Research Article

Cognitive Control of Sequential Knowledge in 2-Year-Olds

Evidence From an Incidental Sequence-Learning and -Generation Task

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ABSTRACT—*Under incidental instructions, thirty-eight 2-year-olds were trained on a six-element deterministic sequence of spatial locations. Following training, subjects were informed of the presence of a sequence and asked to either reproduce or suppress the learned material. Children's production of the trained sequence was modulated by these instructions. When asked to suppress the trained sequence, the children were able to increase generation of paths that were not from the training sequence. Their performance was thus dependent on active suppression of knowledge, rather than on a random generation strategy. This degree of control in 2-year-olds stands in stark contrast to 3-year-olds' failure to control explicitly instructed rule-based knowledge (as measured by the dimensional-change card-sort task). We suggest that the incidental nature of a learning episode enables the acquisition of a more procedural form of knowledge with which this age group has more experience prior to the onset of fluent language.*

Research into cognitive control in infancy and early childhood is central to understanding the origins and development of cognition. In addition to establishing that children of a given age have attained a certain level of knowledge or conceptual complexity, it is important to determine the extent of control that they have over this knowledge. Knowledge that cannot be controlled and used appropriately is of little value.

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One popular test of cognitive control is the dimensional-change card-sort (DCCS) task (e.g., Kirkham, Cruess, & Diamond, 2003; Kloo & Perner, 2005; Munakata & Yerys, 2001; Zelazo, Frye, & Rapus, 1996). In this task, children are asked to sort bivalent cards (e.g., red cars and blue rabbits) according to one of two dimensions (e.g., by color). After successfully sorting the cards by the first dimension, they are asked to switch to sorting by the second dimension (e.g., by shape, not color). Despite responding correctly to questions concerning the game rules, 3-year-olds typically fail to switch the rule by which they sort. By the age of 4 years, children are typically able to switch rules. Explanations of this developmental shift involve acquisition of a wide variety of executive functions, such as ability to inhibit attentional inertia (Kirkham et al., 2003), ability to modulate one's perspective of a single object (Kloo & Perner, 2005), and ability to integrate hierarchical rule structures (Zelazo, 2004). All such developmental accounts address changes in children's ability to manipulate or inhibit mental representations of the stimulus features and rules acquired through explicit instruction.

Given that success in the DCCS task depends on an ability to control knowledge acquired through explicit instruction, it is worth asking whether knowledge acquired under incidental instructions might follow a different developmental trajectory. Incidental-learning paradigms are frequently used in the adult learning literature to examine the acquisition of putative implicit knowledge (Cleeremans, Destrebecqz, & Boyer, 1998)—knowledge that is in some way inaccessible to explicit report (Shanks & St. John, 1994). Moreover, incidental learning (e.g., through the observation of peers' and adults' activities) is a central form of early learning, prior to the onset of fluent language (Rogoff, 1990).

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The serial reaction time (SRT) task involves teaching adult subjects a sequence of motor responses under incidental instructions (Cleeremans & McClelland, 1991; Nissen & Bullemer, 1987). Subjects respond to a series of visual cues by pressing corresponding keys as quickly as possible. The cue presentation and correspondingly the subjects' responses contain sequential structure. However, the subjects are not informed that this is the case. After training, knowledge of the sequential regularities is probed through direct and indirect measures (Jiménez, Méndez, & Cleeremans, 1996). Here, we report on an adaptation of this paradigm that makes it possible to explore 2-year-olds' ability to control sequence knowledge acquired incidentally.

To assess cognitive control of knowledge learned in the SRT task, we (Destrebecqz & Cleeremans, 2001) adapted Jacoby's (1991) process-dissociation procedure (PDP) for use with the SRT. The PDP compares performance in two separate tasks: (a) an *inclusion task*, in which learned material should be reproduced, and (b) an *exclusion task*, in which learned material should be suppressed. Our adaptation therefore involves asking trained subjects to generate sequences of key presses that either resemble (inclusion) or differ from (exclusion) the training sequence as much as possible. In the exclusion task, subjects must first activate the learned response and then inhibit this and select another response. In this task, unlike in traditional cognitive-control tasks such as the DCCS task, learning and control of the sequential regularities contained in the material are based not on mastering explicit rule structures, but rather on intentionally using incidentally acquired knowledge. In the following experiment, 2-year-olds were first taught one of two six-element deterministic sequences of spatial locations. We then tested their ability to control this acquired knowledge by comparing their generation of sequences under inclusion and exclusion instructions.

