Strengthening the Case for Stimulus-Specificity in Artificial Grammar Learning
No Evidence for Abstract Representations With Extended Exposure

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Abstract. Different theories have been proposed regarding the nature of the mental representations formed as a result of implicit learning of sequential regularities. Some theories postulate abstract surface-independent representations, while other theories postulate stimulus-specific representations. This article reports three experiments investigating the development of abstract representations in artificial grammar learning (AGL), using a methodological approach developed by Conway and Christiansen (2006). In all the experiments, the number of blocks during the exposure phase was manipulated (6 blocks vs. 18 blocks of exposure to sequences). Experiments 1 and 2 investigated both visual and auditory learning where sequences were presented element-by-element. Experiment 3 investigated visual learning using a sequence-by-sequence presentation technique more commonly used in visual AGL studies. Extending previous research (Conway & Christiansen, 2006) and in support of stimulus-specific accounts, the results of the experiments showed that extended observational learning results in increased stimulus-specific knowledge rather than abstraction towards surface-independent representations.

Keywords: implicit learning, artificial grammar learning, abstraction, stimulus-specificity

People have a remarkable ability for incidental adaptation to structural regularities in the environment. Language learning, concept learning, musical appreciation, motor skill learning, and socialization in general all seem to involve largely incidental adaptation to (and construction of) structure. Accordingly, much research has been devoted to understanding the nature of the mental representations and learning mechanisms that provide a basis for such structural sensitivity (Perruchet & Pacton, 2006; Pothos, 2007; Saffran, 2003). One important question pertains to the specificity/abstractness of the mental representations supporting sensitivity to sequential structure, an issue which continues to divide researchers.

In this study, three experiments investigated the nature of knowledge representations acquired in artificial grammar learning (AGL), a key paradigm for investigating incidental adaptation to sequential structure. Specifically, the experiments explored whether more abstract (as defined below) representations are formed as a function of extended exposure to structural regularities in AGL.

AGL and Abstraction

Research on AGL has convincingly shown that participants can incidentally become sensitive to the local sequential structure of finite-state grammars such as those in Figure 1 (Pothos, 2007; Reber, 1989). After incidental exposure to legal symbol sequences (i.e., sequences conforming to the experimental grammar) participants can classify new legal and illegal test sequences above chance levels. Impressively, participants are also able to transfer knowledge between domains. For example, if the exposure sequences are instantiated as tone sequences then participants can classify above chance even if the test sequences are instantiated as letter sequences (Altmann, Dienes, & Goode, 1995; Manza & Reber, 1997). One explanation of such transfer effects from one domain to another is that they result from spontaneously induced surface-independent, amodal representations of abstract regularities divorced from the specific surface features and modality of the input (Manza & Reber, 1997; Marcus, Vijayan, Bandi Rao, & Vishton, 1999). Such surface-independent representations are here referred to as abstract representations. Additional possible meanings of “abstract” are discussed in for example Redington and Chater (1996), but are not considered in this study.

Others have argued that low-level perceptual representations tied to the surface features of the input can support transfer across or within dimensions of modalities in AGL without formation of abstract surface-independent representations during the incidental learning phase. In these accounts, transfer may occur through the mapping of
statistical regularities across domains at test (Dienes, Altmann, & Gao, 1999; Redington & Chater, 1996; Tunney & Altmann, 2001) or through low-level representations in combination with explicit abstract analogies during the test phase (e.g., the sequence XVVRMM is similar to the sequence LQQKPP on an abstract level) when the actual direct need for abstraction arises (Brooks & Vokey, 1991). Thus, these transfer accounts do not postulate spontaneous formation of surface-independent abstract representations. Instead, the knowledge formed during exposure to regularities is tied to the surface format of the input and the processes specifically responsible for transfer are cued by demands to apply knowledge in a new domain. Low-level perceptual representations that preserve the surface features of encoded stimuli are here referred to as stimulus-specific representations (cf. Conway & Christiansen, 2006, for an identical distinction between abstract and stimulus-specific representations).

Since transfer effects in AGL do not by themselves distinguish empirically between the formation of abstract versus stimulus-specific representations during learning, the debates between proponents of the two accounts can be difficult to settle (e.g., Marcus, 1999; Marcus et al., 1999; Seidenberg & Elman, 1999). However, experiments conducted by Conway and Christiansen (2006; cf. Whittlesea & Dorken, 1993, for similar studies) represent a step forward by illustrating how abstract and stimulus-specific accounts can be pitted against each other through the derivation of differential predictions. In the exposure phase of Experiment 1 by Conway and Christiansen (2006) participants incidentally observed symbol transitions within sequences generated from the two grammars shown in Figure 1. Sequences from one grammar were tones (i.e., auditory modality) and sequences from the other grammar were colors (i.e., visual modality). In the test phase, the participants were shown new grammatical sequences only, from each of the two grammars. For half of the participants the test sequences were instantiated as tones, and for half as colors. Before the test phase, the participants were told that the previously seen and heard sequences conformed to a set of rules, and that the task was to classify new sequences with respect to the rules.

