Serial Reaction Time Learning in Preschool- and School-Age Children

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Visuomotor sequence learning was assessed in 4- to 10-year-old children using a serial reaction time (SRT) task with both random and sequenced trials. One-half of the children received exposure to the sequence prior to performing the reaction time (RT) task. In Experiment 1, 7- and 10-year-old children demonstrated sequence-specific decreases in RT. As in the adult SRT literature, participants with explicit awareness of the sequence at the end of the session showed larger sequence-specific reaction time decrements than those without explicit awareness. Contrary to expectation, preexposure to the sequence did not reliably predict the level of awareness attained. Results from Experiment 2 indicate that 4-year-olds also demonstrate significant sequence learning on a variant of the SRT task. This article provides preliminary data regarding developmental changes in sequential learning and the development and use of implicit and explicit knowledge. Age-related differences emerged primarily in explicit rather than implicit knowledge.

Key Words: children’s learning; serial reaction time; SRT; implicit; explicit; motor skill learning.

Human learning and memory functions can be divided into at least two broad subsystems, loosely termed explicit and implicit, that differ in terms of the encoding and retrieval mechanisms that are used, and the degree to which the learned...
information is accessible to intentional or conscious manipulation (Mandler, 1989; Sherry & Schacter, 1987; Squire, Knowlton, & Musen, 1993, for review). Explicit functions appear to be supported by a fast learning system that is particularly useful for episodic encoding from a single instance. The knowledge acquired is declarative in that the learner can verbally explicate the learned information, it can be manipulated by conscious strategy use, and it is relatively flexible, allowing transfer of learning to new yet analogous settings (Eichenbaum, Matthew, & Cohen, 1989; Saunders & Weiskrantz, 1989). In contrast, implicit function is thought to involve a slower learning system in which encoding can be incidental or unintentional, and retrieval occurs outside of conscious awareness or deliberation (Tulving & Schacter, 1990). This type of learning tends to result in knowledge that is more tightly bound to the particular features of the learning context (Reber, 1993; Schacter, 1992).

One of the most studied behavioral learning tasks is the serial reaction time (SRT) task described by Nissen and Bullemer (1987). In this paradigm, a target stimulus appears in one of several spatial locations. Participants are asked to respond as quickly as possible by pressing a button that corresponds to the location of the stimulus. When the order of locations is random, this task reflects simple motor-skill training. However, when a repeating sequence of locations is imposed in the task, adults show improved RTs during patterned trials compared to random trials, indicating some anticipation of where the next stimulus will appear. This learning is implicit when RT improvements occur despite no explicit awareness of the presence of a sequence (Cohen, Ivry, & Keele, 1990; Curran & Keele, 1993; Nissen & Bullemer, 1987; Willingham, Greenley, & Bardona, 1993). Subjects who develop explicit knowledge of the underlying sequence usually show additional reaction-time improvements (Curran & Keele, 1993; Willingham, Nissen, & Bullemer, 1989). More interesting, individuals with damage to medial-temporal lobe brain regions, classic amnesics, perform as well as control participants on the reaction time task but have no explicit awareness of the sequence at the completion of testing (Nissen, Willingham, & Hartman, 1989). In contrast, patients with Huntington’s or Parkinson’s diseases (Ferraro, Balota, & Connor, 1993; Knopman & Nissen, 1991) are impaired in the sequence learning phase of the SRT task, suggesting that basal ganglia circuits may be critical for implicit learning while other regions may underlie the development of explicit awareness.

Functional magnetic resonance imaging (fMRI) and positron emission tomography (PET) studies of the SRT task have generally demonstrated separate neural systems activated under implicit and explicit learning conditions. Implicit learning is associated with activity in sensorimotor, premotor, motor, and parietal cortices, as well as the basal ganglia and thalamus in normal adults (Grafton, Hazeltine, & Ivry, 1995; Rauch et al., 1995, 1997). In contrast, explicit learning results in signal change in prefrontal cortex, visual cortex, and cerebellar regions, similar to studies of spatial working memory (Jonides et al., 1993) and long-term memory retrieval (Buckner & Tulving, 1995). These regions are not specific to
the learning of spatial locations. Hazeltine, Grafton, and Ivry (1997) reported strikingly similar regions of signal change during implicit and explicit learning of color stimuli.

An intriguing question resulting from the literature on multiple learning and memory systems is how these different forms of cognitive function develop, and whether implicit and explicit processes develop in a unitary or dissociable fashion. Given the prolonged development of prefrontal cortex systems involved in explicit learning as compared to the relatively early maturation of basal ganglia structures, one might expect implicit function to develop earlier than explicit function (Bachevalier & Mishkin, 1984; Bourgeois, Goldman-Rakic, & Rakic, 1994; Chugani, Phelps, & Mazziotta, 1987; Huttenlocher, 1990; Huttenlocher & Dabholkar, 1997; Schacter & Moscovitch, 1984). Reber (1993) proposed that implicit learning should be independent of age since the neural structures thought to underlie implicit function are evolutionarily more primitive. However, recent developmental neuroimaging studies suggest that, although metabolic rate and myelination of the basal ganglia peak quite early in the first year of life (Chugani et al., 1987; Sidman & Rakic, 1982), developmental changes are still occurring well into early childhood. For example, subcortical gray structures decrease in volume during childhood, especially in males (Giedd et al, 1996; Rajapakse et al., 1996; Reiss, Abrams, Singer, Ross, & Denckla, 1996). In fact, subcortical gray matter, including the basal ganglia, may continue to undergo late developmental change in concert with changes in frontal regions (Sowell, Thompson, Holmes, Jernigan, & Toga, 1999).

