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Analogical inference: The role of awareness in abstract learning

William L. Gross and Anthony J. Greene
University of Wisconsin, Milwaukee, WI, USA

The acquisition and flexible expression of complex relations is often attributed to declarative memory processes. The extent to which such tasks may be done implicitly has not been sufficiently explored. We report that analogical or transfer processes may be accomplished implicitly. Our analogy task requires acquisition of a transverse patterning set, and then tests for transfer on an unrelated set. Participants learn the relations A > B (given a choice between A and B choose A) and B > C and the unrelated set X > Y and Y > Z. Only the experimental group was trained on the transverse pair C > A. At test all trials are unreinforced: A?B, B?C, A?C, X?Y, Y?Z, X?Z. Analogy was observed when the experimental group chose Z > X at greater frequency than controls who uniformly chose X > Z. Analogy occurred with or without awareness of the transfer. The capacity to transfer relations to an analogous set demonstrates a level of flexibility and abstraction not generally thought to be possible for implicit processes.

The capacities to acquire abstract or conditional contingencies and express them under novel circumstances are central to the adaptivity of learning and memory. That is, the extent to which learning can model complex relations (e.g., context-dependent outcomes) determines the upper limit of predictive capacity (Bialek, Nemenman, & Tishby, 2001) and similarly, the capacity to appropriately generalise (Shepard, 1987) and make inferences (Over & Green, 2001) allows behavioural repertoires to be extended well beyond the specific instances in which the learning occurred.

It is widely asserted that for learning and memory to be expressed flexibly, they must be declarative (Cohen, Poldrack, & Eichenbaum, 1997; Manns, Hopkins, Reed, Kitchener, & Squire, 2003; Reber, Knowlton, & Squire, 1996; Reed & Squire, 1999; Schacter, 1998). According to this view declarative memory (i.e., episodic and semantic memory) is required in learning tasks where the contingencies are sufficiently complex to require conscious deliberation; those tasks require the hippocampus because they depend on declarative memory processes which depend on the hippocampus (Clark, Manns, & Squire, 2001; Reed & Squire, 1999; Smith & Squire, 2005). In addition, the capacity to generalise a set of learned contingencies to new circumstances has been presumed to be an exclusively declarative memory process accomplished by deliberation (e.g., Reed & Squire, 1999). Conversely, non-conscious or implicit forms of learning (e.g., perceptual facilitation or procedural learning) are often characterised as inflexible (e.g., Cohen et al., 1997; Reber et al., 1996) and do not require the hippocampus (for a review see Squire, Shimamura, & Graf, 1985). Presently few experimental paradigms have directly tested the representational flexibility of implicit learning (see Greene, in press).

To clarify these issues, we introduce an analogical inference task that biases a transfer of contingencies learned in the transverse patterning

Address correspondence to: Anthony Greene, University of Wisconsin, Milwaukee, Department of Psychology, 2441 E Hartford Ave., Garland 224, Milwaukee, WI, 53211, USA. E-mail: ag@uwm.edu

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task to novel arrays (cf. Dienes & Altmann, 1997). As with transverse patterning, in the analogical inference task participants learn three items that form circular associations: A > B, B > C, and C > A. When only A > B and B > C are learned, humans and animals naturally select A > C, so the introduction of C > A is initially difficult to acquire (e.g., Dusek & Eichenbaum, 1998). However, the items can be organised into a global and internally consistent set of relationships, depicted in the left panel of Figure 1. Our goal was to test the flexibility of these conditional relationships and the necessity of awareness by observing whether participants would implicitly transfer relations learned in the transverse patterning task to a simultaneous analogy task. We refer to this combined task as the analogical inference task. The question was whether learning a transverse patterning sequence (left panel of Figure 1) would bias participants towards applying transverse patterning relations to a novel sequence (right panel of Figure 1).

Approaches emphasising the inflexibility of implicit learning would predict that the relational flexibility of analogy would only be possible with conscious strategies. We designed analogical inference to reduce the participants' conscious awareness of the task contingencies. The instructions given to the participants were minimal and the task was designed to be fast paced. We used homogeneous faces as stimuli in order to minimise the likelihood that participants would name the items. Verbal reasoning would likely make the task substantially easier, increase the likelihood of conscious memory, and limit the extent to which findings could be compared between humans and other species.

