. The attitude expressed toward Homer's poems is best described as
   - A. undecided.
   - B. critical.
   - C. positive.
   - D. objective.
   - E. accepting.

6. What does the second paragraph emphasize about Homer's poems?
   - F. their artistic excellence
   - G. Homer, the author
   - H. their novelty
   - I. their importance
   - J. their humanness

7. Points were clarified most frequently by
   - A. relating past to present.
   - B. using a story form.
   - C. describing actions.
   - D. listing details.
   - E. quoting authorities.

8. Points in this passage were developed primarily by
   - F. concrete illustrations.
   - G. appeal to emotions.
   - H. logical reasoning.
   - I. use of anecdotes.
   - J. cause-effect connections.

GO ON ▼

APPENDIX K

Ruff 2&7 test materials

7	G	O	2	A	F	2	B	2	7	A	C	I	J	H	A	J	D	C	2	A	B	G	E	7	E	D	B	2	H	J	C	J	B	A	F	E	J	H	7	A	B	C	I	F	7	D	J	A	E
J	C	A	F	7	H	J	B	2	H	C	B	I	F	G	H	7	7	J	A	C	E	F	2	H	G	I	E	E	2	J	7	A	J	I	E	2	A	7	I	E	D	H	D	E	F	D	2	B	G
A	2	B	C	D	E	F	G	H	I	7	2	J	I	H	G	E	D	B	2	A	C	B	D	F	E	I	7	J	B	C	D	E	F	G	2	I	J	I	G	7	2	7	H	E	F	F	A	7	D
2	J	I	H	2	G	E	D	7	F	B	C	A	A	C	B	D	E	F	G	H	7	I	7	J	F	G	E	E	C	2	B	A	C	7	E	D	F	D	J	I	7	F	2	A	B	C	D	G	2
B	7	C	D	A	2	I	7	F	H	G	E	D	2	E	C	B	D	A	H	J	I	E	H	7	A	2	B	C	D	E	F	G	H	I	J	H	B	2	C	D	A	E	D	F	2	7	E	7	A
7	A	C	2	B	D	E	F	7	G	2	2	J	I	B	D	C	A	7	H	I	J	C	B	D	A	E	D	E	2	J	I	E	E	A	7	C	D	B	7	F	E	F	G	D	A	J	2	C	B
1	3	4	2	5	7	6	2	0	9	8	9	0	1	3	7	4	5	4	6	8	9	0	1	3	2	1	5	4	0	9	5	8	7	1	3	5	4	6	7	9	0	0	8	2	6	1	3	2	7
7	1	2	3	7	5	4	6	2	8	9	1	0	9	8	6	5	4	5	6	2	1	3	4	3	5	4	0	9	7	8	6	4	3	1	0	9	8	6	5	8	2	7	9	0	7	1	2	0	4
0	7	1	3	4	5	6	2	8	9	0	9	8	6	0	2	2	9	6	5	4	3	1	7	4	5	3	2	1	0	9	6	5	8	5	7	6	4	7	3	1	1	3	0	4	5	2	1	7	8
9	8	7	0	7	2	1	3	4	5	6	8	9	0	2	1	3	4	5	6	8	9	0	9	8	7	6	2	5	4	3	1	1	3	5	9	8	0	8	6	7	8	4	2	6	7	5	5	0	2
2	4	0	2	6	8	7	9	1	3	5	7	5	4	3	1	1	0	8	9	2	9	8	6	5	4	3	4	5	7	7	8	5	1	3	5	2	4	0	0	8	9	1	2	3	1	6	5	7	8