Endorsements of test sequences from a grammar whose exposure modality (the modality instantiation of the grammar during the exposure phase) corresponded to the test modality were scored as correct, and so were rejections of test sequences from a grammar whose exposure modality did not correspond to the test modality. All other responses were scored as incorrect. On the basis of this scoring procedure, accounts positing abstract representations predict a performance level of 50% correct, since modality correspondence should not affect the utilization of surface-independent representations. Accounts positing stimulus-specific representations predict a performance level of > 50% correct, since modality correspondence is expected to trigger representations specific to the modality in question. Conway and Christiansen (2006) found evidence for stimulus-specific representations. Interestingly, the performance of another group of participants trained on only one grammar and tested on the same materials as described above (although always in the training modality) did not differ significantly from the dual-grammar group. This indicates that simultaneous learning in different modalities can proceed quite independently of each other.

As acknowledged by Conway and Christiansen (2006), it is possible that the participants did develop abstract representations in addition to stimulus-specific ones, but that the former were not as strong as the latter. One possibility is that the exposure levels commonly used in AGL studies (usually somewhere between 3 blocks and 6 blocks of exposure to sequences) are not enough for abstract representations to form and/or influence performance. For example, Meulemans and Van der Linden (1997) argued that abstract structure, rather than superficial similarity, had a larger impact on classification in AGL when the exposure phase was extended with many sequences from the grammar (for a reevaluation of that conclusion, see Johnstone & Shanks, 1999). Furthermore, Manza and Reber (1997) suggested short exposure phases to be the reason for transfer decrement in AGL, that is the finding that transfer performance is lower than same-domain performance. Thus, it could be argued that the exposure levels used by Conway and Christiansen (2006), namely 6 blocks of exposure to sequences, were insufficient to yield demonstrable abstract knowledge.

Figure 1. The two grammars used in the experiments. Legal sequences are generated by entering the grammar from the left side and following the arrows until one reaches the exit on the right side. For example, in Grammar 1, XMMXRVM is legal (the consecutive Ms are due to the M loop, i.e., the arrow going from and to the same state). The same grammars were originally used in “Statistical learning within and between modalities: Pitting abstract against stimulus-specific representations” by Conway and Christiansen (2006).
However, Pacton, Perruchet, Fayol, and Cleeremans (2001) investigated children’s incidental sensitivity to real-life orthographic regularities over a time course of several years, and found a consistent transfer decrement. Thus, speaking against the not-enough-exposure argument, there is evidence that transfer lags behind same-domain performance even over very long time courses. This continuing transfer decrement is predicted by stimulus-specific accounts, since stimulus-specific knowledge does not apply in the same way across different domains. Despite the intriguing results of Pacton et al. (2001), the logic of the standard transfer paradigm in AGL is problematic in that both abstract and stimulus-specific accounts predict changes in the same direction. Longer exposure to regularities might result in more (even though perhaps not fully) abstract knowledge supporting transfer, and/or in more detailed stimulus-specific knowledge supporting transfer. Thus, a crucial question is whether varying exposure levels has an effect in experimental paradigms where it is possible to put abstract and stimulus-specific representations in opposition.

The experiments reported in this article extend the research reported in Conway and Christiansen (2006) by investigating whether increasing exposure levels leads to more abstract representations in AGL. Using a scoring procedure similar to that of Conway and Christiansen (2006) abstraction accounts predict that classification (C) scores will decrease towards chance levels with increasing exposure to regularities when stimulus-specific and abstract representation are pitted against each other. Stimulus-specific accounts predict that C scores will increase with increasing exposure. In Experiment 1, both visual and auditory learning were investigated at different exposure levels (6 blocks vs. 18 blocks) using a sequential element-by-element presentation technique identical to that in Conway and Christiansen (2006). Experiment 2 investigated classification based on exposure to a single grammar in one modality for each participant and served as a control experiment for Experiment 1. Experiment 3 used a dual-grammar design like that in Experiment 1, but incorporated only visual materials and a sequence-by-sequence presentation technique more commonly used in AGL studies.

