Implicit and Explicit Learning of Abstract Rules

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Abstract

Implicit and Explicit Learning of Abstract Rules

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In everyday life, there is considerable need for rule learning. Behavioral and human brain imaging studies have explored the psychological processes through which people abstract rules. The aim of this study was to investigate implicit and explicit learning and transfer in a biconditional grammar using three types of training conditions: memorization versus two versions of hypothesis-testing. After training, all participants performed the same three classification tasks: Task 1: categorizing strings made of the same set of letters and rules as in training; Task 2: different set of letters and same rules and Task 3: different set of letters and rules. Results comparing performance on the three tasks showed that participants trained in the new version of the hypothesis-testing condition performed better on all three tasks. On Tasks 1 and 2, participants made use of patterns within the strings that were related to the general rule, called secondary rules. Use of secondary rules explained a large proportion of the variance in all three groups of participants. Only the new Hypothesis-testing group showed the same pattern of endorsement in both Tasks 1 and 2, indicating transfer of learning. Participants were making use of secondary rules in an earlier stage, until they learn the most general rule. If this process is continuum, in the first step, participants recognize and endorse all types of secondary rules; in the second step, they only endorse those that do not violate another type of secondary rule; on the final step, they are able to state the most general rule of the grammar.

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Implicit and Explicit Learning of Abstract Rules

In everyday life, there is considerable need for rule learning. In order to learn a set of rules, people need to be able to abstract principles from specific examples in a variety of contexts. In other words, they need to integrate memory for specific events with the memory for general aspects of those events. The ability to abstract information from specific experiences is an important component of higher cognition because it allows people to develop general concepts and principles. Research has demonstrated that the memory for specific events and memory for general properties of objects and events are based on separate psychological and neurological systems (for a review, see Polster et al., 1991).

Squire (1992, 1995) distinguished declarative and nondeclarative memories. The first refers to memory for specific situations, and is thought to depend on hippocampal and diencephalic brain systems (Squire, 1992). Nondeclarative memory refers to memory for general properties of events and objects, and it appears to be independent of hippocampal and diencephalic brain systems. Patients with global anterograde amnesia are able to show nondeclarative memory when assessed through judgments of strings of letters from Artificial Grammars (Knowlton 1994; Nissen and Bullemer, 1987; Nissen, Willingham and Hartman, 1989; Reber and Squire, 1992), but the exact neural substrate of this process is still unknown (Skosnik et al., 2002). When healthy participants make use of nondeclarative memory on such tasks, they are unable to state explicitly the knowledge they have acquired and demonstrate learning only by performing better than chance. Because of the lack of awareness, this kind of learning has been referred to as implicit, in opposition to situations in which participants are aware of the knowledge or skill acquired, referred to as explicit learning.

In an influential study, Reber (1967) proposed that people are able to abstract rules through simple exposure to exemplars of a specific category, supporting the idea that implicit learning mechanisms are sufficient to abstract rules. This study made use of an artificial grammar (AG) to study the processes involved in the abstraction of rules. An AG consists of a set of rules governing the concatenation of letters. Depending on the complexity of the rules, people are more or less likely to learn them explicitly. A traditional AG is built under very complex rules (see Figure 1) and, therefore, participants do not usually learn them explicitly. In a typical AG, participants are exposed to strings of letters during a learning period and then asked to judge as correct or incorrect new strings built under the same set of rules (Reber, 1967, 1989). However, it has been argued that abstract rule learning, when assessed with this type of artificial grammar, can be equally well explained in terms of categorization based on superficial similarity, either between whole exemplars (similarity between the training and test strings) or between exemplar parts (all strings begin by the same two or three letters) (Nosofsky, 1986; Perruchet, 1990). For example, if all the strings shown in training start with MV, VM or MX, one can judge the string MVXXV as correct based on the knowledge of an abstract rule (M can be followed by V or X, etc.) or simply by judging based on structural similarity to the training strings (the presence of MX, MV, VM). So, instead of measuring abstract learning, the performance on this type of AG may be more related to non-abstract learning.

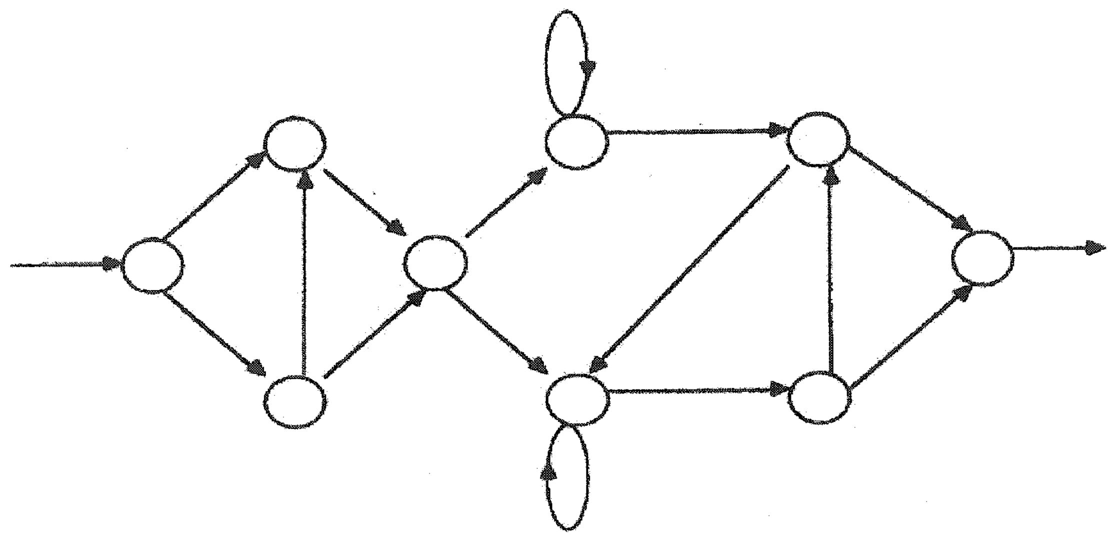

Figure 1: Traditional Artificial Grammar. Each circle represents a letter. Strings are formed by starting with the arrow from the left and ending when the arrow leading out to the right is reached. When there is a circular arrow, it means that there can be a repetition of this letter in the string.

Neuroimaging studies support the idea that different brain systems may be involved in the expression of explicit versus implicit knowledge of abstract rules in AG. Seger et al. (2000) used functional magnetic resonance imaging (fMRI) to investigate the neural substrates of retrieval of implicit and explicit knowledge about letter strings generated from a traditional AG. In the learning phase, participants were asked to memorize the strings. In the retrieval phase, there were two different conditions: in the implicit condition, participants judged whether the strings were grammatical or ungrammatical and, in the explicit condition, participants simply judged whether or not they recognized a series of new and old strings. Recognition (the explicit condition) activated the right frontal lobe (inferior frontal gyrus), which is a region that has been associated with explicit memory processing. Correct grammatical judgements (the implicit condition) activated the left dorsolateral prefrontal cortex, associated with abstraction, and left and right occipitoparietal cortexes.