Classic implicit learning tasks like the SRT task, which are impaired in patients with basal ganglia damage, have not been well studied in a developmental context. Similar tasks have been examined in infants using visual-expectancy paradigms (Canfield & Haith, 1991; Canfield, Smith, Brezsnyak, & Snow, 1997; Haith, Hazan, & Goodman, 1988; Haith, Wentworth, & Canfield, 1993; Smith et al., 1984; Smith, Arehart, Haaf, & deSaint Victor, 1989; Smith, Jankowski, Brewster, & Loboschefski, 1990; Smith, Loboschefski, Davidson, & Dixon, 1997; Wentworth & Haith, 1992). Typically, infants are shown a simple repeating pattern of stimuli on a video screen. The speed and accuracy of eye movements are recorded as evidence to whether the infant has learned to anticipate where subsequent stimuli will appear. Infants as young as 3 months of age demonstrate a reliable, if small degree of anticipatory looking for simple

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1 A handful of papers have been published examining implicit memory in children using priming measures. These publications are quite consistent in reporting no developmental differences between preschool and older children on measures of perceptual (DiGiulio, Seidenberg, O’Leary, & Raz, 1994; Drummey & Newcombe, 1995; Ellis, Ellis, & Hosie, 1993; Naito, 1990; Parkin & Streef, 1988) or conceptual priming (Greenbaum & Graf, 1989; Perruchet, Frazier, & Lautrey, 1995). In contrast, age-related changes have been observed in eye-blink conditioning paradigms (Ohlrich & Ross, 1968; Werden & Ross, 1972); however, this type of learning is known in lower animals to be mediated by cerebellar and hippocampal brain systems rather than basal ganglia structures (see Woodruff-Pak, Logan, & Thompson, 1990, for review).
sequences like left-right alternation (Haith & McCarty, 1990). Similarly, 5-month-old infants show above-chance anticipation of locations in a 1-2-3-4 pattern as well as longer combinations of four locations, such as 1-2-3-2-3-4 (Smith et al., 1984, 1989, 1990, 1997). However, the age and degree of successful anticipation can be manipulated by altering the sequence complexity. For example, Clohessy, Posner, and Rothbart (2001) suggest that an ambiguous sequence like 1-2-1-3, in which subsequent positions cannot be determined solely by the current position, may not be learned successfully until much later in infancy, perhaps as late as 18 to 24 months. This result is reminiscent of data from the adult SRT literature suggesting that increasing the complexity of the sequence can affect the degree of learning, occasionally preventing learning completely (Cohen et al., 1990).

To date, only two studies have been published specifically examining implicit learning in school-age children. Meulemans, Van der Linden, and Perruchet (1998) reported no age-related changes in implicit SRT learning by 6- and 10-year-olds and adults. In their paradigm, the task parameters were selected specifically to minimize the probability that participants would develop any explicit awareness. Each presentation of a 10-item sequence was alternated with six random trials throughout each block. None of the 96 participants demonstrated explicit knowledge of the sequence as measured by a sequence-fragment recognition test at the end of five blocks (420 trials) or after a second learning episode one week later (48 participants). These data provide clear support for the implicit learning abilities of school-age children and suggest that implicit function does not differ significantly for children and adults when measured in a SRT paradigm. The data depart from the adult SRT literature in that none of the adults developed any explicit awareness of the sequence despite as many as 840 reaction-time trials (500 sequence trials). Clearly, the unusual practice of interleaving random and sequence trials rather than grouping the trial types in separate blocks had a large impact on type of learning and resultant knowledge that was available to participants.

In contrast to these results, Maybery, Taylor, and O’Brien-Malone (1995) reported age-related improvements in both implicit and explicit learning of covariation rules with 5- to 7-year-olds and 10- to 12-year-olds. The implicit learning task required guessing the location of a target stimulus in a 4 × 4 matrix of hidden pictures. The location of the target stimulus covaried with two other factors: the color of the matrix display board and the experimenter’s side of approach on each trial. Implicit learning was measured by increased guessing accuracy across trials. None of the children demonstrated explicit awareness of the covariation rules during verbal questioning at the end of the task. An analogous explicit learning task was administered in which children were shown a 3 × 3 test matrix and explicitly told the dimensions of the stimuli that determined their locations in the matrix. Children were then given cards for a new matrix and required to learn, through accuracy feedback, which dimensions were relevant for placing the cards in each row and column of the new matrix. The learning was explicit since children were aware that the stimulus dimensions were important
and they were intentionally trying to discover the rules. Although both age groups showed significant learning under the two task versions, the 10- to 12-year-olds demonstrated significantly better prediction of the target location than 5- to 7-year-olds in the implicit task. Whereas the older children learned about both covariation rules, the younger children appeared to learn only the color covariant. Older children also made fewer errors in learning the correct stimulus locations in the explicit task. When the explicit task was made more difficult by adding irrelevant dimensions to the stimuli to be sorted, the same pattern of age-related differences emerged despite much lower rates of learning overall. These data suggest that both implicit and explicit learning may show developmental change rather than age invariance.