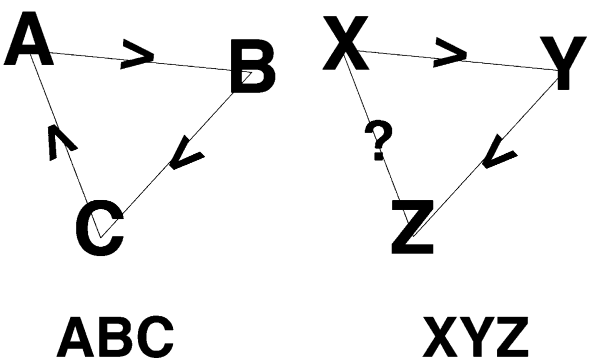

Figure 1. Schematic drawing of the two sets of stimuli and their relationships. ABC is a complete transverse patterning, while XYZ is missing the relationship between X and Z.

METHOD

The analogical inference experiment consisted of 42 participants (mean age: 20.3; $SD = 2.5$; 12 male, 18 female). All participants were naive to the transverse patterning problem prior to the experiment. A total of 20 participants were randomly assigned to the transverse patterning exposed condition, 10 to the non-exposed condition, and 12 to the recognition task.

Materials

Stimuli were pictures of faces, shoulder high, taken from a 1952 local high-school yearbook. Pictures from this era were chosen for their relative homogeneity of hairstyle and clothing in order to incline participants to rely exclusively on facial features for recognition. In order to reduce the possibility that participants would name the items we excluded all faces that were easily named by participants. From a pool of 300 pictures, we used a simple 2-back task (e.g., Owen, McMillan, Laird, & Bullmore, 2005) to determine the six most recognisable faces. Stimuli assignments were counterbalanced. Trials consisted of two faces (~ 8 cm tall) displayed side-by-side on a computer screen, and the distance from the eye to the screen was determined by the participant (~ 30 cm). Faces were rendered in greyscale and displayed against a black background. The location of the faces on the screen was pseudorandom; all faces were shown an equal number of times on the left and right of the screen.

Analogy procedure

The faces were displayed for 1750 ms followed by a 250 ms feedback screen displaying either "Correct" in blue, or "Incorrect" / "No Response" in red. Participants were instructed that for each pair of faces they would have to learn, through trial and error, which face to select. Selection was made by pressing either the left or right mouse button corresponding to the position of the correct face.

Participants were randomly assigned to either the transverse patterning condition ($n = 20$) or the control condition ($n = 10$). While all participants were trained on A > B and B > C, only those assigned to the transverse patterning condition were trained on the transverse patterning pair

C > A. All were concurrently trained on an unrelated set X > Y and Y > Z (see Figure 1 and Table 1).

As can be seen in Table 1, a staged training design (Greene, Spellman, Dusek, Eichenbaum, & Levy, 2001) was used such that training began with only two pairs, and additional pairs were introduced in subsequent training blocks. In each of three training blocks and at test, a given pair was presented 60 times in pseudo-random order. For a given training block, participants needed to reach 80% correct (48); no participants failed to reach criterion. Because each training pair was presented an equal number of times, those in the transverse patterning group received more net training than those in the control group. The test block consisted of the six unreinforced, forced-choice pairs: A?B, B?C, A?C, X?Y, Y?Z, X?Z.

For those in the transverse patterning condition, the ABC sequence constitutes a transverse patterning task. For all participants, the XYZ sequence was missing the critical Z > X pair. The control group was not trained on C > A and at test uniformly selected A given the unreinforced choice A?C. Note that using the relationships in the full transverse patterning ABC sequence, one could complete the XYZ sequence with the transverse patterning analogue, Z > X. Because controls were never shown the C > A transverse patterning pair they have no basis for this analogue. Our test for analogical transfer was to measure whether participants exposed to the full ABC transverse patterning set would transfer an analogous solution to the incomplete XYZ set at rates greater than controls.