Fletcher et al (1999) described similar results. They used fMRI to investigate the regions involved in learning of a traditional AG. The difference between the task used in this study and the usual AG is that a learning paradigm was used where participants received trial-by-trial feedback. There were six blocks of training in total and each block used different strings. Within blocks, strings were repeated; the authors argued that participants in this situation would make grammaticality judgments based on recognition. Between blocks, strings were changed, so that at the beginning of each block the strings were novel; the authors argued that, in this situation, participants would make grammatical judgments on the basis of abstracted patterns or rules. Performance showed a linear improvement within block and across blocks. The same region associated with memory retrieval (right prefrontal cortex) was active within blocks, when judgments were based mostly on recognition. The left prefrontal cortex was active across the beginning of blocks, when judgments were based mostly on abstracted information, which was acquired implicitly.

These two studies have examined one aspect of AG learning: explicit versus implicit retrieval of rule information. Another important aspect of AG learning that has been less well studied is explicit versus implicit learning. I will now present two studies that analyzed the performance and brain activity of participants who learned a set of rules in two different training conditions: implicit and explicit. In contrast to experiments where the retrieval tasks are different, when participants have different modes of learning and the same retrieval tasks the hypothesis is that effects of retrieval mechanisms are isolated and that any differences, behavioral or brain activity related, are due to differences in the kind of information learned during training. Training promotes implicit learning when participants are not aware of the existence of hidden rules, and are told to memorize the strings of letters, for example (Reber, 1967). Training promotes explicit learning when participants are encouraged to work out the hidden rules of the stimuli (Reber, 1993; Gomez, 1997; Frensch, 1998; Shanks, 2001).

Reber et al (2003) used a visual category task (which involves learning of abstract patterns, similar to an AG) to explore brain activity of healthy participants during a categorization test. They compared fMRI data acquired during classification of category members and nonmembers. Participants who did not know about the existence of a set of abstract rules (implicit condition) showed decreased activity in visual cortex for novel categorical stimuli compared with noncategorical stimuli. Participants who knew about the existence of abstract rules (explicit condition) showed increased activity in the hippocampus, right prefrontal cortex, left inferior temporal cortex, precuneus, and posterior cingulate when judging novel categorical stimuli compared to when they were judging non-categorical stimuli. Their results support the idea that two separates sets of processes occur depending on whether the knowledge of the category was acquired incidentally or intentionally.

Johnstone et al. (2001) used a novel type of AG proposed by Shanks (1994) called biconditional grammar to analyze the effect of training mode on the expression of knowledge of abstract rules. This paradigm offers advantages over the traditional AG because it controls for similarity between training and testing strings and it allows participants to gain explicit knowledge of the rules, because they are not as complex as those underlying a traditional AG. In the biconditional grammar (see Figure 2), strings are constructed with 6 letters distributed in 8 positions, four on either side of a dot. The letters form 3 pairs with each letter of the pair appearing on one side of the dot in fixed positions (1 and 5, 2 and 6 and so on). For example, a correct string, using the pairs FD, KX and LG, would be FXLK.DKGX. Most importantly, all letters appear with the same frequency in all positions and, consequently, the judgment cannot be made with success based on the concrete features of the strings alone. In this experiment, there were two training conditions. In the hypothesis testing condition, participants judged whether each letter of the string conformed to the rules, which they were not told explicitly. In the memory condition, participants were told to memorize the strings and were given a forced choice recognition test for each trial. During the test phase, all participants were asked to classify a set of new strings as grammatical or ungrammatical. Their results showed that participants trained in the memory condition, which promoted implicit learning of the rules, were not able to abstract the rules, and only recognized those strings that were most similar to the trainings strings. In contrast, participants in the hypothesis-testing condition, which promoted explicit learning of the rules, could classify the strings at near perfect levels, classifying correctly even those strings that were most dissimilar to those from training. Participants who could explicitly describe the rules showed the best performance. However, the two training conditions were not very comparable, since participants in the hypothesis-testing condition had a longer exposure to the stimuli.

The main objective of the present study was to analyze differences in expression of knowledge about abstract rules in a biconditional grammar depending on whether the learning mode was explicit or implicit.

Participants were randomly assigned to one of three different training conditions and performed three classification tasks, where they had to classify strings of letters as grammatical or ungrammatical. The biconditional grammar was used because it allows an unconfounded analysis of grammaticality (successful judgement can only be made on the basis of abstract knowledge), fragment similarity and whole item similarity (all letters appear with the same frequency in all position) and is more susceptible to acquisition of explicit knowledge of the rules (Johnstone and Shanks, 2001).

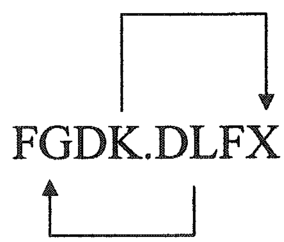

Figure 2: Example of a grammatical string from Biconditional Grammar

The memory training condition was designed as described by Johnstone and Shanks (2001). We made the hypothesis-testing training condition more similar to the memory training condition with regard to exposure to the strings. We constrained the time for judging each letter and the total time they could see the correct string during feedback. In a second experiment, we developed a third training condition, which provided participants with a strategy more conducive to learning the patterns and judging the new strings in the testing phase. We hypothesized that participants were not learning a useful strategy during the hypothesis-testing training in order to classify strings during training. This was because they were supposed to judge letter by letter, and were timed to do so, which did not offer them the opportunity to explore the whole string and look for a general pattern.

Because we wanted to understand transfer of knowledge, we retained the classification task described by Jonhstone et al. (2001) where participants judge strings of letters made under the same set of rules and letters as in training and we added two tasks in the testing phase. Task 2 provided a measure of transfer of knowledge. From the third task, we made assumptions about how specific to a given task was the knowledge acquired during training and we could infer whether participants were learning strategies that could be used in any kind of task, or if they were learning the set of rules, which can not be generalized to the third testing task.

Method

Experiment I

Participants:

Participants in this experiment were 27 right handed young adults (15 men, 12 women; age range 20-35 years, mean 24.5 years; mean years of education = 16.28; SD= 2.4) with no history of medical or psychiatric disease. One participant had to be excluded due to computer error during data acquisition. All participants signed a consent form and were compensated for their time.

Stimuli:

Training: Strings of letters composed of two sets of four characters separated by a dot, created from the six consonants D, F, G, K, L and X.

In Grammatical strings, there was a relationship between the letters in equivalent positions on either side of the dot (Figure 2). The letters were paired (D-F, K-X and G-L) and the distribution of the letters respected four letter-position relationships: Position 1 paired with 5, 2 with 6, 3 with 7 and 4 with 8, such that when one letter of the pair appeared in position 1, the other appeared in position 5, and so on. Grammatical strings were designed so that the same letter was never repeated in consecutive locations on one side of a string and the use of each of the 6 possible letters was balanced across all 8 letter locations. Ungrammatical strings were created by replacing either one or two letters of a correct string, so that the letter pair relationship was violated. Two ungrammatical strings were created from each grammatical training string, yielding 18 grammatical strings and 36 ungrammatical strings.

Task 1: A new set of 72 grammatical strings and 72 ungrammatical strings were created for Task 1 following the same set of rules and letters as training.