The contradiction apparent in these two studies indicates that additional pediatric research is needed to better understand the development of both implicit and explicit processes in learning. Neuroimaging evidence of continued change in the structural development of the basal ganglia suggests the possibility that functional changes are also occurring with age. The simple nature of the task instructions, as well as the quantitative means of assessing learning make the SRT paradigm an excellent task for use with children. Like Meulemans et al. (1998), the current article provides data addressing visuomotor sequence learning in children using a variant of the SRT task. This article also assesses the development of explicit awareness in children by using a more traditional arrangement of random and sequence trial blocks and extends the use of the SRT paradigm down to preschool-age children.

**EXPERIMENT 1**

**Method**

**Participants.** Children were recruited from an existing community participant pool in the Minneapolis/St. Paul metro area. The final sample consisted of twenty-two 7-year-olds (mean age = 7 years 9 months; range = 7:03 to 7:11; 12 girls) and twenty 10-year-olds (mean age = 10 years 7 months; range = 10:02 to 10:11; 12 girls). Ninety percent (90%) were Caucasian (2 African American, 1 Hispanic, 1 Pacific Islander, 1 Native American), and most came from upper middle-class, two-parent families. All children were right-handed, had normal or corrected vision, and no known neurological or behavioral diagnoses. Participants were randomly assigned to either the preexposure or no exposure condition, with equal numbers of boys and girls in each condition. All children provided written assent to participate and were paid $5.00 for their effort.

Data from an additional two 10-year-olds (2 girls) and four 7-year-olds (1 girl) were dropped from all analyses due to: experimenter error (1), failure to meet exclusion criteria (4), or failure to follow task instructions (1).

**Materials and procedure.** Participants were told that they would be playing a computer game several times in a row to examine how children learn new skills with practice. On each experimental trial, a 5-cm × 5.5-cm bitmap image of a golden retriever was presented in one of four frames (Fig. 1). The frames were
arranged in a linear array on a blue background and each subtended approximately 3° of visual angle. A “+” symbol (1 cm × 1 cm) at the center of the display served as a visual fixation point. Children were instructed to “catch” the dog as quickly as possible by pressing the button that corresponded to the dog’s spatial location. This paradigm was modeled in part after an unpublished study described by Reber (1993). In addition, children were asked to try to maintain central fixation rather than shifting their gaze to the dog’s location, and to make as few mistakes as possible. Participants used a four-button response box with their right hand to record RTs. Each button measured 1 cm × 1 cm, with 7 mm separation between adjacent buttons. Reaction-time responses were sampled with a Dell Pentium microcomputer and were accurate to one ms. Pilot testing revealed that a significant number of 7-year-olds were unable to coordinate using all four fingers of one hand. Therefore, children were allowed to use any finger combination to make their responses as long as their movements remained consistent throughout the study. Most 7-year-olds used the index finger regardless of the stimulus location while 10-year-olds generally used separate fingers for each location. Each participant completed five blocks of 100 trials with short breaks (approximately 2 min) between blocks. The location of the stimulus was pseudo-randomly determined in blocks 1 and 4, but followed a 10-item sequence in
blocks 2, 3, and 5 (Fig. 1). The sequence followed the pattern 1-3-2-4-1-2-3-4-2-4, where 1 represents the left-most frame. Frames were not labeled for the participants.

Children were randomly assigned to either the no-exposure or the preexposure condition. Children in the preexposure condition were given explicit information about the presence of a sequence: “Sometimes the dog likes to go to the same places over and over; he goes in a pattern. I’m going to show you the pattern now. If you know the pattern that the dog likes, you might be even faster at catching him.” These participants were then shown the sequence three times before beginning the RT blocks. Children were not instructed to memorize the pattern. Children in the no-exposure condition received no information about the presence of a sequence but were encouraged to respond as quickly and accurately as possible.

Upon completing the five blocks, all children were asked a series of questions to assess their subsequent explicit awareness of the sequence as measured by uncued free recall: “Do you think you got faster at catching the dog? Could you ever tell where the dog was going to go next? Show me where the dog would go.” Children were encouraged to indicate their knowledge of a pattern verbally or by pointing to the screen or the response buttons. In the preexposure condition, children were asked, “Do you think you got faster at catching the dog? Could you tell when the dog was going in that pattern I showed you and when he wasn’t? Can you remember what the pattern was? Show me where the dog would go.”

Finally, all participants completed a generate version of the response-time task. The initial position in the sequence was displayed on the screen and participants were asked to indicate, using a button-press response, where the dog would appear on the next trial. Children were told that the stimulus locations would be similar to the previous trials: “This game is like the last game. The dog goes to the same places as the last game.” The stimulus remained in the location until the child correctly “guessed” the next spatial location. This procedure continued for 20 trials (two repetitions of the 10-item sequence).