Post-experimental questionnaire

Awareness was measured through a post-experimental questionnaire designed to assess participants' awareness through a series of increasingly leading questions (Frank, Rudy, & O'Reilly, 2003; Greene, Gross, Elsinger, & Rao, 2006; Greene et al., 2001; Smith & Squire, 2005). The questionnaire and the scoring procedure are provided in the Appendix. The questionnaires were rated by five independent judges using a 5-point scale with 1 corresponding to no awareness of transfer and 5 corresponding to clear evidence of a transfer across stimulus sets (ABC–XYZ).

TABLE 1
Staged training design

Block	*Arrays presented*	
Training 1	A > B	X > Y
Training 2	A > B, B > C	X > Y, Y > Z
Training 3	A > B, B > C, ***C > A***	X > Y, Y > Z
Test	A?B, B?C, C?A	X?Y, Y?Z, Z?X

Training blocks 1–3 were reinforced training trials, and test trials were unreinforced. Those assigned to the transverse patterning (transverse patterning) condition were trained on the C > A pair in block 3 while those in the control condition were not.

Recognition procedure

One possibility is that the transfer effect depends on deliberate strategies that are not detected in the post-experimental questionnaire. To further assess the possible use of explicit strategies, we implemented a recognition task. If participants acquire the relations at study in a manner that allows explicit analogy (that is, they understand that ABC and XYZ are parallel relations and that they have deliberately inferred the untrained ZX relation) then they should be able to distinguish studied pairs (AB, BC, CA, XY, YZ) from the non-studied pair that they deliberately inferred (ZX). If, on the other hand, the relations are implicitly organised, they may not recognise ZX as a non-studied, inferred pair (for this argument see Greene et al., 2006). The study portion of the recognition task is identical to the study portion of the transverse patterning condition, while at test they are instructed to distinguished studied from non-studied pairs. Studied pairs (AB, BC, CA, XY, YZ) were compared to the inferred pair (ZX) and foil pairs consisting of studied faces in novel configuration (e.g., AX, BZ, etc.; for each participant, five of the nine possible foils were randomly selected). While correct rejection of XZ as a studied item could imply the use of explicit or implicit strategies, consistent false positive on XZ compared to foils would be inconsistent with the use of a deliberate inference strategy.

RESULTS

Overall performance on the C > A pair for the transverse patterning group was 88.25% ($SE =$ 2.49%). This was significantly different than chance, $t_{(19)} = 14.84$, $p < 0.01$, while the control group never chose C > A. Likewise, control participants rarely chose Z > X (0.29%, $SE = 0.18\%$).

The exposure to transverse patterning contingencies predisposed some participants to adopt a transverse patterning strategy when interpreting a novel set of contingencies where no transverse patterning contingencies had been trained. For those exposed to transverse patterning, the overall tendency to select Z > X was 41.31% (*SE* = 9.14%), significantly more than controls, $t_{(30)} = 3.42$, $p < 0.01$. The overall Z > X score of 41.31% does not indicate that participants are guessing because the distribution of Z > X was distinctly bimodal: 10 participants (analogy) reliably chose Z > X (80.2%, *SE* 3.9%; range 60.87–100%), significantly above chance $t_{(9)} = 7.64$, $p < 0.01$, while the other 10 participants (no-analogy) did not reliably choose Z > X (2.40%, *SE* 1.01%; range 0–9.09%) and no participants had intermediate scores. In addition, performance during training did not differ for those who would later engage an analogy strategy compared to those who would not ($F < 1$, *ns*). While only half of transverse patterning participants adopted an analogy strategy, there is no compelling reason that all participants should, since the analogical solution is not explicitly trained, nor is there a correct answer. We did not expect every transverse patterning participant to choose Z > X because during training X is always right and Z is always wrong. The result demonstrates that prior exposure to transverse patterning contingencies biases participants to apply those contingencies on a similar but unrelated set.