Task 2: Construction of the strings for Task 2 followed the same set of rules as described for training and Task 1, but the six consonants W, R, Q, H, N and T were used instead. There were 72 ungrammatical and 72 grammatical strings.

Task 3: A different set of rules determined the distribution of letters in Task 3. To be correct, one letter per string had to be repeated, with a separation of four letters between the repeated pair. If there was no repetition, or if there were fewer than four letters between the two repeated letters, the string was ungrammatical. For example: BMVZ.TBSP is grammatical and BMMV.TPSZ is ungrammatical.

Procedure

Prior to testing on the three tasks, participants were randomly assigned to one of two training conditions: the memory condition, in which training promoted only implicit learning of the rules, and the hypothesis testing condition, in which training promoted explicit learning of the rules. The three testing conditions were the same for all participants. In Tasks 1 and 2 participants did not receive feedback so that acquisition of the rules was restricted to the learning phase. In Task 3, all participants had to learn a new set of rules, and therefore received feedback after every response. Participants were tested on 144 strings in each testing task.

In the memory training condition (Figure 3), participants were told that they were taking part in a short-term memory experiment. Participants saw series of grammatical strings for 7 seconds each and were asked to memorize them. After each presentation of a grammatical string, the screen went blank for 2 s and a list of three strings was displayed. These strings consisted of the grammatical string they had memorized and two ungrammatical strings. Participants were asked to press a mouse button (left, middle or right) corresponding to the string they thought matched the one they had memorized.

In the hypothesis testing training condition (Figure 4) participants were told that they would be taking part in a rule-discovery experiment and their task was to work out these rules. On each trial, participants were presented with an ungrammatical string. Each string had between two and four letters that violated the rules. For each letter in the string, participants indicated by pressing the mouse buttons whether they felt that the letter conformed to the rules (left button) or violated the rules (right button). Following their completed response, the screen went blank and they received feedback in the form of the correct string.

Between tasks, participants answered two questions concerning the strategies used during the task: 1) did you adopt any particular strategy during this task? 2) Did you notice any rule during this task?

Analyses:

Differences in percent correct between participants in the two conditions when judging the grammaticality of strings on Task 1, 2 and 3 were analyzed with ANOVA for repeated measures (with Geenhouse-Geiser correction). Significant effects were followed by post-hoc t-tests (Bonferroni correction).

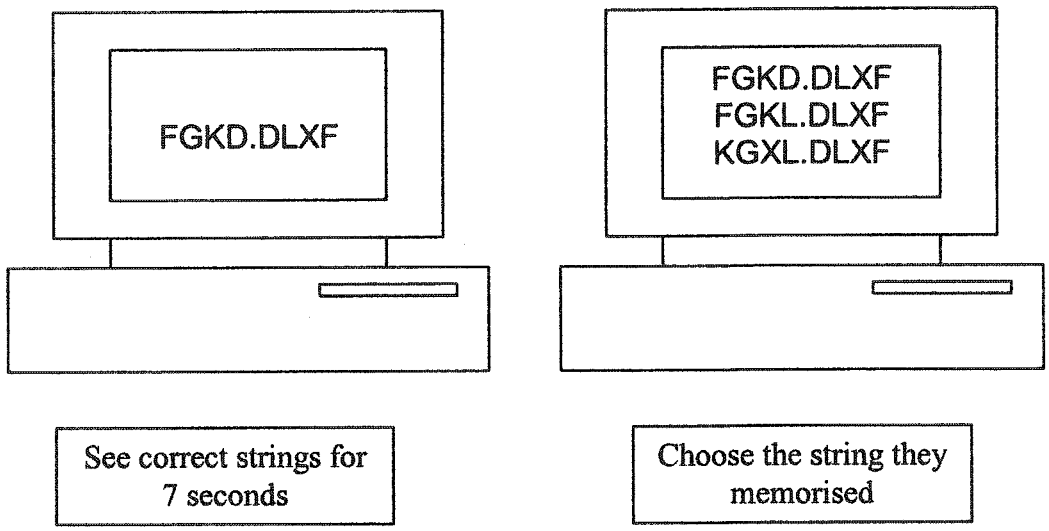

Figure 3: Memory condition training condition. On the left, image that appears on the screen when participants are memorizing the string. On the right, the image from which they selected one of the three strings.

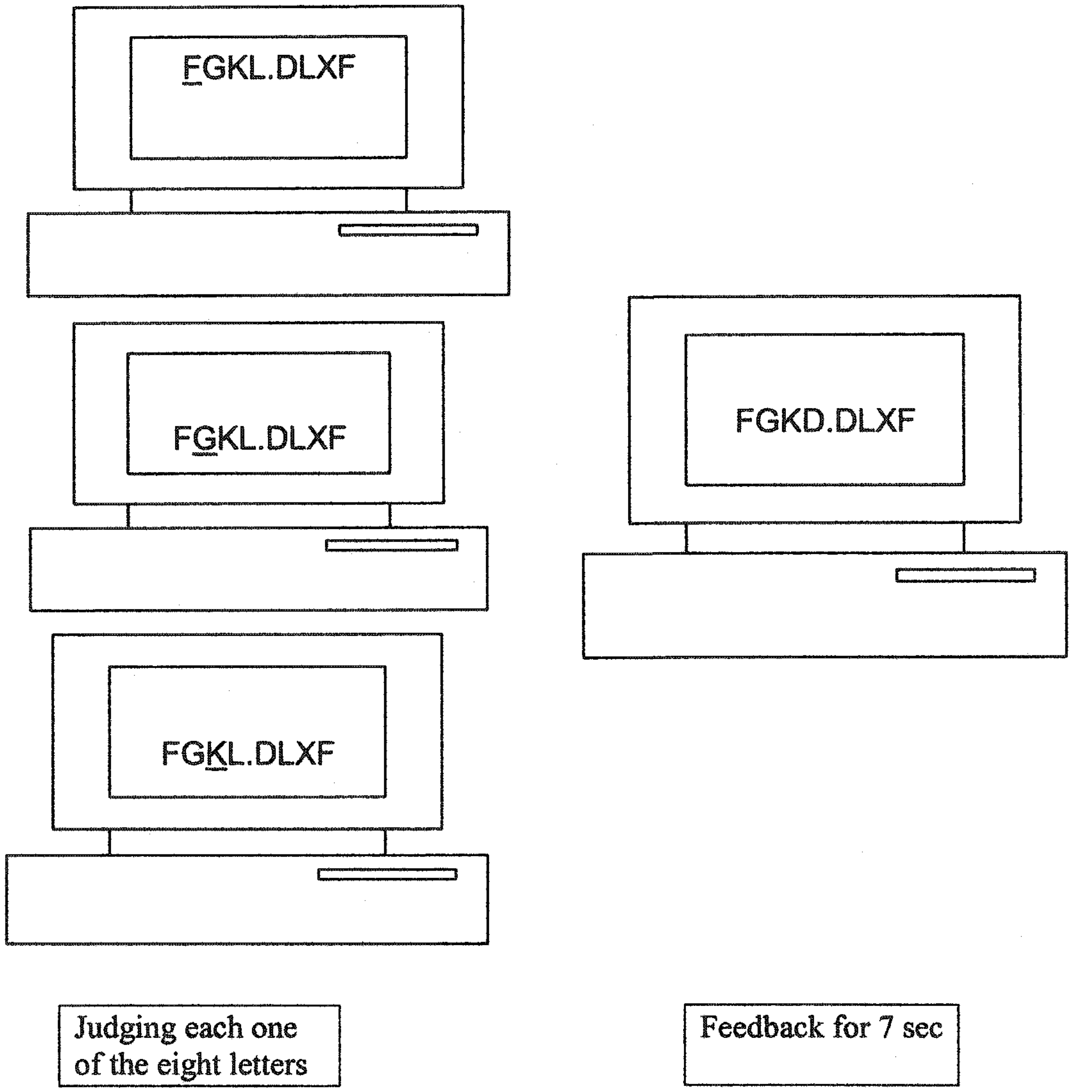

Figure 04: Hypothesis-testing training condition. On the left side, reproduction of what participants see when judging letter by letter. On the right side, the feedback.