**Results**

An alpha level of .05 was used for all statistical comparisons. As a first pass, analyses of variance (ANOVAs) were conducted on reaction-time and accuracy data to examine the overall learning patterns between groups. Post hoc contrasts included simple effects or Tukey HSD tests. Second, a single learning measure was defined and ANOVAs were conducted by group. Finally, a chi-square procedure was used to evaluate distribution differences between groups when nominal variables were used, as in the case of the exposure manipulation and the resultant explicit-awareness measures.

**Learning.** For each participant, the median RT was calculated for sets of 10 trials, resulting in 50 medians across the 500 trials. Medians excluded any responses made before the appearance of the stimulus, RTs longer than 10 s, and any trials on which the initial response was incorrect. The mean of these medians was then calculated for each block, resulting in five overall block means for each
A 2 × 2 × 5 (age × condition × block) mixed-model ANOVA with block as a repeated measure revealed significant main effects of age, $F(1, 34) = 48.51$, $p < .001$, and block, $F(4, 136) = 90.99$, $p < .0001$, but not condition. Ten-year-olds responded faster than 7-year-olds in general (345 ms vs 583 ms), and RTs improved with each successive sequence block (471 ms, 411 ms, and 351 ms) but slowed during the intervening random block (494 ms) (Fig. 2). Overall, children responded significantly faster during the second random block than during the first random block (494 ms vs 658 ms), $t(4) = 11.0$, $p < .01$. A significant age-by-block interaction was also observed, $F(4, 136) = 3.73$, $p < .05$. Although 7-year-olds performed more slowly than 10-year-olds in every block, this difference was largest during the first block, suggesting that 7-year-olds showed more general motor-skill improvement than 10-year-olds.

An examination of the individual learning curves suggests that a small number of children did not show significant sequence-specific learning. Although every 10-year-old showed performance improvements across the sequence blocks and at least a slight performance decrement during the intervening random trials, three 7-year-olds demonstrated questionable sequence learning. Two of these children showed little or no performance disruption during the random block, but an RT improvement in the final sequence block that was larger than would be expected for simple motor-performance improvement. An additional 7-year-old showed only simple motor learning across the five blocks, with no evidence of sequence-specific learning.

FIG. 2. Learning patterns for 7- and 10-year-old children. Data points indicate the mean reaction time per block of 100 trials with bars indicating the standard error of the mean.
To control for baseline reaction-time differences between groups, a sequence-specific learning effect was calculated using a proportional measure of magnitude comparing the difference between random and sequence trials to overall RT for each subject (i.e., \([\text{Block 4} - \text{Block 5}] \div [\text{Block 4} + \text{Block 5}]\); Cherry & Stadler, 1995; Meulemans et al., 1998). A trend was observed between age groups suggesting somewhat more sequence-specific learning by 10-year-olds than by 7-year-olds (0.22 vs 0.17 respectively). \(F(1, 34) = 3.07, p = .08, ns\). Power for detecting this difference was fairly low (0.41), and analyses suggest that a minimum of 10 additional subjects would be needed for this effect to be significant. No significant differences in sequence-specific learning were observed between the preexposure and no-exposure conditions.

Accuracy during the RT trials was high for both age groups. Ten-year-olds made errors on 10.6% of trials and 7-year-olds made errors on 9.3% of trials. A \(2 \times 2 \times 5\) (age \(\times\) condition \(\times\) block) ANOVA suggested that the number of errors increased across blocks, \(F(4, 144) = 6.85, p < .001\), with the first block showing significantly fewer errors than the final block (7% vs 13%), \(t(41) = 6.86, p < .01\) (Table 1). Error rates did not differ overall by trial type (random vs sequence). No significant interactions occurred between block and age or condition. Although not statistically significant, the number of errors made during sequence blocks increased as RT decreased. Importantly, the error rate also increased in block 4 (random trials) despite a significant increase in RT, suggesting that the decrease in RT across sequence trials cannot be explained simply by a speed-accuracy trade-off.

Another measure of sequence-specific knowledge is the degree to which the participant anticipates the next stimulus location. Anticipations were defined as any responses during sequence trials that occurred earlier than the fastest possible RT for that individual (i.e., fastest response during random trials). Anticipations could be either correct or incorrect (errors). The total number of anticipations committed was compared in a \(2 \times 2 \times 3\) (age group \(\times\) condition \(\times\) sequence block) ANOVA. Results indicated significant main effects of age, \(F(1, 34) = 4.59, p < .05\), and block, \(F(2, 68) = 15.35, p < .0001\). Overall, 10-year-