METHOD

Design

Children were trained on one of two six-element sequences of spatial locations on a game board (S1: -A-C-B-D-A-B-; S2: -C-A-D-B-A-B-). Across all children, the elements A through D were consistent in their spatial relations to one another. However, the assignment of the elements (A–D) to the locations on the game board (1–4) was varied. Each numbered location was identified by the same picture across all children. Thus, for example, the sequence A-C-B-D-A-B might trace the path 1-3-2-4-1-2 (table-chair-sofa-hat-table-sofa) for one child, but 2-1-4-3-2-4 for another (sofa-table-hat-chair-sofa-hat; see Fig. 1).

S1 and S2 were balanced for the frequency of individual elements (in both S1 and S2, A and B each occurred twice and C and D each occurred only once) and for the number of predictable elements given one or two elements of context. The sequential differences between S1 and S2 made it possible to assess learning by comparing subjects' generation of material

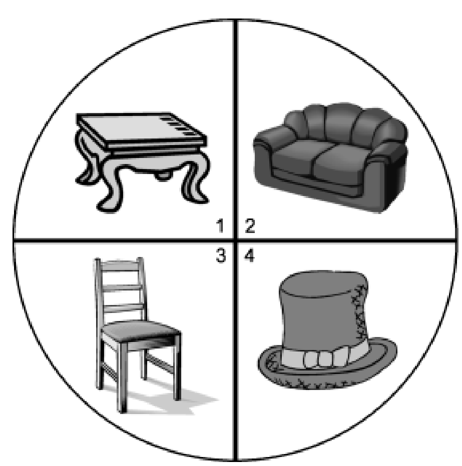

Fig. 1. The game board used in the task (the number labels were not visible to the subjects). Children were assigned to one of four groups in which the elements of the training sequences were aligned to the locations on the board in the following ways: (a) A-1, B-2, C-3, D-4, (b) A-2, B-4, C-1, D-3, (c) A-4, B-3, C-2, D-1, or (d) A-3, B-1, C-4, D-2.

from the training sequence with their generation of material from the control sequence.

Following training, the children were asked to perform a generation task under either inclusion or exclusion instructions. Generation condition (inclusion or exclusion), sequence (S1 or S2), and element locations (arrangement 1, 2, 3, or 4) were counterbalanced across subjects.

Subjects

Sixty 2-year-olds took part in this study. Usable data were obtained from 38 subjects (26 girls), who had a mean age of 723 days (24.1 months; $SD = 8.3$ days). Of the 22 excluded subjects, 9 refused to complete the task, 1 was excluded because of experimenter error, 2 were excluded because of interference by their parent, 7 failed to meet the minimum training requirement (five sequence repetitions), and 3 failed to meet the minimum generation-task requirement (to have visited each location at least once). Parents volunteered their children to participate in the research program.

Materials

The game board (Fig. 1) was 60 cm in diameter. Each of its four locations was marked with a picture of an object (a sofa, a chair, a hat, and a table). Other materials consisted of two toy cats and six toy dogs.

Procedure

The child was seated on his or her parent's lap, with the game board placed on the table directly in front of them. The experimenter sat across the table, facing the child. The experimenter explained that the study involved a chasing game in which the experimenter would move a cat from place to place on a game board and the child's task was to chase the cat with a toy dog as quickly as possible. The parent was asked to encourage the child to chase the cat, but not to prompt the child to move in any particular direction. Neither the parent nor the child was told that the task contained sequential structure.

Training Phase

The experimental session began once the child was seated. The game board was covered by a sheet of cardboard, on which all six toy dogs were placed. The child was encouraged to pick his or her favorite dog, and then the other five were removed. Next, the experimenter introduced a toy cat and explained that in the game, "I will be the cat, and you [the child] will be the dog."