Another set of similar analyzes was made for differences in percent correct between learners (>51% correct on Task 1) and non-learners (< 51% on Task 1) when judging the grammaticality of strings on Task 1, 2 and 3.

We analyzed percentage of endorsement for each string in a multiple regression analyses. This measure was the result of the number of participants who endorsed the string divided by the total number of participants in the group multiplied by 100. We used as independent variables grammaticality of the string and other patterns perceived by participants and used to judge the grammaticality of the strings.

Method

Experiment II

Participants:

Ten new participants were recruited for this experiment. They were all right handed young adults (4 men, 6 women; age range 20-35 years, mean 24.3 years; mean years of education = 16.4) with no history of medical or psychiatric disease. All participants signed a consent form and were compensated for their time.

Stimuli:

Stimuli used in Experiment I were also used in Experiment II.

Procedure:

All participants were trained in a modified version of the Hypothesis-testing condition (Figure 5). They were told that they would be taking part in a rule-discovery experiment. On each trial, participants saw grammatical strings of letters for 7 seconds, and were asked to work out the hidden rules, by looking for patterns in the strings. Then the screen went blank for 2 s and a list of three strings was displayed. These strings consisted of a new grammatical string and two ungrammatical strings. Participants were asked to press a mouse button (left, middle or right) corresponding to the string they thought followed the rules they had been learning. Participants were encouraged to look for a general abstract rule across trials.

As in Experiment I, all participants were tested on Tasks 1, 2 and 3. Between tasks, participants answered the same two questions concerning the strategies they used during the task.

Analyses:

Participants in this experiment were compared to participants from experiment I. The same set of analyses was performed.

Results Experiment I

We compared performance of participants on the Memory and Hypothesis-testing training conditions on Task 1, 2 and 3 (figure 06). All participants performed better on Task 3 compared to Tasks 1 and 2 [$F\ (2, 26) = 3.528$; $p = 0.058$]. The training condition did not predict performance on Task 1, 2 or 3 [$F\ (2,26) = .468$; $p = 0.554$].

Participants were divided into high performers and low performers based on their performance on Task1. Their performance on Task 2 and 3 were compared (figure 07). Subjects were considered high performers when they had more than 51% correct responses on Task 1. Repeated measures ANOVA revealed a main effect of Task [$F(1.4, 26) = 4.939$; $p = 0.023$] and a Task by Group interaction [$F(1.4,26) = 4.607$; $p = 0.026$].

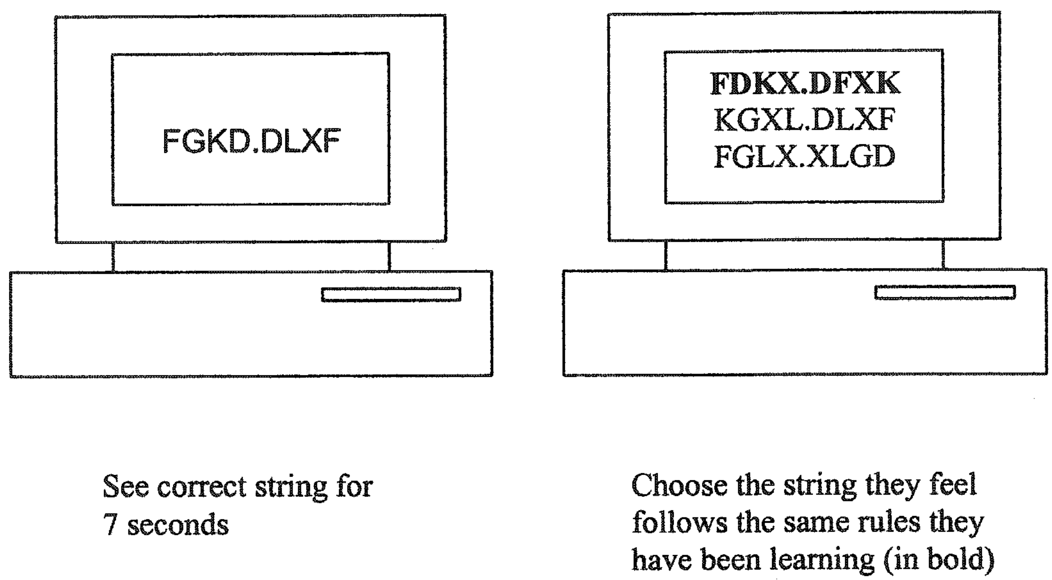

Figure 5: New Hypothesis-testing training condition. On the left side is what appears in the screen when participants are analysing the string, looking for a pattern. On the right, screen from which they have to choose one of the three strings.

According to post-hoc comparisons using the Bonferroni correction for multiple comparisons, only low performers showed a significant increase on performance when Task 3 was compared to Task 1 ($p= .004$) and to Task 2 ($p=.032$). High and low performers differed significantly in their performance on Task 1 ($p<.001$) and on Task 2 ($p=.005$).

Analyses of the questionnaires answered by participants between the tasks, allowed the formulation of categories of strategies and rules (Table 1). These categories were used as independent variables in a multiple regression analysis. The dependent variable was the percentage of endorsement as grammatical for each string on Task 1 and 2. This measure is the quotient of the number of participants who endorsed a string by the total sample, multiplied by 100. On Task 1, use of "secondary" rules explains 66% of the variance of endorsement for total sample, 55% for Hypothesis-testing condition, 53% for Memory condition, 52% for high performers and 70% for low performers. On Task 2, use of "secondary" rules explains 5.8% of the variance for Hypothesis-testing condition, 11.7% for Memory condition, 3.4% for high performers and 6.4% for low performers. On Task 1, all participants seemed to make use of secondary rules to make their judgments about the grammaticality of the strings. However, on Task 2 the same pattern was not as clear. In general, participants endorsed fewer strings as grammatical on Task 2, and seemed to endorse all categories of secondary rules indiscriminately, indicating that they did not transfer what they had learned in training to the second classification task.