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**TABLE 1**

<table>
<thead>
<tr>
<th></th>
<th>Block 1 random</th>
<th>Block 2 sequence</th>
<th>Block 3 sequence</th>
<th>Block 4 random</th>
<th>Block 5 sequence</th>
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<tr>
<td><strong>Experiment 1</strong></td>
<td></td>
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<tr>
<td>Seven-year-olds</td>
<td>(M) 6.23</td>
<td>8.64</td>
<td>9.95</td>
<td>10.45</td>
<td>11.27</td>
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<td></td>
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<td>(7.90)</td>
<td>(8.88)</td>
<td>(9.93)</td>
<td>(10.35)</td>
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<tr>
<td>Ten-year-olds</td>
<td>(M) 7.15</td>
<td>8.75</td>
<td>11.10</td>
<td>11.65</td>
<td>14.10</td>
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<td></td>
<td>(SD) (4.39)</td>
<td>(5.95)</td>
<td>(10.81)</td>
<td>(7.29)</td>
<td>(13.58)</td>
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<tr>
<td><strong>Experiment 2</strong></td>
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<tr>
<td>Four-year-olds</td>
<td>(M) 9.98</td>
<td>11.28</td>
<td>12.10</td>
<td>12.25</td>
<td>14.25</td>
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<tr>
<td></td>
<td>(SD) (7.95)</td>
<td>(8.37)</td>
<td>(7.39)</td>
<td>(8.95)</td>
<td>(9.68)</td>
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</tbody>
</table>
olds made more anticipations than 7-year-olds (16.4% vs 7.3%), and on the whole, the number of anticipations increased with practice at the sequence (6.4%, 12.9%, and 15.6% anticipations in blocks 2, 3, and 5 respectively). A significant interaction was observed between age and block ($F[2, 68] = 4.58, p < .05$) suggesting that the increase in anticipations across blocks was predominantly carried by the 10-year-olds (8.1%, 15.4%, and 21.5%). Seven-year-olds did not demonstrate differences in anticipations between blocks 3 and 5 (3.9, 9.4, 8.6%). The total number of anticipations did not differ between exposure conditions.

Analyses of the accuracy of anticipatory responding suggest that children in the preexposure condition showed a somewhat higher percentage of correct anticipations than children in the no-exposure condition (89% correct vs 80% correct, where chance performance is 33% accuracy), $F(1, 34) = 5.00, p < .05$. No other accuracy effects were significant.

**Explicit knowledge.** Free-recall and generate task performance were analyzed to assess the effectiveness of the preexposure manipulation. Children were considered to have complete explicit knowledge if they recalled or generated at least eight sequential correct locations. Analyses including a group with partial explicit knowledge (five to seven item strings) demonstrated no significant differences between participants with partial knowledge and participants with no knowledge; therefore, children were classified as having complete explicit knowledge (eight or more items) or not. A chi-square analysis of the independence of condition (preexposure or no-exposure) and ending knowledge state (implicit or explicit) suggests that the two exposure conditions produced significantly different patterns of explicit awareness, with the preexposure condition resulting in more subjects with complete knowledge than the no-exposure condition (60% of participants vs 27% of participants; $\chi^2(1, N = 42) = 4.48, p < .05$). However, some subjects in each exposure group showed the opposite pattern of awareness (e.g., explicit awareness in the no-exposure condition and no awareness in the preexposure condition).

To examine the effects of explicit knowledge on sequence-specific learning, data were collapsed across the two exposure conditions and re-analyzed by ending knowledge state. A $2 \times 2$ (age $\times$ knowledge) ANOVA revealed a main effect of knowledge state ($F(2, 38) = 10.58, p < .005$), and a trend for an effect of age ($F(1, 38) = 3.05, p = .088$). Children with complete explicit awareness demonstrated a larger sequence-specific learning effect than children without explicit awareness (0.25 vs 0.16; Table 2). No significant age differences were observed in the number of children with explicit knowledge (50% of 10-year-olds vs 37% of 7-year-olds; $\chi^2(1, N = 42) = .80, ns$). The interaction of age and knowledge was not significant.

When the overall number of anticipations was re-analyzed by ending knowledge state, both 10-year-olds and 7-year-olds showed a knowledge effect, with explicitly-aware subjects showing more anticipations than unaware subjects ($F[1, 38] = 12.7, p < .001$). However, a significant interaction of age and knowledge illustrates a developmental effect ($F[1, 38] = 6.37, p < .05$) (Fig. 3). Explicitly-
aware 10-year-olds made significantly more anticipations than explicitly-aware 7-year-olds (24.5% vs 9.4%; $F[1, 38] = 10.32, p < .005$), whereas anticipations did not differ by age for unaware children (5.5% vs 6.1%; $F[1, 38] = .02, ns$).

**Discussion**

In general, results from the current study support the conclusions of Meulemans et al. (1998). Seven- and ten-year-old children demonstrate significant learning of a visuomotor sequence using a SRT paradigm with button-press responses. As would be predicted from the motor-development literature (e.g., Southard, 1985), 7-year-olds were slower responders overall than 10-year-olds.

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**TABLE 2**
Magntitude of the Sequence-Specific Learning Effect for All Age Groups by Ending Knowledge State

<table>
<thead>
<tr>
<th>Age group</th>
<th>Implicit knowledge $M$ (SD)</th>
<th>Explicit knowledge $M$ (SD)</th>
</tr>
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<tbody>
<tr>
<td>Four-year-olds</td>
<td>0.08 (0.06)</td>
<td>0.14$^{a}$ (n/a)</td>
</tr>
<tr>
<td>Seven-year-olds</td>
<td>0.15 (0.10)</td>
<td>0.20 (0.08)</td>
</tr>
<tr>
<td>Ten-year-olds</td>
<td>0.16 (0.04)</td>
<td>0.28 (0.10)</td>
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$^{a}$ Only one child in the 4-year-old age group demonstrated explicit knowledge of at least eight sequential items.