8	9	7	0	2	1	3	4	7	5	6	8	9	0	9	0	2	1	3	7	6	4	5	8	6	2	0	1	7	3	5	4	6	8	0	9	9	2	1	3	1	5	7	6	4	5	3	2	0	9
2	0	7	3	4	5	6	7	8	9	0	2	1	2	0	8	9	8	6	5	7	4	5	3	1	4	5	8	5	2	9	9	0	8	6	0	1	3	5	4	7	2	6	8	0	1	7	1	8	3
4	7	5	3	1	2	2	6	8	7	9	8	0	1	3	5	2	4	7	6	5	4	3	1	0	8	0	1	3	4	5	6	2	8	9	6	0	8	7	1	3	5	4	6	2	4	3	1	7	0
6	7	8	2	9	0	9	8	6	5	4	3	7	1	0	2	3	4	5	4	5	6	6	7	8	0	9	9	1	0	2	6	8	0	3	3	7	1	2	4	6	8	9	5	3	7	0	2	1	5
7	A	C	2	B	D	E	F	7	G	2	2	J	I	B	D	C	A	7	H	I	J	C	B	D	A	E	D	E	2	J	I	E	E	A	7	C	D	B	7	F	E	F	G	D	A	J	2	C	B
A	2	B	C	D	E	F	G	H	I	7	2	J	I	H	G	E	D	B	2	A	C	B	D	F	E	I	7	J	B	C	D	E	F	G	2	I	J	I	G	7	2	7	H	E	F	F	A	7	D
J	C	A	F	7	H	J	B	2	H	C	B	I	F	G	H	7	7	J	A	C	E	F	2	H	G	I	E	E	2	J	7	A	J	I	E	2	A	7	I	E	D	H	D	E	F	D	2	B	G
2	0	7	3	4	5	6	7	8	9	0	2	1	2	0	8	9	8	6	5	7	4	5	3	1	4	5	8	5	2	9	9	0	8	6	0	1	3	5	4	7	2	6	8	0	1	7	1	8	3
7	1	2	3	7	5	4	6	2	8	9	1	0	9	8	6	5	4	5	6	2	1	3	4	3	5	4	0	9	7	8	6	4	3	1	0	9	8	6	5	8	2	7	9	0	7	1	2	0	4
4	7	5	3	1	2	2	6	8	7	9	8	0	1	3	5	2	4	7	6	5	4	3	1	0	8	0	1	3	4	5	6	2	8	9	6	0	8	7	1	3	5	4	6	2	4	3	1	7	0
J	C	A	F	7	H	J	B	2	H	C	B	I	F	G	H	7	7	J	A	C	E	F	2	H	G	I	E	E	2	J	7	A	J	I	E	2	A	7	I	E	D	H	D	E	F	D	2	B	G
7	G	O	2	A	F	2	B	2	7	A	C	I	J	H	A	J	D	C	2	A	B	G	E	7	E	D	B	2	H	J	C	J	B	A	F	E	J	H	7	A	B	C	I	F	7	D	J	A	E
B	7	C	D	A	2	I	7	F	H	G	E	D	2	E	C	B	D	A	H	J	I	E	H	7	A	2	B	C	D	E	F	G	H	I	J	H	B	2	C	D	A	E	D	F	2	7	E	7	A
1	3	4	2	5	7	6	2	0	9	8	9	0	1	3	7	4	5	4	6	8	9	0	1	3	2	1	5	4	0	9	5	8	7	1	3	5	4	6	7	9	0	0	8	2	6	1	3	2	7
6	7	8	2	9	0	9	8	6	5	4	3	7	1	0	2	3	4	5	4	5	6	6	7	8	0	9	9	1	0	2	6	8	0	3	3	7	1	2	4	6	8	9	5	3	7	0	2	1	5
9	8	7	0	7	2	1	3	4	5	6	8	9	0	2	1	3	4	5	6	8	9	0	9	8	7	6	2	5	4	3	1	1	3	5	9	8	0	8	6	7	8	4	2	6	7	5	5	0	2
J	H	I	7	B	D	2	A	C	2	E	I	J	B	D	F	E	7	7	F	I	E	A	C	B	D	A	C	2	E	E	F	7	J	I	A	B	C	2	D	E	F	G	H	I	J	I	2	7	H
A	2	C	D	7	B	A	E	F	G	H	A	D	2	I	7	J	B	A	D	E	F	2	2	B	C	E	G	H	J	I	A	E	B	G	D	F	7	E	I	7	I	D	B	2	A	C	D	F	7
7	A	B	2	D	C	H	7	F	E	G	J	2	I	A	E	F	B	C	D	2	A	7	D	F	E	G	E	I	7	J	B	A	C	D	2	E	F	G	H	J	I	A	F	E	7	2	B	G	A