**Experiment 1**

**Method**

**Participants**

Eighty students at Växjö University and Lund University (51 women and 29 men, ages 18–50 years, M = 26 years) took part in the experiment in exchange for a voucher (value ~10 USD). Each participant was randomly assigned to one of four groups: short exposure – tone test, short exposure – color test, long exposure – tone test, or long exposure – color test (n = 20 in each condition). Four additional participants were tested but excluded because of equipment failure (n = 2) or color blindness (n = 2).

**Materials**

Experiment 1 used the same two finite-state grammars (Figure 1) and the same sequences as Conway and Christiansen (2006, p. 906), except for the replacement of one of Conway and Christiansen’s test sequences which was listed twice in their materials (the sequences are listed in the Appendix). Nine sequences, with a length of 3–7 symbols, from each grammar were used for the exposure phase and 10 different sequences, also with a length of 3–7 symbols, from each grammar were used for the test phase. Depending on the experimental condition (colors vs. tones) the test sequences were instantiated either as color images or tones. The images (n = 5) were the same colored squares as those used by Conway and Christiansen (2006).1 The tones (n = 5) were sine waves of the same frequencies as Conway and Christiansen’s, and were edited by applying 20 ms fade-ins and fade-outs to produce smooth boundaries. The image sequences were presented on a computer screen and the tone sequences were presented through headphones. The experiment was programmed and run in E-prime 1.1 (Psychology Software Tools Inc.).

**Procedure**

The participants were informed that they would take part in a study on perception and memory and that they would see and hear sequences of images and sounds for a total time of x minutes distributed over y blocks, with x and y varying depending on condition (short condition, x = 12, y = 6; long condition, x = 36, y = 18). The instructions did not mention the existence of underlying rules, but encouraged the participants to attend to the sequences to be prepared for an upcoming test phase.

The exposure phase was modeled after Conway and Christiansen (2006, Experiment 1), except that the number of blocks, each with a total of 18 sequences, was varied across the short (n = 6) and the long (n = 18) exposure conditions. The 18 exposure sequences were shown in a freshly randomized order for each participant in each block. The sequences from one grammar were tones and sequences from the other grammar were images. Modality assignment to grammars was counterbalanced across participants within each experimental condition. Assignment of symbols in the grammars to specific tones and images was balanced across experimental conditions, so that within an experimental condition each participant received a unique assignment, while the same assignments were used in each of the conditions.

The tone and the image sequences were intermixed so that on a given trial the participants did not know whether the next sequence would be auditory or visual. The entire exposure phase was fully automated and timed identically.

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1 I thank Christopher Conway for providing the color images used in Conway and Christiansen (2006, Experiment 1).
for all participants within each experimental condition. Each block started with a prompt to be prepared and a clock counting down from 20 s, after which the sequence presentation started automatically. On each trial (n = 18 per block), a white screen appeared first (1,700 ms), followed by the first element in the sequence (500 ms), followed by a white screen (100 ms), followed by the next element (500 ms), and then a white screen (100 ms), and so on. After the final element in the sequence (500 ms) the next trial started, as just described. After the final element in the final sequence of a block, an additional white screen was shown for 1,700 ms, so that the last sequence would be followed by a white screen just like the other sequences. For the tone sequences, the screen remained white throughout the entire trial. The total time for 1 block, starting from the beginning of the countdown, was 1 min and 52 s. In addition to the 20 s pause between blocks, the participants were given a 1 min extra pause after each 3rd block (but not after the last block, i.e., the 6th in the short group and the 18th in the long group).

After the exposure phase, but before the test phase, the participants were told that the sequences they had just observed were not random, but followed complex rules. They were further told that new sequences would now appear, some of which would follow the same rules as before and some of which would not, and that the task ahead of them was to classify each sequence with respect to the rules, relying on their gut feeling. On each trial a sequence appeared, in exactly the same way as in the exposure phase. Then, a screen appeared saying:

“Do you think that the sequence follows the rules?”

This question was accompanied by 6 different response options and a response was entered using the keyboard (1, 2, 3, 4, 5, or 6; the alternatives below were presented on screen along a horizontal scale):

1. Yes – certain,
2. Yes – fairly certain,
3. Yes – guess,
4. No – guess,
5. No – fairly certain,
6. No – certain.

All of the 20 test sequences were presented in a freshly randomized order for each participant in one single block. Participants in the color test condition received the test sequences as colors, and participants in the tone test condition received them as tones. The test phase was modeled after Conway and Christiansen (2006, Experiment 1) except that those authors used a two-alternative classification scale (yes-no).