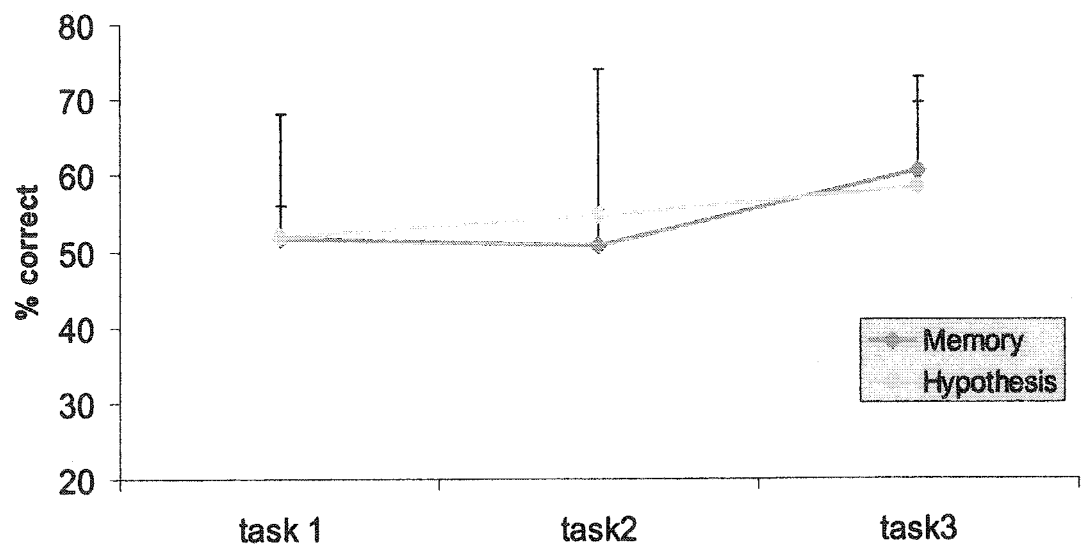

Figure 6: Participants performance on all three classification tasks – Experiment I

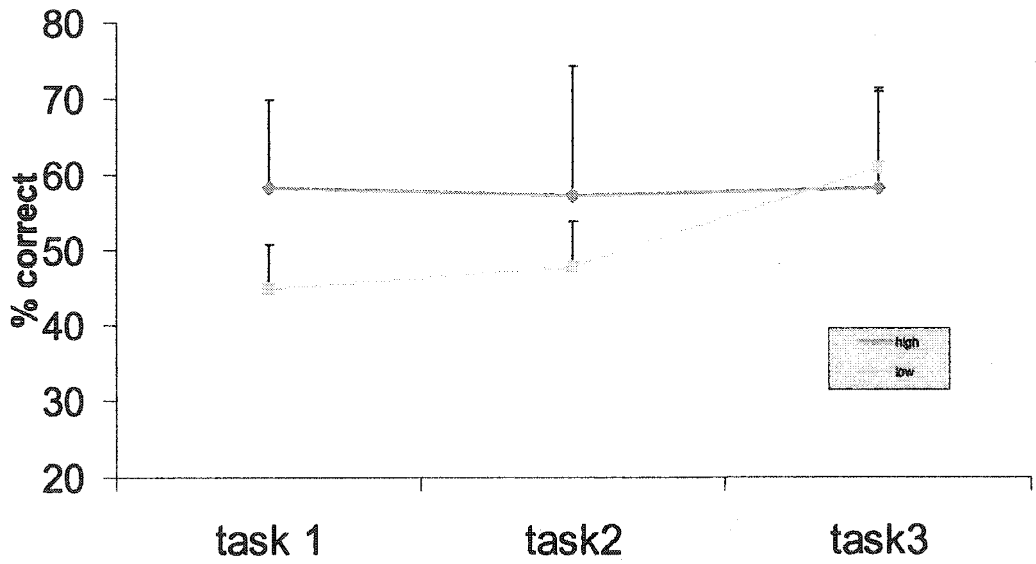

Figure 7: Performance on classification tasks by high and low performers from Experiment I (N=27).

Since data from multiple regression indicated that use of secondary rules explained a large percentage of the variance for endorsement of strings, we then wanted to analyze possible differences between participants on endorsement of strings. Here, the analysis was focused on participants, in opposition to multiple regression, where analysis was focused on strings. Therefore, the dependent variable was the number of strings from a given category of secondary rules endorsed as grammatical by a given subject divided by the total of strings present in this category (figures 8 and 9). We performed a repeated measures ANOVA and we used the Secondary Rules as a within subjects factor and Task (1, 2 and 3), Condition (Memory and Hypothesis-testing) and Level of performance (high and low) as between subjects variables. There was a main effect of Secondary Rules [$F(2.745,26)=7.835; p<.001$] with participants endorsing many fewer strings on Task 2 when compared to the same strings on Task 1. Significant differences were observed for the categories: 1) two reversed pairs of letters in each side of the dot ($p<.001$); 2) same four letters in both sides ($p=.002$); 3) when the letters in both sides were positioned so that one side seemed the "mirror" of the other side ($p<.001$). The only case where participants endorsed significantly more strings on Task 2 when compared to Task 1 was when strings did not follow any secondary rule ($p=.014$). The change in the pattern of endorsement of strings from Task 1 to Task 2 reflects participants' inability to transfer learning from one task to the other. One could argue that participants, on Task 2, endorsed strings from all categories in a random way, contrary to what happened on Task 1.

Table 1 – Categories of Secondary Rules

Secondary Rule	Definition	Example
One reversed pair	One pair of letters appears in reverse on either side of the dot	FDKG.DFXL
Same first and last	The first letter on one side of the dot is the last on the other side, and vice-versa.	FGKD.DLXF
Two reversed pairs	Two pairs of letters appear in reverse on either side of the dot	FDKX.DFXK
Scrambled	The same four letters are present in both sides of the dot, in scrambled positions.	FGKL.DLXG
Mirror	The same four letters are present on both sides of the dot in "mirror" positions.	LKXG.GXKL
Same three letters	The same three letters are present on both sides of the dot (this is always ungrammatical)	GLKD.LGXD
None	No apparent secondary rule.	FGXL.DLKG

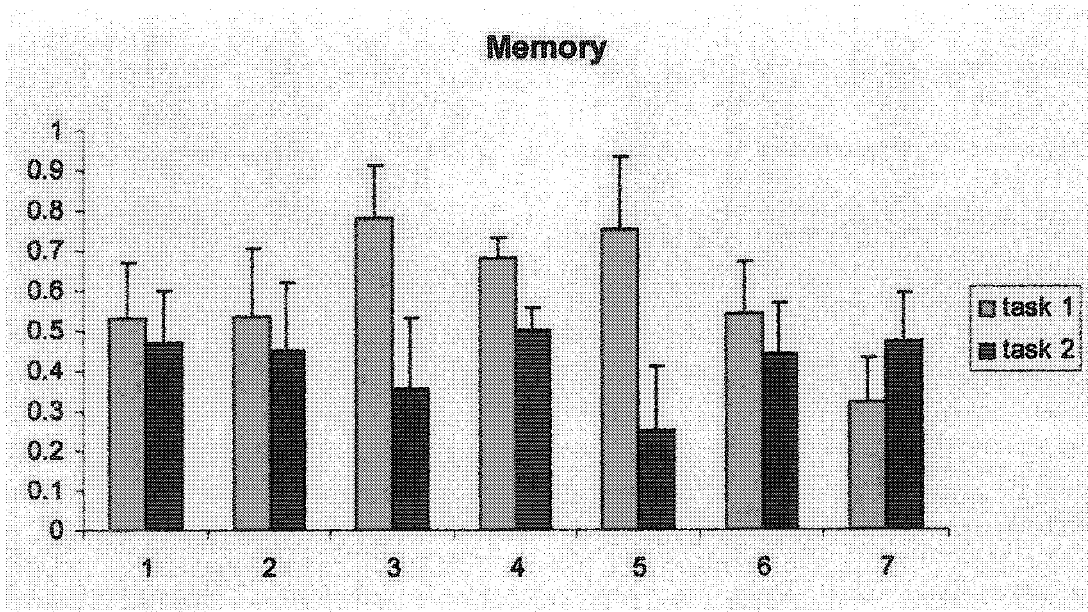

Figure 8: Endorsement of strings by participants from Memory Condition – Experiment I