Once the child had successfully followed the cat to two successive practice locations on either side of the midline, the game board was revealed, and the experimenter exclaimed, "Look at all these places where the cat can hide from the dog! Can the dog catch the cat here?" The experimenter then placed the cat on the first location in the training sequence. Once the child had placed the dog in the same location on the game board, the experimenter moved the cat to the next location in the sequence. This was repeated until the child had chased the cat to all locations in the sequence. The sequence was repeated a minimum of 5 times and a maximum of 12 times. So that the child would maintain interest in the game for as long as possible, he or she was given the opportunity to chase with different toy dogs. This gap in training always occurred between repetitions of the sequence.

We used a subject-controlled variable training procedure. The training phase was terminated if the child became too disinterested to continue the training or if the maximum of 12 repetitions of the sequence (blocks) had been reached.

Generation Phase

The experimenter introduced the generation phase directly following the training phase: "This time you are going to be a cat, and I'll be a dog." The child was then told that during the first game, "the cat was always running away in a special way, from place to place." The child was then prompted with the first two locations that the cat had visited—the first two elements of the training sequence (S1: A-C; S2: C-A). At this point, the procedure for the inclusion and exclusion conditions differed.

If the child was in the inclusion condition, he or she was asked, "Do you think you can remember which way the cat went next? Can you go the same way as the cat was going before?" The experimenter then encouraged the child to pick up the cat (placed at the second of the two prompt locations) and move it to a new location. Throughout the generation phase of this condition, the experimenter reminded the child to go "the same way as the cat was going before." The child was included in the analysis only if he or she visited each of the locations at least once.

If the child was in the exclusion condition, he or she was shown a new cat. The experimenter said, "This is a different cat, and this cat goes a different way than the other cat." The experimenter then prompted the child with two locations constituting a transition that had not been present in the training sequence (S1: A-D; S2: C-B). Throughout the generation phase in this condition, the experimenter reminded the child to go "a different way than the other cat." As in the inclusion condition, the child was included in the analysis only if he or she visited each of the locations at least once.

Children were encouraged to generate a minimum of 4 and a maximum of 18 transitions. Sessions were recorded on videotape so that the sequences generated by each child could be coded later from these records. If a child visited the same location consecutively (e.g., A-A), only one visit to that location was included in the scored generation sequence. Interobserver reliability was estimated by comparing the coded generation sequences of 12 randomly selected children (6 from the inclusion condition and 6 from the exclusion condition) with those of a second observer. The sequences as coded by the first and second observers were aligned with respect to the largest continuous string of agreements between the two. Cohen's κ was then calculated, yielding a satisfactory reliability of .85.

RESULTS

Children were trained on a mean of 7.2 (SE = 0.23) repetitions of the training sequence. The number of repetitions did not differ between the inclusion and exclusion conditions (inclusion: M = 7.4, SE = 0.35; exclusion: M = 7.1, SE = 0.30), $t(36) < 1$. The proportion of generated pairs (e.g., A-C), triplets (e.g., A-C-B), and quadruplets (e.g., A-C-B-D) that were part of the training sequence was calculated for each child by dividing the number of generated pairs, triplets, and quadruplets from the training sequence by the total number of pairs, triplets, and quadruplets generated. The mean proportions are shown in Figure 2.

We conducted a mixed-design analysis of covariance (ANCOVA) on these proportion scores. The ANCOVA included one within-subjects factor (length of chunk: pair, triplet, or quadruplet), one between-subjects factor (instructions: inclusion or exclusion), and one covariate (number of training blocks received). This analysis revealed a significant effect of length of chunk, $F(2, 70) = 7.3$, $p_{rep} = .99$, $\eta_p^2 = .172$. Children produced fewer long than short chunks from the training sequence, because the probability of making an error increases with increasing length of the chunk. There was also a significant effect of instructions, $F(1, 35) = 4.0$, $p_{rep} = .88$, $\eta_p^2 = .102$. Children produced less of the training material under exclusion than under inclusion instructions. No other effects or interactions reached significance (Fs < 1).