Data Analysis

For each participant, a C score was computed that quantified the extent to which the participant tended to endorse test sequences on the basis of stimulus-specific representations. The C score was based on the endorsement probabilities, computed from the responses given by the participants, so that 1, 2, and 3 corresponded to endorsements and 4, 5, and 6 corresponded to rejections.

A matching test trial (half of the test trials) was defined as a test trial including a sequence belonging to a grammar whose test modality matched the training modality. For example, if a visual test sequence belonged to a grammar that was used to generate visual training sequences, then the test sequence was part of a matching trial. The other half of the test trials were nonmatching, and included test sequences belonging to a grammar that was instantiated in a different modality during training compared to testing. The C score was computed as

\[(M_{\text{matching}}) - (M_{\text{nonmatching}}),\]

the two terms referring to the mean endorsement probabilities (with a possible range from 0 to 1) for matching and nonmatching trials, respectively. A C score > 0 indicates use of stimulus-specific representations, while a score of 0 indicates either use of abstract representations or a general lack of learning (cf. Conway & Christiansen, 2006).

The 6-point confidence response scale used in the experiments reported in this study (also used by Channon et al., 2002) was included with the possible intent of analyzing the subjective phenomenology associated with classification in AGL, since a lack of metaknowledge is often viewed as an indication of implicit knowledge (Dienes & Scott, 2005; Tunney, 2005). However, knowledge and metaknowledge are separate issues and in this article I focus on the expression of knowledge regardless of its subjective phenomenology. The natural dividing line for such an analysis, also used in other implicit learning studies (e.g., Channon et al., 2002; Tunney, 2005), is between endorsements and rejections and I therefore report C scores based on endorsement probabilities in what follows. (Analyses using C scores based on the entire confidence response scale, although not entirely appropriate since the scale may not be an interval scale, showed results similar to analyses using C scores based on endorsement probabilities. The only noticeable difference was that the latter, but not the former, resulted in a reliable main effect of exposure in Experiment 3; although the former effect was clearly in the same direction. There are various possible reasons for this difference, but since the focus of the present article is not the subjective states accompanying the expression of knowledge it will not be discussed further.)

An α level of .05 was adopted, so that any effect referred to as reliable is associated with a p value below this level. Effect sizes are reported as classical eta-squared (η²), which is a measure of the proportion of variation (ranging from 0 to 1) attributable to a certain factor, that is (SSfactor/SStotal) (Pierce, Block, & Auginis, 2004). Reported t tests are two-tailed unless noted otherwise.

Results and Discussion

The C scores were entered into a two-way between-subjects analysis of variance (ANOVA) with the two fixed factors exposure (long vs. short) and modality (colors vs. tones). Figure 2a shows the mean C scores as a function of
exposure and modality. The results from the ANOVA showed a reliable main effect of modality, $F(1, 76) = 14.30$, $MSE = 0.07$, $\eta^2 = .14$, and also a reliable main effect of exposure, $F(1, 76) = 8.80$, $MSE = 0.07$, $\eta^2 = .09$. As can be seen from Figure 2a, the C scores were higher for the auditory test modality (tones) than for the visual (colors), and also higher for long exposure to regularities than for short. There was no reliable interaction between modality and exposure, $F < 1$.

The idea that longer exposure to AGL materials results in more abstract representations (Manza & Reber, 1997; Meulemans & Van der Linden, 1997) was not supported by the results of Experiment 1. In fact, the data showed a directly opposite pattern, in that correspondence between training and test modalities had a larger impact on classification with longer exposure to regularities, indicating the operation and development of rather stimulus-specific representations. The formation of abstract representations would drive the C scores in the other direction, towards zero, as exposure increases.

As can be seen from Figure 2a, the C scores were particularly low for the visual short condition. Simply looking at the standard errors (SEs) of Figure 2a is enough to conclude that this particular condition was the only one where classification was not reliably different from 0. Is it possible that performance in this condition was based on abstract representations, since the C scores were so close to 0? Although the possibility cannot be definitely ruled out, there are at least three severe problems with such an interpretation.

First, to the best of my knowledge, no AGL account predicts that shorter training phases should result in more abstract representations. If abstract representations are formed, longer exposure to structural regularities would presumably support such formation rather than act against it, a prediction which is opposite to the results of Experiment 1.