G	H	O	B	A	F	B	F	B	G	A	C	I	J	H	A	J	D	C	B	A	F	E	E	G	E	D	C	B	H	J	C	J	A	A	F	E	J	H	G	A	D	C	I	F	G	D	J	A	E
J	C	A	F	G	H	J	A	B	H	C	D	I	F	A	H	G	G	J	A	C	E	F	B	H	C	I	E	E	B	J	G	A	J	I	E	B	A	G	I	E	D	H	D	E	F	D	B	J	H
A	B	E	C	D	E	F	C	H	I	G	B	J	I	H	A	E	D	C	B	A	C	J	D	F	E	I	G	J	I	C	D	E	F	F	B	I	J	I	J	G	B	G	H	E	F	F	A	G	D
B	J	I	H	B	A	E	D	G	F	A	C	A	A	C	F	D	E	F	J	H	G	I	G	J	F	D	E	E	C	B	E	A	C	G	E	D	F	D	J	I	G	F	B	A	H	C	D	F	B
A	G	C	D	A	B	I	G	F	H	F	E	D	B	E	C	F	D	A	H	J	I	E	H	G	A	B	J	C	D	E	F	A	H	I	J	H	E	B	C	D	A	E	D	F	B	G	E	G	A
G	A	C	B	I	D	E	F	G	I	B	B	J	I	A	D	C	A	G	H	I	J	C	E	D	A	E	D	E	B	J	I	E	E	A	G	C	D	A	G	C	E	F	J	D	A	J	B	C	H
1	3	4	B	5	G	6	B	0	9	8	9	0	1	3	G	4	5	4	6	8	9	0	1	3	B	1	5	4	0	9	5	8	G	1	3	5	4	6	G	9	0	0	8	B	6	1	3	B	G
G	1	B	3	G	5	4	6	B	8	9	1	0	9	8	6	5	4	5	6	B	1	3	4	3	5	4	0	9	G	8	6	4	3	1	0	9	8	6	5	8	B	G	9	0	G	1	B	0	4
0	G	1	3	4	5	6	B	8	9	0	9	8	6	0	B	B	9	6	5	4	3	1	G	4	5	3	B	1	0	9	6	5	8	5	G	6	4	G	3	1	1	3	0	4	5	B	1	G	8
9	8	G	0	G	B	1	3	4	5	6	8	9	0	B	1	3	4	5	6	8	9	0	9	8	G	6	B	5	4	3	1	1	3	5	9	8	0	8	6	G	8	4	B	6	G	5	5	0	B
B	4	0	B	6	8	G	9	1	3	5	G	5	4	3	1	1	0	8	9	B	9	8	6	5	4	3	4	5	G	G	8	5	1	3	5	B	4	0	0	8	9	1	B	3	1	6	5	G	8
8	9	G	0	B	1	3	4	G	5	6	8	9	0	9	0	B	1	3	G	6	4	5	8	6	B	0	1	G	3	5	4	6	8	0	9	9	B	1	3	1	5	G	6	4	5	3	B	0	9
B	0	G	3	4	5	6	G	8	9	0	B	1	B	0	8	9	8	6	5	G	4	5	3	1	4	5	8	5	B	9	9	0	8	6	0	1	3	5	4	G	B	6	8	0	1	G	1	8	3
4	G	5	3	1	B	B	6	8	G	9	8	0	1	3	5	B	4	G	6	5	4	3	1	0	8	0	1	3	4	5	6	B	8	9	6	0	8	G	1	3	5	4	6	B	4	3	1	G	0
6	G	8	B	9	0	9	8	6	5	4	3	G	1	0	B	3	4	5	4	5	6	6	G	8	0	9	9	1	0	B	6	8	0	3	3	G	1	B	4	6	8	9	5	3	G	0	B	1	5
G	A	C	B	I	D	E	F	G	I	B	B	J	I	A	D	C	A	G	H	I	J	C	E	D	A	E	D	E	B	J	I	E	E	A	G	C	D	A	G	C	E	F	J	D	A	J	B	C	H
A	G	C	D	A	B	I	G	F	H	F	E	D	B	E	C	F	D	A	H	J	I	E	H	G	A	B	J	C	D	E	F	A	H	I	J	H	E	B	C	D	A	E	D	F	B	G	E	G	A
G	H	O	B	A	F	B	F	B	G	A	C	I	J	H	A	J	D	C	B	A	F	E	E	G	E	D	C	B	H	J	C	J	A	A	F	E	J	H	G	A	D	C	I	F	G	D	J	A	E
1	3	4	B	5	G	6	B	0	9	8	9	0	1	3	G	4	5	4	6	8	9	0	1	3	B	1	5	4	0	9	5	8	G	1	3	5	4	6	G	9	0	0	8	B	6	1	3	B	G
0	G	1	3	4	5	6	B	8	9	0	9	8	6	0	B	B	9	6	5	4	3	1	G	4	5	3	B	1	0	9	6	5	8	5	G	6	4	G	3	1	1	3	0	4	5	B	1	G	8
4	G	5	3	1	B	B	6	8	G	9	8	0	1	3	5	B	4	G	6	5	4	3	1	0	8	0	1	3	4	5	6	B	8	9	6	0	8	G	1	3	5	4	6	B	4	3	1	G	0
J	C	A	F	G	H	J	E	B	H	C	E	I	F	F	H	G	G	J	A	C	E	F	B	H	F	I	E	E	B	J	G	A	J	I	E	B	A	G	I	E	D	H	D	E	F	D	B	E	F
G	F	O	B	A	F	B	E	B	G	A	C	I	J	H	A	J	D	C	B	A	E	F	E	G	E	D	E	B	H	J	C	J	E	A	F	E	J	H	G	A	E	C	I	F	G	D	J	A	E
E	G	C	D	A	B	I	G	F	H	F	E	D	B	E	C	E	D	A	H	J	I	E	H	G	A	B	E	C	D	E	F	F	H	I	J	H	E	B	C	D	A	E	D	F	B	G	E	G	A
1	3	4	B	5	G	6	B	0	9	8	9	0	1	3	G	4	5	4	6	8	9	0	1	3	B	1	5	4	0	9	5	8	G	1	3	5	4	6	G	9	0	0	8	B	6	1	3	B	G
6	G	8	B	9	0	9	8	6	5	4	3	G	1	0	B	3	4	5	4	5	6	6	G	8	0	9	9	1	0	B	6	8	0	3	3	G	1	B	4	6	8	9	5	3	G	0	B	1	5
9	8	G	0	G	B	1	3	4	5	6	8	9	0	B	1	3	4	5	6	8	9	0	9	8	G	6	B	5	4	3	1	1	3	5	9	8	0	8	6	G	8	4	B	6	G	5	5	0	B
J	H	I	G	J	D	B	A	C	B	E	I	J	J	D	F	E	G	G	F	I	E	A	C	J	D	A	C	B	E	E	F	G	J	I	A	J	C	B	D	E	F	D	H	I	J	I	B	G	H
A	B	C	D	G	J	A	E	F	D	H	A	D	B	I	G	J	J	A	D	E	F	B	B	J	C	E	D	H	J	I	A	E	J	D	D	F	G	E	I	G	I	D	J	B	A	C	D	F	G
G	A	J	B	D	C	H	G	F	E	D	J	B	I	A	E	F	J	C	D	B	A	G	D	F	E	D	E	I	G	J	J	A	C	D	B	E	F	D	H	J	I	A	F	E	G	B	J	D	A