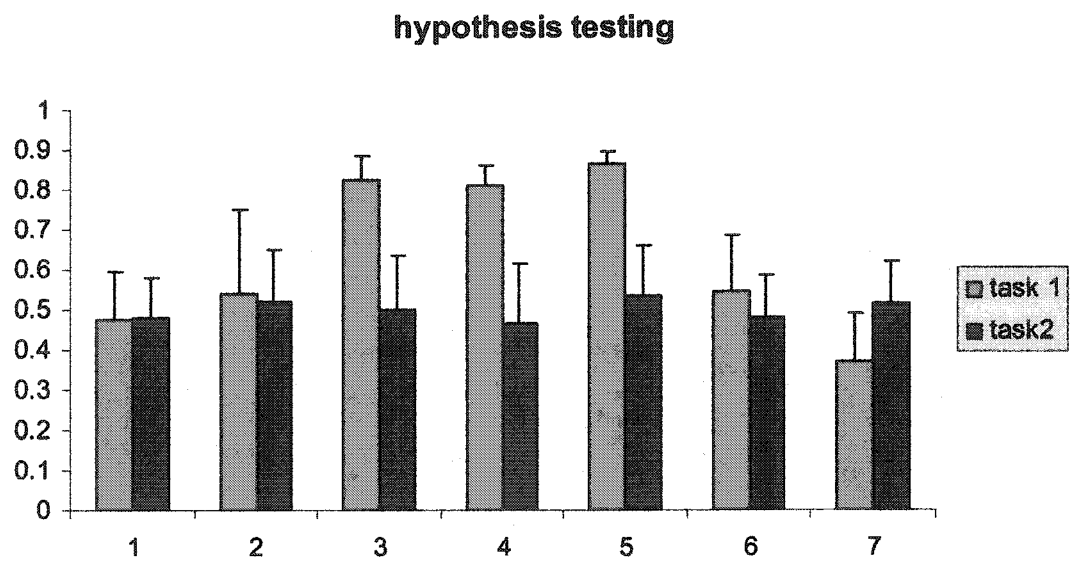

Figure 9: Endorsement of strings by participants from Hypothesis-testing Condition – Experiment I

Results Experiment II

Performance of participants on Experiment II was statistically compared to performance of those from Experiment I (Figure 10). Similar to previous results, all participants performed better on Task 3 [$F(1.34, 36)= 8.881$; $p= 0.02$]. Post-hoc pairwise comparisons using the Bonferroni correction for multiple comparisons showed that participants trained in the new version of Hypothesis-testing condition performed better on all three tasks when compared to those from the Memory condition ($p=0.035$) and to those from Hypothesis-testing condition ($p=0.036$).

As in Experiment I, participants in the new hypothesis-testing condition were divided according to their level of performance in Task1. Their performance on Task 2 and 3 were compared (figures 11 and 12). There was a main effect of Task [$F(1.38, 36)= 11.141$; $p= 0.001$] and a Task (1, 2 and 3) by Group (high and low performers) interaction [$F(1.38,36)= 6.63$; $p= 0.07$]. According to post-hoc pairwise comparisons using the Bonferroni correction for multiple comparisons, low performers showed a greater increase in performance when comparing Task 3 and Task1 ($p<.001$) and Task 2 ($p=.003$).

Categories of Secondary Rules were used as independent variables in a multiple regression analyses, like in Experiment I. Endorsement of strings on Task 1 and 2 was used as the dependent variable. On Task 1, use of secondary rules explains 63.6% of the variance of endorsement for total sample; 57.3% for high performers and 62.4% for low performers. On Task 2, use of secondary rules explains 54.6% of the variance of endorsement for total sample, 49.4% for high performers and 57.1% for low performers.

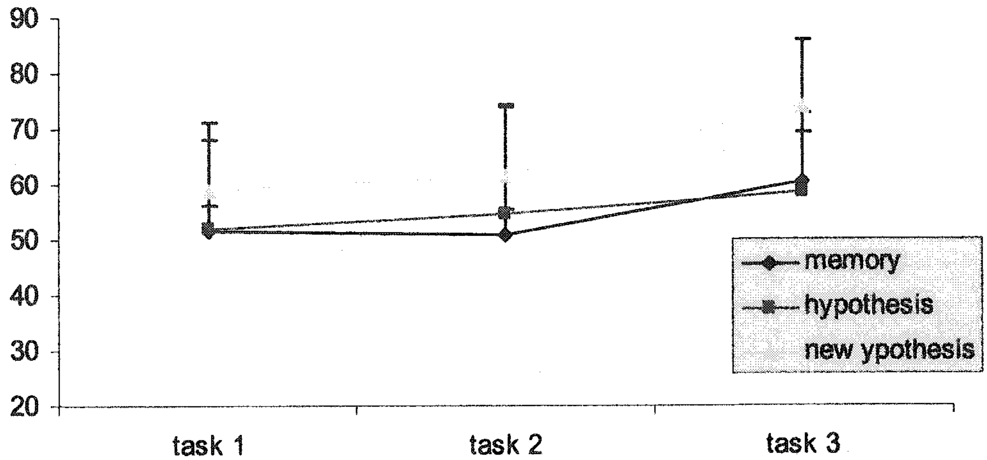

Figure 10: Participants performance on all three classification tasks – Experiment II

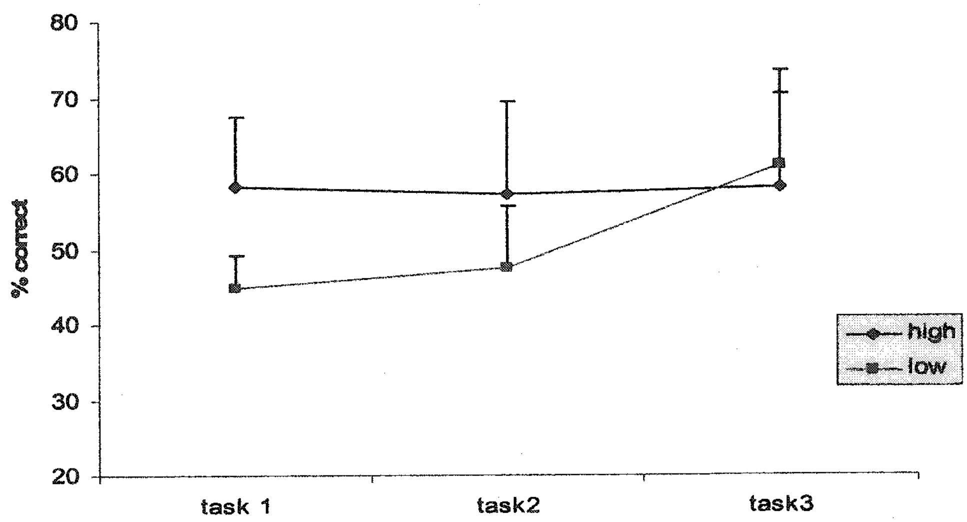

Figure 11: Performance on classification tasks of participants from Experiment I and II