Of the 20 participants in the control condition, average awareness on the post-experimental questionnaire was 1.47 (*SE* = 0.3). The inter-rater reliability was high: Cronbach's $\alpha = 0.97$ (Bland & Altman, 1997); lowest pairwise $r = 0.84$ (Pearson's *r*). Awareness scores did not differ between those who adopted an analogy strategy and those who did not ($t < 1$, *ns*). In addition, a majority of participants asserted that no logical choice for the ZX pair existed (see Appendix, question 5) and so received the lowest awareness rating; those participants did not differ from others in their rate of Z > X selection ($t < 1$, *ns*).

In addition, the recognition task revealed that participants mistook the ZX pair for a studied item, which is inconsistent with the use of an explicit transfer strategy. The rate of false alarms for ZX pairs (91.67%, *SE* = 8.33%) and the rate of correct recognition for studied items (93.33%, *SE* = 2.85%) did not differ, $t_{(11)} < 1$, while the rate of false alarms for foils (21.67%, *SE* = 4.58%) was significantly different than that for ZX pairs, $t_{(11)} = 7.47$, $p < .01$.

DISCUSSION

Introducing an analogous array can affect how participants treat an independent set of stimuli. Introducing the transverse patterning sequence increases Z > X choice significantly from controls. We showed that participants performing the analogical inference task were largely unaware of the task paradigm. While some assert that complex relations must be consciously learned (e.g., Reed & Squire, 1999), much recent research has cast doubt on this claim (Chun & Phelps, 1999; Dienes & Altmann, 1997; Ellenbogen, Hu, Payne, Titone, & Walker, 2007; Greene et al., 2006; Greene et al., 2001; Harrison, Duggins, & Friston, 2006; Park, Quinlan, Thornton, & Reder, 2004). Analogical inference is another task that shows implicit, flexible learning. It is becoming increasingly evident that flexible representations suitable for novel expression are not the sole domain of deliberative processes. Rather than construing one processing mode as more flexible than another, it is perhaps more instructive to recognise that each mode is flexible in unique ways (Willingham, 1997, 1998) and that in addition, flexibility is further served by competitive access to multiple processing modes (e.g., Gold, 2004; Poldrack & Packard, 2003).

One potential problem with the post-experimental assessment of awareness is the possibility that it is not identical to awareness at test. While it is possible that awareness could increase during or after test, it seems unlikely that awareness could decrease (cf. Greene et al., 2001), particularly if it were the foundation for participants' response pattern. Moreover, levels of awareness insufficient for articulation are likely to be insufficient to direct performance (for this argument see Frank, Rudy, Levy, & O'Reilly, 2005). Thus by demonstrating transfer in those with little or no post-experimental awareness, we suggest it is likely these participants are unaware during test.

An interesting caveat to the present results is the finding that transverse patterning is not observed in adult human amnesic patients (Astur & Sutherland, 1998; Reed & Squire, 1999; Rickard & Grafman, 1998) nor in rodents with hippocampal lesions (Alvarado & Rudy, 1995; Dusek &

Eichenbaum, 1998; Rondi-Reig, Libbey, Eichenbaum, & Tonegawa, 2001). The declarative memory model (e.g., Squire, 1987) asserts that conditional learning and flexibility are related in that they both require the hippocampus and medial temporal lobe for conscious memory processing (e.g., Reed & Squire, 1999). Clearly the present findings present a difficulty for the declarative memory model if transverse patterning relations can be transferred to novel sets without participants' awareness. An alternative framework for understanding the potential role of the hippocampus in transverse patterning is configural association theory (Rudy & Sutherland, 1989, 1995). Accordingly, conditional associations are acquired by binding complex contingencies into unitary contingencies (e.g., items B and C are reconfigured into a new item BC); the acquisition of conditional associations is distinct from processes that allow flexibility (e.g., Frank, O'Reilly, & Curran, 2006; Frank, Rudy, Levy, & O'Reilly, 2005; Van Elzakker, O'Reilly, & Rudy, 2003). If transverse patterning is acquired using a configural strategy—in which the relationships are bound to the stimuli with which they were learned—one would not predict that there could be any transfer to a novel set of stimuli. Relational learning theory (e.g., Ryan, Althoff, Whitlow, & Cohen, 2000) asserts that relationships are learned which can be abstracted from the specific instances or stimuli and expressed in novel circumstances (e.g., Greene et al., 2001). That is not to say that configural learning strategies could not be useful under other conditions: one might encode complex relationships in a chunked, stimulus-bound form (i.e., configural) or in an abstract form (i.e., relational) depending on cognitive pressures and the salience of relationships. Similarly, certain complex tasks may be optimally solved with verbal or other declarative strategies. It may be that task demands determine whether the optimal strategy is relational, configural, or declarative. However the capacity to engage in multiple strategies is itself not predicted by configural or declarative models, but is consistent with relational learning. It may also be that the present version of transverse patterning does not entail the hippocampus, in which case it would be unique; further resolution of this issue requires a methodology such as functional magnetic resonance imaging to simultaneously assess task performance, awareness, and the involvement of the hippocampus. However, the present data do show clearly that a level of encoding exhibiting a high degree of abstraction and flexibility is possible without deliberative processes or awareness.