Second, the sequential presentation of regularities (one element at a time) used in Experiment 1 is less suited for visual than for auditory processing, since hearing is more adapted to temporal information and vision is more adapted to spatial information (Conway & Christiansen, 2005; Saffran, 2002). Indeed, the main effect of modality in Experiment 1 is consistent with an auditory advantage for sequential element-by-element presentations (cf. Conway & Christiansen, 2005). Third, if the participants acquired abstract knowledge of the visual sequences in the short condition, then why were the C scores so high in the auditory short condition? Given that these participants acquired either (1) abstract knowledge of both visual and auditory sequences or (2) abstract knowledge of visual sequences and stimulus-specific knowledge of auditory sequences, one would expect a C score of 0 in the auditory short condition, which was not the case (Figure 2a). Thus, it seems reasonable to conclude that the low C scores in the visual short condition indicates lack of learning rather than abstract representations.

To sum up, the most plausible interpretation of the results is that under the procedural circumstances of Experiment 1 longer exposure to regularities leads to increased stimulus-specific adaptation to structural regularities, and that learning under these circumstances is superior in the auditory modality.

### Experiment 2

To further test the validity of the interpretation of the results of Experiment 1 offered above, Experiment 2 used a design similar to Experiment 1, except that each participant was only exposed to sequences from one grammar (Grammar 1 or 2) in one modality (colors or tones) during the exposure...
phase. In the test phase, the participants classified new sequences instantiated in the training modality. Half of the sequences were from the exposure phase grammar and half from another grammar (cf. Conway & Christiansen, 2006, for similar control groups). If classification accuracy in Experiment 2 turns out to be similar to the pattern of $C$ scores observed in Experiment 1, this would be a strong indication that the results of Experiment 1 indicate stimulus-specific representations. For example, if the low score observed in the visual short condition of Experiment 1 was due to the lack of learning rather than abstract representations, then one would expect a similar low score in Experiment 2, which assesses learning regardless of abstractness of representation. The same holds for the modality differences observed in Experiment 1; if these differences were due to modality learning differences rather than differences in abstractness of representation across modalities, then the same differences should appear in Experiment 2 using a single grammar design. Finally, a comparison can be made between Experiments 1 and 2 for the difference between the short and long exposure conditions. A similar difference between the short and the long conditions across experiments would indicate that the stimulus-specific increase in $C$ scores from short to long exposure observed in Experiment 1 (the main effect of exposure) accounts for the whole knowledge increase associated with the short to long exposure transition. In effect, such a pattern would leave little room for any abstract surface-independent knowledge associated with the transition from short to long exposure.

Results and Discussion

Since the participants in each group of Experiment 2 were only exposed to sequences from a single grammar in the exposure phase, the $C$ scores were computed from endorsement probabilities based on accuracy, subtracting the mean endorsement probability for ungrammatical sequences from the mean endorsement probability for grammatical sequences for each participant. The $C$ scores were then submitted to a two-way between-subjects ANOVA with the two fixed factors exposure (long vs. short) and modality (colors vs. tones). Figure 2b shows the mean $C$ scores as a function of exposure and modality.

The results from the ANOVA showed a reliable main effect of exposure, $F(1, 36) = 8.42, MSE = 0.05, \eta^2 = .17,$ and a reliable main effect main effect of modality, $F(1, 36) = 4.21, MSE = 0.05, \eta^2 = .09.$ There was no interaction between exposure and modality, $F < 1.$ As can be seen from Figure 2b, long exposure was associated with higher $C$ scores than short exposure, and tone sequences were associated with higher $C$ scores than color sequences. Looking at the results of both Experiments 1 and 2 (cf. Figure 2a vs. b) it turns out the two experiments showed very similar $C$ scores. In both the experiments, the results showed main effects of exposure and modality in the same direction, with no interaction between these two factors, and a particularly low score for the short color condition. The similarity of the results between the two experiments was further supported by two tests. First, as in Experiment 1, the only group that was not associated with a $C$ score reliably different from zero in Experiment 2 was the short color group, $t(9) = 1.50.$ Second, a three-way between-subjects ANOVA with the factors exposure, modality, and experiment (Experiment 1 vs. 2) only reinforced the main effects of modality and exposure, without showing any indication of a main effect of experiment or any interactions (apart from the reliable main effects of modality and exposure, all $Fs < 1.$)

The similarity between the results of Experiments 1 and 2 reinforces a number of conclusions. First, the knowledge acquired in AGL under these circumstances (learning by observation and element-by-element presentation of sequences) is primarily stimulus-specific overall (cf. Conway & Christiansen, 2006). Had the knowledge been abstract, the scores in Experiment 1 would have been considerably lower than those in Experiment 2. Second, learning under these circumstances is superior in the auditory modality compared to the visual modality (cf. Conway & Christiansen, 2005; Saffran, 2002). If the modality differences observed in Experiment 1 were due to differences in the abstractness of knowledge associated with different modalities rather than learning differences, then the same modality differences should not have been observed in Experiment 2, yet they were. Third, the results are inconsistent with the idea that extended observational exposure to regularities is associated with the establishment of increasingly abstract representations. Instead, extended exposure under these circumstances seems to lead to an increase in stimulus-specific knowledge. If extended exposure was associated with increasingly abstract representations, then the difference in $C$ scores between the long and the short