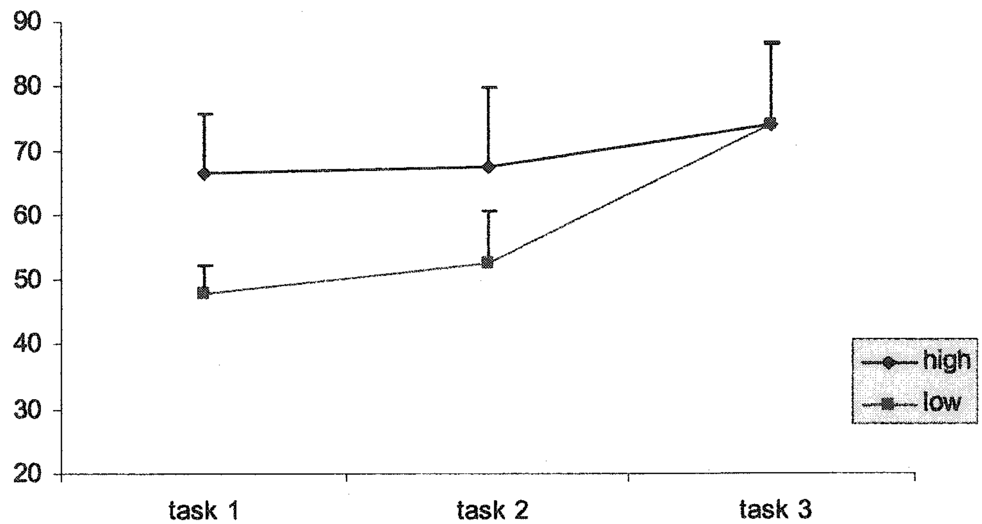

Figure 12: Performance on classification tasks of participants from Experiment II

In opposition to what was observed in Experiment I, participants trained on the New Hypothesis-Testing condition seem to make use of Secondary Rules on Task 2 as well as on Task 1. Their judgment does not seem to be made randomly, which can be interpreted as a good indication of transfer of knowledge from Task 1 to Task 2.

As in Experiment I, endorsement of strings among participants in the Memory, Hypothesis-testing and New Hypothesis-testing conditions, both on Task 1 and 2, was analyzed through repeated measures ANOVA (figure 13). There was a main effect of Secondary Rules [$F(3.4, 36)=26.633$; $p<.001$). Endorsement of Secondary rules was different depending on the condition [$F(6.872, 36)=5.034$; $p<.001$], on the Task [$F(3.436, 36)=11.839$; $p<.001$] and also on the level of performance of participants [$F(3.436,36)=2.569$; $p=.047$].

Post-hoc pairwise comparisons using the Bonferroni correction for multiple comparisons showed that participants in the Memory condition and in the New Hypothesis-testing condition endorsed differently strings from Task 2 ($p= .049$). This because only participants in the New Hypothesis-testing condition showed a pattern similar to the one presented on Task 1, while participants on the Memory condition seemed to endorse strings as grammatical in a random way.

Strings that presented two reversed pairs of letters on each side of the dot, and strings where the letters in both sides were positioned so that one side seemed the "mirror" of the other side were endorsed more by participants from the New Hypothesis-testing condition when compared to participants from the Memory condition ($p<.001$ for both secondary rules) and when compared to participants from Hypothesis-testing condition ($p=.008$ and $p= .010$, respectively).

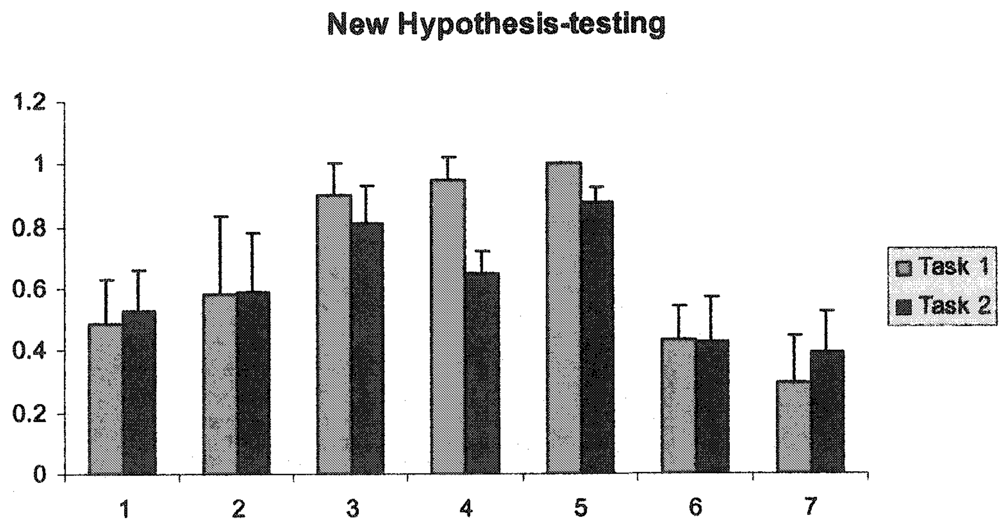

Figure 13: Endorsement of strings by participants from New Hypothesis-testing Condition – Experiment II

High performers endorsed as grammatical more strings that did not show any Secondary rules when compared to Low performers (p=.013). In contrast, Low performers endorsed strings with three repeated letters on both sides of the dot more than High performers did (p=.016). This is an interesting pattern, since all strings with three repeated letters on both sides of the dot are ungrammatical and knowledge of some more abstract set of rules is required to endorse strings that do not present any Secondary Rules. So, one could conclude that the pattern of endorsement of those two groups, on these specific categories of Secondary rules, reflect the abstract knowledge of the set of rules present on the stimuli.

Participants endorsed strings with the same secondary rules in a significantly different way on Task 1 and 2. They endorsed less strings that presented two reversed pairs of letters on each side of the dot on Task 2 when compared to Task 1 (p<.001), when they presented the same four letters on both sides (p=.002), and also when the letters in both sides were positioned so that one side seemed the "mirror" of the other side (p<.001). Participants endorsed more strings that did not present any apparent secondary rule on Task 2 when compared to Task 1 (p=.014).