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APPENDIX: POST-EXPERIMENTAL QUESTIONNAIRE

Questions

1. What did you think we were trying to find out with this experiment?
2. What did you think was the point of the trials where you were not told if you were right or wrong (the no feedback condition)?
3. Regarding question 2, were all the face configurations in the no feedback condition the same as face configurations you had already learned when feedback was given?
   ___ Yes ___ Not Sure ___ No
   If no, do you think there was a correct answer? ___ Yes ___ Not Sure ___ No
   If you believe there was a correct answer, explain why:__________________
4. You were given the following pair of faces several times, but never told an answer. Circle the face you believe is correct (guess if necessary):
   [The Z–X stimulus pair is here]
5. Regarding question 4, what reason (if any) did you have for your choice (check one):
   ___ There is a logically correct choice because (explain):
   ___ One just seemed right but I can't explain why.
   ___ I guessed: There may be a correct face, but I don't know what it is.
   ___ I made a random choice because there is no correct choice.
   ___Other: Explain:________________________________
6. What strategy (if any) did you use to learn the faces (check one):
   ___ I already knew the faces: If so, from where?
   ____
   ___ I gave them names. ___ I memorized each face. ___ I memorized part of the each face.
   ___ I just watched and eventually got it. ___ I used their similarity to familiar faces.
   ___ No strategy. ___ Other strategy (please describe in the space below)

Procedure for scoring questionnaires

Raters were trained to assign a rating between 1 and 5 in the following manner: 5 = an explicit statement of a deliberate strategy for Z?X; 4 = probable use of a deliberate strategy although not directly stated (e.g., an assertion that the two sets—ABC & XYZ—may be related); 3 = uncertain reference to relationships between stimulus sets but no indication of a deliberate strategy relating the two sets; 2 = no evidence of knowledge of contingencies or purpose of the task; 1 = assertion that there was no rationale for making the Z?X choice.

Ratings on the basis of question responses were assigned as follows: Questions 1–3: some assertion that there was a relationship between the stimulus sets or a deliberate strategy for the Z?X choice resulted in a score of 4 or 5 depending on the clarity of the assertion. No participants asserted knowledge of a relationship between the two sets, or a deliberate strategy for the Z?X decision. Question 4 displays the Z?X pair and asks the participant which face they chose, while Question 5 asks the participant to explain the reason for their selection on Question 4. The first of several choices is: "There is a logically correct choice because (explain)" while the last is "I made a random choice because there is no correct choice". Those selecting that there was a logical choice and then providing a rationale (regardless of whether it was correct) were given a score of 3 or 4 depending on the clarity. Those who provided no logical rationale but provided vague statements that they suspected a rationale might exist were given a score of 2 or 3 depending on the clarity. If participants did not choose the first option (a logical choice was made) they were assigned a score of 2 or 1. Those who chose that they had guessed because there is no correct choice were given a score of 1. During the debriefing when the parallel relationship between stimulus sets was explicitly explained, most participants were quite surprised about its existence and thought that they had been trained on ZX.