Despite the effect of instructions, we cannot conclude from this evidence alone that subjects could control their expression of the training sequence on the basis of knowledge acquired during the training phase. The scores for the inclusion and exclusion conditions might also reflect controlled expression of nonsequential information, such as the frequencies of the

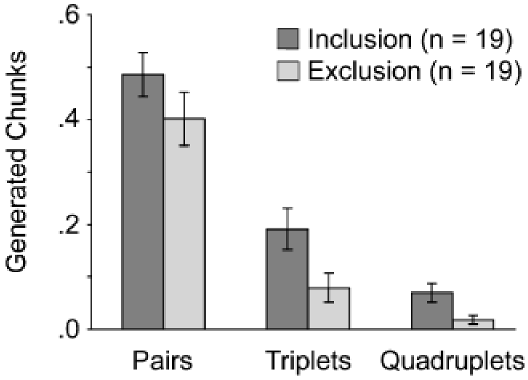

Fig. 2. Children's generation of chunks from the training sequence under inclusion and exclusion instructions. Generation scores correspond to the number of generated pairs, triplets, and quadruplets from the training sequence divided by the total number of pairs, triplets, and quadruplets that were generated. Error bars correspond to standard errors.

different locations (which were unequal in the training sets) or simple spatial patterns, such as the frequencies of reversals (which were rare in the training sets—S1: A-B-A, which occurred across the transition from one repetition of the training sequence to the next; S2: B-A-B).

To determine whether the effect of instructions was due to differential expression of genuine sequential knowledge, we compared the conditional probabilities associated with particular generated pairings of elements (Jiménez et al., 1996). We examined the probabilities that prior to a specified target element, the children had generated a specific context element that occurred immediately before the target in the training sequence rather than a context element that occurred immediately before the target in the other (control) sequence or a context element that occurred immediately before the target in both sequences. Thus, the target pairings were selected such that their grammaticality differed with respect to the training sequences (e.g., they were grammatical in S1 but not S2). Conditional probabilities for the two training sequences could then be used as controls for each other. Conditional probability data also provided a measure of the degree to which the sequences were learned, as they could be compared with the baseline chance level of performance.

Thus, we compared the probabilities of children having generated the elements C and D immediately prior to generation of B (denoted as C|B and D|B respectively).[1] As element A appeared before element B in both S1 and S2, we did not compare A|B between conditions. Because it was possible to generate one of three elements prior to B (repetitions were not allowed), the baseline probability for C|B and D|B was .33. During S1 training, C appeared before B (A-*C*-*B*-D-A-B), whereas during S2 training, D appeared before B (C-A-*D*-*B*-A-B). Thus, if children in the inclusion condition had learned the sequence, one would expect higher probabilities of C|B than of D|B among those children trained on S1, and higher probabilities of D|B than of C|B among those children trained on S2. One would also expect generation of C|B and D|B to be above chance for children trained on each of these transitions (children trained on S1 and S2, respectively). Moreover, if children in the exclusion conditions were able to control their expression of the trained sequence, they would be expected to avoid generating strings that were grammatical in their taught sequence and, thus, would be more likely to generate sequences that were in fact grammatical in the alternative (untaught) sequence; in other words, children taught S1 would be expected to generate D|B more than C|B, whereas those in S2 would be expected to generate C|B more than D|B. Figure 3 demonstrates the predicted patterns indicating knowledge and expression of the training sequences in the inclusion conditions and knowledge and suppression of the training sequences in the exclusion conditions.

We analyzed the conditional probabilities of children's generation of C|B and D|B using a mixed-design ANCOVA. The ANCOVA included one within-subjects factor (context element: C or D), two between-subjects factors (training sequence: S1 or S2; instructions: inclusion or exclusion), and one covariate (number of training blocks received). This analysis revealed a significant three-way Context Element × Training Sequence × Instructions interaction, $F(1, 33) = 9.7$, $p_{\text{rep}} = .98$, $\eta_p^2 = .227$. No other effects or interactions were significant (Fs < 2). This interaction confirmed that the children were able to control their expression of the sequence they had learned during training according to the instructions they received. To explore the children's performance further, we conducted separate conditional-probability analyses within the inclusion and exclusion conditions.