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**FIG. 3.** Percentage of anticipatory responses committed by 7- and 10-year-olds during sequence trials plotted by ending knowledge state (implicit or explicit).
The mean RT difference between age groups was approximately 240 ms. The two groups showed very little overlap in the distribution of RTs with the fastest RTs for the younger group approaching the slowest RTs for the older group. All children showed RT improvements with practice at button pressing. For most children, this change reflected both general motor-performance improvements, as measured by differences between random blocks 1 and 4, and sequence-specific RT differences, as measured by the interference due to random trials in block 4. The proportional sequence-specific learning measure revealed only a nonsignificant trend for age, indicating that 7- and 10-year-olds demonstrated equivalent learning of the sequence.

Response accuracy was at nearly 90% overall, suggesting that task performance was well within the physical and cognitive abilities of these age groups, including the children who did not show sequence-specific learning. Error rates were not different between age groups, suggesting that 7-year-olds had no more difficulty completing the task than 10-year-olds did. Overall, errors increased slightly with each successive block suggesting an element of fatigue, but mean accuracy remained above 85% for both age groups, even during the final block of trials. More important, the RT improvement cannot by dismissed as a speed-accuracy trade-off since both accuracy and RT worsened during the second random block.

Unlike the Meulemans et al. (1998) paradigm, we did not try to prevent the development of explicit awareness. In fact, we attempted to promote explicit awareness in one-half our subjects by providing explicit information about the sequence before the RT trials. More interesting, a comparison of the preexposure and no-exposure conditions indicates that prior knowledge of the presence of a sequence did not produce the expected dissociation between implicit and explicit awareness. Although the preexposure condition resulted in significantly more children with complete explicit knowledge and the no-exposure condition resulted in significantly more children with no awareness, the distribution was not 100% in either case. When children were grouped by ending knowledge state rather than the exposure manipulation, it is apparent that children with complete explicit knowledge of the sequence showed a larger sequence-learning effect than those without explicit knowledge. Although the group means suggest that this explicit learning may be greater for 10-year-olds than for 7-year-olds, the age-by-knowledge interaction was not significant in this sample.

Age-related differences were observed in other aspects of the learning task. The number of anticipatory responses increased with age, suggesting that older children had learned something more about the sequence. From this measure, one cannot determine whether that knowledge is implicit or explicit; however, the

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2 Eighteen adult pilot subjects completed the identical RT task used with the children. Adults receiving preexposure to the sequence demonstrated complete explicit knowledge after the RT trials. Adults with explicit knowledge (from both exposure conditions) demonstrated larger sequence-specific learning effects than adults without awareness ($F(1, 16) = 6.35, p < .05; 0.23$ vs $0.13$).
number of anticipations increased significantly for children with complete explicit knowledge, especially for the 10-year-old age group. In addition, a few of the 7-year-olds did not show significant sequence-specific learning effects but showed only practice-related motor improvements, suggesting that individual differences may be significant in developmental applications of this task. In general, Experiment 1 provides support for the hypothesis that implicit learning is relatively stable across development while explicit learning may continue to improve throughout middle childhood.

EXPERIMENT 2

Although the 7- and 10-year-olds generally were successful in learning the sequence, a few of the 7-year-olds did not show sequence-specific learning. It is not clear from these data whether the pattern of learning would diverge more in younger children. To address the developmental time course of sequence learning mechanisms, 4-year-olds were tested on a variant of the SRT task used in Experiment 1. Rather than the linear presentation used in previous SRT experiments (and here in Experiment 1), a quadrant presentation was used to separate the locations into large spatial domains. A large response box was similarly designed with buttons allowing a whole-hand movement, rather than a small-finger motor response. Presumably, this arrangement facilitates mapping of the one-to-one relationship between any stimulus position and its correct response button. Despite the lack of clear dissociations between preexposure and no-exposure conditions in Experiment 1, the same manipulations were used in Experiment 2 to maintain as much similarity as possible across the age groups tested.

Method

Participants. Forty-six 4-year-olds (mean = 4 years 9 months; range = 4:01 to 4:11) were recruited as previously. Ninety-six percent (96%) of these participants were Caucasian (1 African American, 1 Asian American). Data from six children were not included in any analyses for one of the following reasons: incomplete data due to lack of interest in the task (3), failure to learn the association between the visual locations and the response buttons (1), or extreme and/or highly erratic RT scores (2). Equal numbers of boys and girls were tested in each condition.

Materials and procedure. Stimulus locations were arranged in quadrant fashion rather than the linear array used previously (Fig. 1); however, the degree of visual angle subtended by each stimulus was identical to the linear version of the task. The participant held a large (35.5 cm × 35.5 cm) four-button response panel on his or her lap. Buttons were arranged in the same spatial arrangement as the frames in the visual display. Each button measured 5 cm × 5 cm, and was positioned 7 cm from the edges of the panel, allowing for a whole-hand movement and a resting position at the center of the response box.

Prior to testing, children were assessed for their ability to map each visual position to the corresponding response button. Children were randomly assigned to either a no-exposure or a preexposure condition. Instructions were identical to
Experiment 1. Participants were given short breaks between blocks (average 2 min) to rest. Unlike the previous experiment, 4-year-olds were not asked free-recall questions about their explicit knowledge of the sequence. Initial testing revealed that children in this age group had a very difficult time understanding the nature of the questions and were unable to give meaningful information. All 4-year-olds did complete a generate version of the quadrant RT task.