Method

Participants

Forty students at the Lund University (20 women and 20 men, ages 19–35 years, $M = 23$ years) took part in the experiment without any compensation. Each participant was randomly assigned to one of the four groups: short exposure – color, short exposure – tones, long exposure – color, or long exposure – tones ($n = 10$ in each condition).

Materials

The materials were the same as in Experiment 1.

Procedure

The procedure was the same as in Experiment 1, except that the participants were only exposed to one grammar instantiated in one modality during the exposure phase. Participants in the color groups saw color sequences from one grammar during the exposure phase and the participants in the tone groups heard tone sequences from one grammar during the exposure phase. Half of the participants in each group were exposed to Grammar 1 sequences and half to Grammar 2 sequences. At test, the participants classified sequences from Grammar 1 and sequences from Grammar 2 in the same modality as that used during the exposure phase.
groups should have been considerably larger for Experiment 2 compared to Experiment 1, yet the scores turned out to be very similar across exposure levels for the two experiments. An abstraction dissociation index for the long versus short exposure manipulation can be computed from the averages shown in Figure 2a and b. The difference between the average long exposure score and the average short exposure score was .17 for Experiment 1 and .21 for Experiment 2, which amounts to a between-experiments difference of .04 for the long versus short difference (the effect size for this difference in the three-way ANOVA reported above was \( \eta^2 = .0046 \), which may be considered a small effect size according to Cohen, 1988). Although that difference might have turned out to be reliable given enough statistical power, it is certainly also questionable whether such a small difference is enough to serve as a reasonable basis for an abstractionist account of AGL. For example, assuming a conventionally small effect size (\( f = .10 \)) in a hypothetical 2 \times 2 between-subjects design (long and short exposure vs. single and dual grammars) one would need at least 787 participants to detect the effect with a statistical power of .80 according to the program G*Power3 (Faul, Erdfelder, Lang, & Buchner, 2007). In practice, even more participants may very well be required since the effect size \( f = .10 \) is a liberal estimate. The lack of evidence for abstraction as a result of extended exposure in Experiments 1 and 2 can be contrasted to the direct evidence for increased stimulus-specific knowledge associated with the transition from short to long exposure in Experiment 1, a reliable average C increase of .17.

Experiment 3

Experiment 3 was designed to more closely investigate the possible formation of abstract representations in the visual modality (using color sequences and shape sequences). For that purpose, a sequence-by-sequence presentation technique where the whole sequence is visible on screen was used rather than the element-by-element presentation technique used in Experiment 1. Making the entire sequence visible on screen might enable visual learning to a larger extent than in Experiment 1 and might also encourage abstract visual learning to a larger extent, since the relations between different elements of a sequence become more apparent. In addition, since most AGL studies have used visual materials and sequence-by-sequence presentation techniques it is of interest to investigate the formation of abstract representations in such a paradigm.

Method

Participants

Forty students at the Lund University (26 women and 14 men, ages 18–56 years, \( M = 23 \) years) took part in the experiment in exchange for a voucher (value ~10 USD). Each participant was randomly assigned to one of the four groups: short exposure – shape test, short exposure – color test, long exposure – shape test, or long exposure – color test (\( n = 10 \) in each condition).

Materials

The materials were the same as in Experiment 1, except that the auditory sequences were replaced by sequences of geometric shapes (Figure 3).

Procedure

The procedure was the same as in Experiment 1, except that on each trial (both exposure and test) an entire sequence of 3–7 elements was shown for 500 ms times the number of elements in the sequence. Thus, a sequence of 3 elements was shown for 1,500 ms, a sequence of 4 elements for 2,000 ms, and so on. All participants observed color sequences from one grammar and shape sequences from the other grammar during the exposure phase. The exposure phase was either 6 blocks (the short conditions) or 18 blocks (the long conditions). At test, participants classified either color sequences or shape sequences depending on condition (the color conditions vs. the shape conditions). The same counterbalancing procedures as those described for Experiment 1 were used.

Results and Discussion

As in Experiment 1, \( C \) scores based on endorsement probabilities for matching and nonmatching test trials were computed and then submitted to a two-way between-subjects ANOVA with the two fixed factors exposure (long vs. short) and domain (color vs. shape). Figure 2c shows the mean \( C \) scores as a function of exposure and domain.