Inclusion Performance

A mixed-design ANCOVA with one within-subjects factor (context element: C or D), one between-subjects factor (training sequence: S1 or S2), and one covariate (number of training blocks received) revealed a significant Context Element × Training Sequence interaction, $F(1, 16) = 4.6$, $p_{\text{rep}} = .88$, $\eta_p^2 = .224$. Thus, the conditional probabilities associated with the generation of C|B and D|B depended on whether the children had been trained on S1 (in which C|B was grammatical) or S2 (in which D|B was grammatical). In both training conditions, the children in the inclusion condition were more likely to generate a grammatical path than an ungrammatical path. This indicates that the 2-year-olds had at least partially learned and were able to express the sequence that they had been trained on. No other effects were significant (Fs < 1). The probabilities of S1 children producing

[1]This particular analysis was chosen because it was unique in comparing learning of transitions that (a) were not presented across the gaps in training (which occasionally occurred between repetitions of the sequence), as would be the case if, for example, we compared the conditional probability of generating D or C after B, and (b) were not explicitly taught in the prompted pair at the beginning of the test phase, as would be the case if we compared the conditional probability of generating C or D before A. Choosing A or B as the target element in the conditional pairing was the most suitable approach for analyzing performance because the only possibility for subjects in the exclusion condition was to generate an element from the alternate (control) sequence.

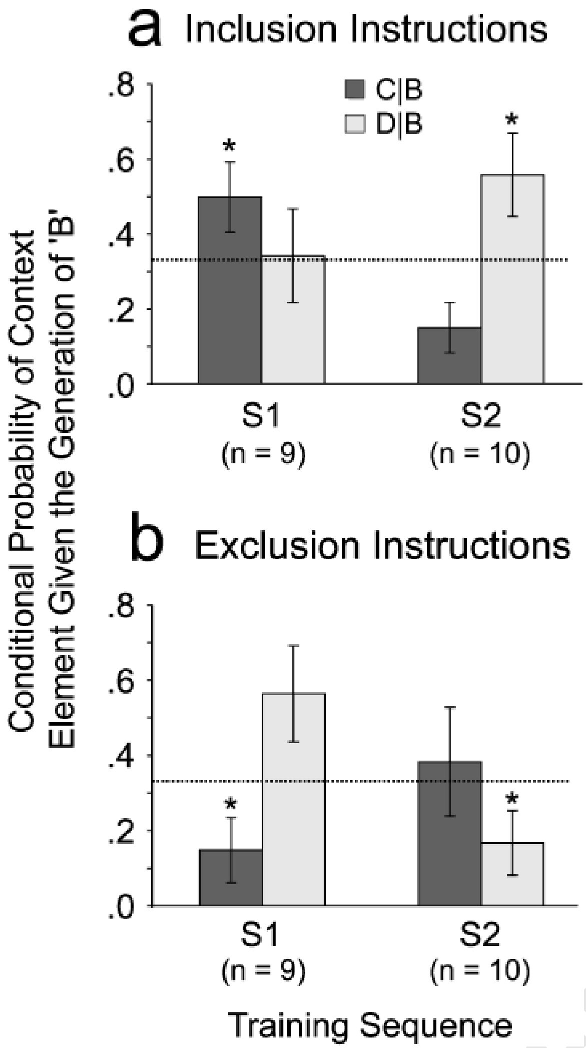

Fig. 3. Conditional probabilities associated with generation of elements C and D before element B (i.e., C|B and D|B, respectively) for children given inclusion instructions (a) and those given exclusion instructions (b), as a function of training sequence. For children trained on S1, C|B was grammatical and D|B ungrammatical. For children trained on S2, D|B was grammatical and C|B ungrammatical. Error bars correspond to standard errors. The dotted line corresponds to the chance level of .33, and the asterisks indicate conditional probabilities reliably different from chance, $^*p_{rep} > .88$.

C|B and of S2 children producing D|B (see Fig. 3a) were, as predicted, both significantly greater than chance (.33), $t(8) = 1.8$, $p_{rep} = .88$, $d = 0.59$, and $t(9) = 2.0$, $p_{rep} = .89$, $d = 0.64$.