Discussion

The present study compared participants trained in two different hypothesis-testing conditions and a memory condition. Performance and transfer of rule learning were tested on Task 1 and Task 2, where participants classified strings from the same biconditional grammar. In Task 3 the effect of training on the ability to learn a new set of rules was tested. In Experiment I, there was no significant difference between performance of hypothesis-testing and memory groups for any of the tasks. All participants performed better on Task 3 when compared to Tasks 1 and 2, probably because they received trial-by-trial feedback on the third task. The sample was divided into high and low performers based on participants' performance on Task 1. From Task 1 to Task 2, there was no statistically significant change: high performers on Task 1 were high performers on Task 2, and low performers on Task 1 were low performers on Task 2. Both high and low performers showed a similar level of performance on Task 3; with only low performers showing a significant increase in performance when Task 3 was compared to Task 1. Analysis of participants' categorization of strings according to the secondary rules showed that use of secondary rules explained a large proportion of the variance for participants in both training conditions. On Task 2, use of secondary rules explains a smaller amount of variance, implying that they did not transfer what they had learned in training to the second classification task.

In Experiment II, participants trained in the new version of Hypothesis-testing condition performed better on all three tasks when compared to those from the Memory condition and to those from original Hypothesis-testing condition. The new version of the Hypothesis-testing condition allowed participants to observe the whole string, and encouraged them to compare both sides of the string and look for patterns across trials. This proved to be a useful strategy in all three testing tasks. As in Experiment I, participants were divided into high and low performers based on their performance on Task 1. Similar to Experiment I, there was no statistically significant improvement in performance form Task 1 to Task 2 and all participants performed better on Task 3. Low performers showed a greater increase in performance when comparing Task 3 and Task 1 and Task 2. Analysis of the use of secondary rules revealed that participants trained on the new version of Hypothesis-testing condition showed a similar pattern of rule endorsement on Tasks 1 and 2, indicating transfer of what they had learned.

The findings from Experiment I did not replicate the findings of Johnstone & Shanks (2001) where participants in the hypothesis-testing condition performed significantly better than participants in the memory condition. This might be because of differences between the hypothesis-testing and the memory training conditions in the original study that favoured learning in the hypothesis-testing group. In Johnstone & Shanks' (2001) study, being aware of the existence of abstract rules was not the only factor that differentiated participants in the two conditions. Participants in the hypothesis-testing condition also had more time to analyze the strings, and more exposure to the correct strings. Therefore, in order to make the Memory and Hypothesis-testing conditions more similar, we constrained the time for judging each letter in the hypothesis-testing condition as well as the total time they saw the feedback. In our study, the imposed strategy of judging letter by letter did not help participants to learn the rules of the biconditional grammar, probably because they did not have time to explore the whole string and look for a general pattern. It is inherent to the nature of the biconditional grammar that, in a grammatical string, there are similarities between the two sides of the string. Therefore, the most efficient strategy during training is to compare both sides of the string.

In contrast, participants trained in the new version of Hypothesis-testing condition performed better on all three tasks when compared to those from the Memory condition and to those from the original Hypothesis-testing condition. This is because during the new training condition participants analyze the whole string trial by trial and compare it to three other examples of strings, among which one is correct. This process allows participants to: 1) look for a pattern in grammatical strings that could be generalized across trials and 2) recognize patterns of ungrammatical strings based on the other two examples in each trial.

Because we were interested in transfer of learning, we added two tasks in the testing phase. The idea of Task 2 was to have a measure of transfer of knowledge about the abstract rules of the grammar, since the only difference between Task 1 and 2 was the set of letters used to build the strings. The idea of having a third task was to look at generalization of the hypothesis-testing strategy to a new set of rules. We did not observe either increase or decrease on performance from Task 1 to Task 2. Independent of the training mode, all participants performed better on Task 3 when compared to Task 1 and 2. The improvement was greater for low performers, which may indicate that having learned one type of rule does not enhance the chances of learning another type of rule, or that transferring knowledge about one specific set of rules may actually prevent participants from learning the new set of rules with the same accuracy as participants who did not show knowledge of the rules on Task 1 and 2. The most plausible explanation for the fact that all participants had a better performance on Task 3 is the fact that participants receive feedback after each trial.

Analyzing the whole string and comparing both sides is an efficient strategy to use on all three testing tasks. On Task 1 and 2, some particular patterns of features, that we call secondary rules, occur with some regularity and are perceived earlier by participants as rules useful for classifying strings. Such features are, in our opinion, used as a previous step before learning the most general rule.

Interestingly, although participants in the Memory and Hypothesis-testing conditions did not differ significantly in performance, they did show a different pattern of endorsement in the testing phase. Participants from both conditions endorsed the same categories of secondary rules on Task 1, but differed on the categories endorsed on Task 2. Therefore, performance in the testing phase did not fully explain the behaviour of participants. Analyses of endorsement of secondary rules gave a more detailed understanding of differences in learning between participants in the three different training groups and between high and low performers. High performers endorsed as grammatical more strings that did not follow any secondary rules and require knowledge of some more general abstract rule when compared to low performers. In contrast, low performers endorsed strings with three repeated letters on both sides of the dot more than high performers did. Low performers seem to be endorsing any type of string that shows similarities between the two halves, without basing classification in a more general abstract rule.

If we think of the rule about pairs of letters as the most general rule in the biconditional grammar, and the secondary rules as intermediate steps to learning the most general one, we can propose a continuum of features that participants use to judge the strings, from the most concrete to the most abstract. The first step would be to recognize the secondary rules identified in training in the testing strings. In this step, participants would endorse as grammatical all strings in which they could recognize any type of secondary rules. The second step would be to combine two or more secondary rules. In this step, participants would start to endorse only those strings that did not violate another secondary rule. The third step would be when participants learn the most general rule in the biconditional grammar (pairs of letters). In this step, participants would be able to endorse even strings that do not follow any secondary rule. In the present study, only high performers trained either in both versions of the hypothesis-testing condition arrived at the third step. However, it is important to note that depending on the combination of secondary rules participants learn, they can perform very well without ever learning the most general rule.

In future studies, we intend to develop a paradigm where the presence of secondary rules does not confound with grammaticality of strings, which means an even distribution of grammatical and ungrammatical strings in each category of secondary rules during both training and testing phases.

In these experiments, we were able to show that judgement of strings in a biconditional grammar was mediated by the use of secondary rules. Depending on the training, participants were more or less able to explicitly state those secondary rules, and to distinguish between the ones that were also congruent with the most general rule of the grammar. We can presume that we would be able to observe differences in the pattern of brain activation if measured during the classification of strings as grammatical when comparing participants trained on the new version of the hypothesis-testing condition and memory condition, low and high performers, type of string being classified according to secondary rules, and phase of learning considering the continuum proposed previously. In a fMRI study, Reber et al. (2003) observed different brain areas of activation when participants were trained either in an implicit condition or an explicit condition.

Interestingly, participants showed only a marginal statistically significant difference on performance when classifying the stimuli.

Therefore, despite the fact that the biconditional grammar was thought to control for categorization based on superficial similarity, our results suggest that the general rule about pairs of letters is not the only one learned by subjects, and that use of secondary rules explains a large amount of the variance, indicating that participants are still making use of structural and abstract features of the strings until they learn the most abstract set of rules from a grammar.

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