Results

Gender was not included as a factor in any analyses as we did not have any specific expectations regarding gender differences in implicit or explicit sequence learning.

Learning. As in Experiment 1, the median RT was calculated for sets of 10 trials, resulting in 50 medians for each individual across the 500 trials. Medians excluded RT's longer than 10 s, and any trials on which the initial response was incorrect. The mean of these medians was then calculated for each block, resulting in five overall block means for each child. A 2 × 5 (condition × block) mixed-model ANOVA using mean RT demonstrated significant differences between conditions, $F(1, 36) = 4.02, p = .05$, and between blocks, $F(4, 144) = 42.12, p < .001$. In general, 4-year-olds in the preexposure condition were faster than those in the no-exposure condition (875 vs 984 ms). Performance improved significantly from block 2 (934 ms) to block 3 (859 ms), $t(39) = 4.9, p < .05$, and from block 3 to block 5 (817 ms), $t(39) = 4.4, p < .05$, indicating significant RT improvements with practice at the sequence. Performance decreased significantly with the introduction of the second random block (RT increase of 66 ms; $t(39) = 4.4, p < .05$). Block 1 (1059 ms) showed significantly slower RTs than any of the other blocks, including the second random block (919 ms), $t(39) = 9.15, p < .01$). Figure 4 indicates the general learning curve for 4-year-olds in comparison to the learning curves obtained for 7- and 10-year-olds in Experiment 1.

Overall, the 4-year-olds were quite accurate in their button pressing with a mean of 12% errors. A mixed-model ANOVA was conducted to assess whether error rates differed significantly between conditions and/or between blocks. The 2 × 5 (condition × block) ANOVA revealed main effects of condition, $F(1, 36) = 10.82, p < .005$ and block, $F(4, 144) = 5.85, p < .005$. In general, children in the preexposure condition made more errors than children in the no-exposure condition (16% vs 9% errors). In addition, the number of errors tended to increase slightly across the five blocks such that the fewest errors were committed during the first block ($M = 10\%$), and the most errors were committed during the last block ($M = 15\%$) (Table 1). No significant interactions occurred between condition and block for measures of accuracy.

The proportional sequence-learning effect was calculated as described in Experiment 1 to provide a learning measure relative to each individual’s baseline RT. No significant differences were observed between conditions for the sequence-learning effect. Four-year-olds showed an overall sequence learning effect of 0.08 (Table 2).
An examination of the individual learning curves suggests that, as observed with the older children, some 4-year-olds did not show significant sequence-specific learning. Eleven children (28%) failed to show the typical pattern of improved performance during sequence blocks and prolonged RTs during random blocks. Five of these children showed no apparent decrement due to the intervening random block, suggesting primarily general motor-performance improvements, three showed little or no RT improvement across all five blocks, and three demonstrated unexpected increases in RT during the second sequence block. These patterns of performance did not distinguish between the preexposure and no-exposure conditions.

The number of anticipatory responses was calculated as in Experiment 1. Although 4-year-olds made very few anticipatory responses overall ($M = 5\%$), the number of anticipations differed across blocks of sequence trials, $F(2, 72) = 3.99, p < .05$, with blocks 3 and 5 showing more anticipations than block 2. A trend emerged such that children in the preexposure group made more anticipations overall than children in the no-exposure group (6.6% vs 3.4%), $F(1, 36) = 3.62, p = .07$. However, a look at the percentage of correct anticipations suggests that only 50% of these anticipatory responses were made to the correct location ($M = 50.3\%$ correct). This number is significantly greater-than-chance performance (33%) but does not compare to the 80% to 90% anticipation accuracy observed with the older children in Experiment 1.

*Explicit knowledge.* Only one 4-year-old met our criterion for demonstrating complete explicit knowledge of the sequence (eight or more sequential locations).
This child was a boy in the no-exposure condition. To look at knowledge in this age group, we created a partial-knowledge category of children completing five to seven sequential items on the generate task. Sequence-specific learning did not differ between children with partial explicit knowledge and children with no explicit knowledge ($F(1, 38) = 0.57, ns$). The number of anticipatory responses also did not differ between children with partial explicit knowledge and those with only implicit knowledge ($F(1, 37) = 0.26, ns$). Figure 5 illustrates the anticipatory behavior of the 4-year-olds in comparison to the 7- and 10-year-olds in Experiment 1 and adult pilot subjects on the linear SRT task. The preschoolers with implicit knowledge demonstrated similar numbers of anticipations as older subjects with implicit knowledge ($F(3, 67) = 0.17, ns$), despite the fact that the 4-year-olds completed a different variant of the SRT task. The difference in accuracy of anticipations between age groups is illustrated in Fig. 6 for participants with implicit and explicit knowledge.

**Discussion**

Like the older children, the majority of 4-year-olds demonstrated significant RT decrements across blocks of trials. Performance improved across the sequence blocks, and the introduction of random trials led to slower response times. Although children in the no-exposure condition were slower than those in the preexposure condition overall, this difference did not interact with block, suggesting that the RT benefit for preexposure participants was unrelated to any prior sequence knowledge since the difference was present in both sequence and ran-
dom blocks. The preexposure manipulation again had no reliable effect on later sequence awareness. Overall, as we observed with the 7-year-olds, 4-year-olds showed significant improvement at the simple motor-response task from the first random block to the second random block, suggesting a relatively poor initial performance level.