Exclusion Performance

A mixed-design ANCOVA with one within-subjects factor (context element: C or D), one between-subjects factor (training sequence: S1 or S2), and one covariate (number of training blocks received) revealed a significant Context Element × Training Sequence interaction in the exclusion condition, $F(1, 16) = 4.8$, $p_{rep} = .88$, $\eta_p^2 = .232$. Thus, the conditional probabilities associated with the generation of C|B and D|B depended on whether the children had been trained on S1 (in which C|B was grammatical) or S2 (in which D|B was grammatical). In both training conditions, children in the exclusion condition were more likely to generate an ungrammatical path than a grammatical path. We conclude that the children in this condition were able to suppress the expression of the training sequence by referring to their knowledge of that sequence. No other effects were significant (Fs < 2). We made no specific predictions concerning how children's generation of grammatical pairs would compare with chance level of performance (a conditional probability of .33) under exclusion instructions. However, it is interesting to note that the probabilities associated with grammatical paths were significantly below chance both for children trained on S1, $t(8) = 2.1$, $p_{rep} = .90$, $d = 0.72$, and for children trained on S2, $t(9) = 1.9$, $p_{rep} = .88$, $d = 0.61$.

DISCUSSION

Following incidental training on a sequence of spatial locations, 2-year-olds were asked to either reproduce or suppress their knowledge of the sequence. Analyses revealed that (a) the children's production of the trained sequential material was modulated by these instructions and (b) those asked to suppress the trained material were able to increase their generation of sequence paths that were not part of the training sequence. Thus, exclusion instructions resulted in active suppression of knowledge of the training sequence, rather than in a random generation strategy. These results provide evidence of incidental sequence learning in 2-year-olds and add to the growing evidence of cognitive flexibility in early childhood (Deák, 2003).

Our findings contrast strikingly with those regarding 3-year-olds' performance on other measures of cognitive control, which typically demonstrate inflexibility (e.g., Zelazo et al., 1996). One potential explanation of the relative ease with which the children controlled their knowledge in the current task is that the task switch was not dimensionally complex. Perner and Lang (2002) found that 3- and 4-year-olds are more successful at a version of the DCCS that requires intradimensional ("reversal") switches (e.g., changing from sorting red to red and blue to blue, to sorting red to blue and blue to red) than at a version that requires interdimensional switches. Nevertheless, some intradimensional-shift control tasks remain a significant challenge to children under 4 years of age (Russell, Hala, & Hill, 2003; Russell, Jarrold, & Potel, 1994; Russell, Mauthner, Sharpe, & Tidswell, 1991).

The most salient difference between the current task and the tasks that preschool children find difficult is that our task involved control of incidentally acquired knowledge acquired through a motor schema, rather than control of declarative, rulelike knowledge acquired through explicit instruction. Our results suggest that young children have more skill in manipulating the former than in manipulating the latter. Intuitively, this is congruent with the fact that learning that occurs before the onset of fluent language tends to be incidental rather than instructed.

An ability to control knowledge in an inclusion/exclusion task is generally taken as an indication that the relevant knowledge is explicit (Jacoby, Toth, & Yonelinas, 1993). However, this need not be the case. Indeed, in this study, as in others using the PDP, children could have based their generated exclusion responses on a feeling of "familiarity" (Richardson-Klavehn, Gardiner, & Java, 1996), rather than on any explicit knowledge of the learned material. Familiarity could have taken the form of sensitivity to the trained transitions themselves or to the motor responses associated with the trained transitions. Thus, the 2-year-olds may have favored specific transitions in the inclusion task (and avoided those transitions in the exclusion task) simply because these were more familiar. We suggest that children's ability to control this less explicit form of knowledge (Dienes, Altmann, Kwan, & Goode, 1995) can help explain why our results depart from those of previous studies of cognitive control in 3-years olds (e.g., Kirkham et al., 2003; Kloo & Perner, 2005; Munakata & Yerys, 2001; Zelazo et al., 1996). Incidental-learning-and-control tasks may thus provide an important addition to the executive control literature, as they allow control of subexplicit knowledge to be measured.

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