The results from the ANOVA showed a reliable main effect of exposure, \( F(1, 36) = 5.75, MSE = 0.05, \eta^2 = .13 \), but no main effect of domain, \( F < 1 \). There was no interaction between exposure and domain, \( F < 1 \). Figure 2c clearly shows the reason for the main effect of exposure: Long exposure was associated with higher \( C \) scores than short exposure.

Like the previous experiments, the results of Experiment 3 support the hypothesis that extended exposure under observational learning conditions in AGL gives rise to increased knowledge that is stimulus-specific in nature. The formation of abstract representations should have driven the \( C \) scores towards zero with extended exposure. In addition, all four conditions of Experiment 3 were associated with \( C \) scores reliably above zero. This is obvious for the
two long conditions simply by looking at the SEs for these conditions in Figure 2c. For the two short conditions shown in Figure 2c, where the results are less obvious, one-sample t tests showed that the scores were reliably above zero, \( t(9) = 1.88 \) (one-tailed) in the color condition, and \( t(9) = 2.54 \) in the shape condition. Taken together with the low performance of the visual short condition in Experiment 1 (where the statistical power to detect an effect was higher than in Experiment 3), the performance of the short conditions in Experiment 3, both of which used visual stimuli, suggests that visual learning of structural regularities benefits from sequence-by-sequence presentation rather than element-by-element presentation.

**General Discussion**

This study investigated the impact of extended exposure on the development of abstract (surface-independent) versus stimulus-specific representations in AGL. In the three experiments, short (6 blocks) and long (18 blocks) incidental observational learning was contrasted, using a methodological procedure developed by Conway and Christiansen (2006). Experiment 1 and 2 investigated auditory versus visual learning using an element-by-element presentation procedure, whereas Experiment 3 investigated visual learning using a sequence-by-sequence presentation procedure. Overall, the results both reinforce and extend results from other studies regarding stimulus-specificity and modality differences (Conway & Christiansen, 2005, 2006; Saffran, 2002). The results of this study clearly suggest that (1) extended exposure under incidental observational learning conditions in AGL leads to increased stimulus-specific knowledge and (2) there are differences between auditory and visual learning, the former being particularly more adapted to temporal information in stimulus displays.

The results of the current experiments stand in contrast to the idea that extended exposure promotes abstract knowledge in AGL (Manza & Reber, 1997; Meulemans & Van der Linden, 1997). Rather the results lend support to theories that propose a central role for surface-dependent knowledge in implicit learning (Kinder, Shanks, Cock, & Tunney, 2003; Perruchet & Vinter, 2002). However, it would be an oversimplification to say that implicit learning *necessarily* gives rise to surface-dependent knowledge. A central idea within episodic and attention-based theories of implicit learning is that the products of learning consist in episodic representations that are formed as a result of task constraints, intentions, expectations, and stimulus structure. In effect, participants may very well acquire abstract surface-independent knowledge if the learning task directly or indirectly encourages processing of abstract features of the materials (cf. Pacton & Perruchet, 2008; Whittlesea & Dorken, 1993). Furthermore, since incidental learning instructions usually encourage simple observation or short-term memorization, the upshot is usually that relational abstract learning is not triggered to any larger extent, and is not generally a mandatory consequence of incidental information processing.

Participants can learn quite abstract principles when they are explicitly instructed to do so, and they are often aware of the abstract rules as well (Johnstone & Shanks, 2001; Kuhn & Dienes, 2006; although see also Kuhn & Dienes, 2005). Furthermore, research on intentional learning of abstract principles underlying complex systems has shown that superficial similarities between domains may reduce attention to and learning of the underlying abstract principles (Goldstone & Sakamoto, 2003). This suggests that learning of abstract principles can occur intentionally and depends on attentional focus. There is little direct evidence to suggest that abstract knowledge is formed in ways that is independent from attention or intentions. In addition, even formal symbolic reasoning has been found to be affected by perceptual details, indicating a perceptual operative component even in these high-level intentional tasks (Landy & Goldstone, 2007).