APPENDIX L

Working memory test materials

8. Letter–Number Sequencing

Item/Trial		(Correct Response)/Response	Score 0 or 1
1.	Trial 1	L – 2 (2 – L)	
	Trial 2	6 – P (6 – P)	
	Trial 3	B – 5 (5 – B)	
2.	Trial 4	F – 7 – L (7 – F – L)	
	Trial 5	R – 4 – D (4 – D – R)	
	Trial 6	H – 1 – 8 (1 – 8 – H)	
3.	Trial 7	T – 9 – A – 3 (3 – 9 – A – T)	
	Trial 8	V – 1 – J – 5 (1 – 5 – J – V)	
	Trial 9	7 – N – 4 – L (4 – 7 – L – N)	
4.	Trial 10	8 – D – 6 – G – 1 (1 – 6 – 8 – D – G)	
	Trial 11	K – 2 – C – 7 – S (2 – 7 – C – K – S)	
	Trial 12	5 – P – 3 – Y – 9 (3 – 5 – 9 – P – Y)	
5.	Trial 13	M – 4 – E – 7 – Q – 2 (2 – 4 – 7 – E – M – Q)	
	Trial 14	W – 8 – H – 5 – F – 3 (3 – 5 – 8 – F – H – W)	
	Trial 15	6 – G – 9 – A – 2 – S (2 – 6 – 9 – A – G – S)	
6.	Trial 16	R – 3 – B – 4 – Z – 1 – C (1 – 3 – 4 – B – C – R – Z)	
	Trial 17	5 – T – 9 – J – 2 – X – 7 (2 – 5 – 7 – 9 – J – T – X)	
	Trial 18	E – 1 – H – 8 – R – 4 – D (1 – 4 – 8 – D – E – H – R)	
7.	Trial 19	5 – H – 9 – S – 2 – N – 6 – A (2 – 5 – 6 – 9 – A – H – N – S)	
	Trial 20	D – 1 – R – 9 – B – 4 – K – 3 (1 – 3 – 4 – 9 – B – D – K – R)	
	Trial 21	7 – M – 2 – T – 6 – F – 1 – Z (1 – 2 – 6 – 7 – F – M – T – Z)	

APPENDIX M

Study 3 ANOVA summary table

Study 3. Performance on modified RAN subtasks – 2x2x2 ANOVA summary table (N=96)

Source	*df*	*F*	*MS*	η^2	*p*
Attention:					
Effect	1	246.944	6628022289	.722	< .001
Error	95		26840134.7		
Stimulus type:					
Effect	1	910.722	5445000000	.906	< .001
Error	95		69782870.6		
Source set size:					
Effect	1	1.298	21213502.1	.013	.257
Error	95		6341085.5		
Attention x Type:					
Effect	1	23.696	262641633.3	.200	< .001
Error	95		1083842.2		
Attention x Size:					
Effect	1	.341	2794881.4	.004	.560
Error	95		8185497.3		
Type x Size:					
Effect	1	27.544	453848475.3	.225	< .001
Error	95		6477196.9		
Attention x Type x Size:					
Effect	1	11.137	109124914.1	.105	.001
Error	95		9798119.2		