Some studies appear to demonstrate genuine dissociations between abstract and surface-bound knowledge in implicit learning situations. Chang and Knowlton (2004) found that a font change between training and test dissociated the influence of chunk strength (a measure of similarity, or chunk overlap, between a test sequence and the entire set of training sequences) and rule adherence in AGL. The influence of chunk strength on classification was reduced by a change in surface characteristics between training and test, while the influence of rule adherence was not reduced. A functional magnetic resonance imaging study conducted by Lieberman, Chang, Chiao, Bookheimer, and Knowlton (2004) found that rule adherence was associated with caudate activation while chunk strength was associated with hippocampal activation, again suggesting a dissociation between abstract and surface-bound knowledge. Furthermore, sequences that violate the rules in AGL have been reported to activate the left inferior frontal gyrus (Broca’s area), a region believed to be implicated in syntactic processing (Forkstam, Hagoort, Fernandez, Ingvar, & Petersson, 2006; Petersson, Forkstam, & Ingvar, 2004).

However, rule adherence, even when balanced for chunk strength, is not a pure measure of abstract rule knowledge. Indeed, Johnstone and Shanks (1999) found that rule adherence had no influence when various similarity predictors were taken into account. Furthermore, the knowledge underlying transfer performance across different domains in AGL seems to be based primarily on repetition patterns (Lotz & Kinder, 2006; Vokey & Higham, 2005). Although, such knowledge can be used in the service of abstraction, it is by no means obvious that the knowledge is abstracted into a symbolic amodal format during learning (unless one does so intentionally and consciously). The same-different relationship is fundamental to most of the organisms and does not mandate a symbolic interpretation in and of itself (Perruchet & Vinter, 2002). The task still remains to specify exactly what it is about legal and illegal sequences that correlates with specific brain activities or is relatively unaffected by surface manipulations. It could be knowledge abstracted into a surface-independent format (e.g., algebraic rules) during learning, but the knowledge may also reflect relatively surface-dependent perceptual knowledge (e.g., repetition-based or statistical knowledge) that can be used intentionally.
or unintentionally in the service of abstraction as a result of task demands when the direct need for abstraction arises (e.g., at test). Both of these possibilities may be cast as varieties of abstraction, although quite different varieties whose respective validity will have implications for the proper view of the automaticity and the perceptual specificity of abstraction. The results of the present study point to an increasingly surface-dependent component of the knowledge associated with the extended observational learning.

Specifying the basis of and circumstances for eventual abstract knowledge is an important and a fundamental research topic for many different domains, such as learning, reasoning, decision making, and problem solving. Future research on abstract representations in implicit learning could investigate the impact of even longer observational exposure phases than the ones used in the present research. For example, if exposure is extended over several days or weeks, will incidental observation automatically lead to abstract knowledge (cf. Mathews et al., 1989; Pacton et al., 2001)? It will also be important to further investigate the impact of intentional learning and/or integrative cues versus unintentional learning on the formation of abstract representations, and the resulting flexibility of the acquired knowledge. Finally, it would be of interest to investigate stimuli differing in familiarity since higher familiarity and ease of representation has been suggested to be positively related to generalization, at least for infants (Saffran, Pollak, Seidel, & Shkolnik, 2007).

To sum up, the experiments reported in this article suggest that extended observational learning in AGL does not result in abstract surface-independent knowledge, but rather in increased stimulus-specific knowledge. This is consistent with a variety of computational learning models where perceptually grounded stimulus-specific, rather than abstract surface-independent, knowledge is formed during exposure to regularities (Christiansen & Curtin, 1999; Dienes et al., 1999; Redington & Chater, 1996; Servan-Schreiber & Anderson, 1990).

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References


Appendix

Exposure and Test Sequences for Experiments 1, 2, and 3

The sequences listed below were instantiated as colors or tones in Experiments 1 and 2, and as colors or as shapes in Experiment 3. The two grammars are shown in Figure 1.

<table>
<thead>
<tr>
<th>Exposure sequences</th>
<th>Test sequences</th>
</tr>
</thead>
<tbody>
<tr>
<td>Grammar 1</td>
<td>Grammar 2</td>
</tr>
<tr>
<td>VVM</td>
<td>XVM</td>
</tr>
<tr>
<td>XMM</td>
<td>VTR</td>
</tr>
<tr>
<td>XMM</td>
<td>VRX</td>
</tr>
<tr>
<td>XMM</td>
<td>VTRX</td>
</tr>
<tr>
<td>XMM</td>
<td>VRTRX</td>
</tr>
<tr>
<td>XMM</td>
<td>VRTRVX</td>
</tr>
<tr>
<td>XMM</td>
<td>VRTRVX</td>
</tr>
<tr>
<td>XMM</td>
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<td>XMM</td>
<td>VRTRVX</td>
</tr>
<tr>
<td>XMM</td>
<td>VRTRVX</td>
</tr>
</tbody>
</table>

*This sequence was not included in Conway and Christiansen (2006), but replaced a sequence that was listed twice in their materials (p. 906).

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