In general, 4-year-olds also seemed to fatigue more quickly; error rates increased from block 1 to block 5, perhaps reflecting boredom with the task, as well as motor and cognitive fatigue. The faster RT observed in the preexposure group was accompanied by a higher general-error rate suggesting that this group difference reflects a speed-accuracy trade-off for the preexposure group but not for the no-exposure group. The sequence-specific learning effect is still present over and above this speed-accuracy relationship, since both groups demonstrated significant interference by the random trials in block 4 (longer RT) despite an increase in error rate in block 4.

Not surprisingly given the results from Experiment 1, measures of sequence learning magnitudes revealed no differences between the preexposure and no exposure conditions. Preexposure to the sequence appeared to have no effect on the degree of learning attained or the degree of explicit knowledge demonstrated on the generate task. Fully one third of the children in the preexposure condition were unable to demonstrate any explicit knowledge on the generate task, let alone eight sequential items. In addition, 28% of the 4-year-olds failed to demonstrate any sequence-specific learning in this RT task, regardless of whether they

FIG. 6. Accuracy of anticipations by 4-, 7-, and 10-year-olds during sequence trials. Chance performance is 33%.
received prior exposure to the sequence or not. Overall, 4-year-olds did not show evidence of sequence-specific learning in their patterns of anticipatory responding either. These children made very few anticipatory responses, and when they did, showed a relatively high error rate.

General Discussion

Children ages 4 to 10 demonstrated significant learning of a sequence in a SRT paradigm while maintaining a high level of response accuracy. This article is only the second to examine motor-sequence learning paradigms with children and extends the feasibility of this task down as young as 4 years of age. Like adult participants, the majority of children in the current experiments showed behavioral RT decrements indicative of sequence-specific learning. Although these data illustrate that preschool and school-age children can perform well on such tasks, developmental differences in simple motor learning and sequence-specific learning were observed.

Preexposure and Explicit Knowledge

Children did not reliably use the preexposure session to facilitate their RT performance. This finding was especially prominent in the 4-year-old group, although it was apparent for the older children as well. Participants were informed that a sequence was present and were shown the sequence three times visually but were not allowed to practice the motor responses. It is likely that the younger children may not have fully encoded or memorized the sequence during the preexposure session. Indeed, this result fits with general developmental finding that younger children often need more trials to reach learning criterion (e.g., Overman, 1990). This problem may be particularly acute given the design of the current paradigm. To minimize the effects of general motor-performance improvements, the first block following the preexposure trials consisted only of random trials to allow for practice at the motor task without any sequence learning. It is possible that some children did not encode the exposure trials sufficiently to maintain this information across a full block of random trials. As evidenced by the poor verbal recall and generate performance of children in the younger age groups, even after 300 trials of the pattern in addition to the preexposure information, 7- and 4-year-olds were often unable to recall much of the pattern explicitly. This distribution is in contrast to the 10-year-olds receiving pre-exposure to the sequence. Most of these older children showed complete explicit awareness (7 of 10 children) while the others showed at least partial explicit knowledge of the sequence (five to seven sequential items). In addition, the 10-year-olds demonstrated significantly more anticipatory responses with explicit awareness than without, and significantly more than younger children with explicit awareness.

Several explanations are possible to explain the explicit-awareness results. It should be recognized that verbal skills are continuing to develop between 4 and 10 years of age and could, in part, explain our lack of explicit awareness for the
younger age groups. As mentioned earlier, pilot testing of 4-year-olds revealed that they did not understand the posttest verbal questioning regarding the presence of a sequence. Although we also tested explicit awareness with a generate version of the task, this measure is not process pure, meaning that both implicit and explicit knowledge can contribute to successful performance. However, this measure actually overestimates explicit knowledge in the youngest age group rather than underestimating it and, therefore, reflects a fairly conservative index of age differences in explicit awareness.

It is possible that our assessment of explicit knowledge was not sensitive to the type of information that these children had available. Some investigators (Curran, 1997; Meulemans et al., 1998; Perruchet & Amorim, 1992; Willingham et al., 1993) have used tests of pattern recognition to address explicit sequence knowledge in the SRT paradigm. However, a number of studies have shown that while self-reports, free-recall, and generation-task performance measures are all sensitive to explicit knowledge (Curran & Keele, 1993; Frensch & Miner, 1994; Rauch et al., 1995) recognition of sequence fragments may not be (Rauch et al., 1995). Future developmental studies should consider the utility of these various tests of explicit knowledge since it is unclear whether the younger children formed no explicit knowledge, or that the methods chosen to assess this knowledge were insensitive. Importantly, children showing explicit knowledge in either the verbal free-recall or the posttest motor generation domains did demonstrate larger magnitude responses for the sequence-specific learning measure.

**Baseline Differences**

One challenge for motor learning studies like the current series is the difficulty in comparing across age groups with different levels of motor ability or expertise. As evidenced in our group of 4-year-olds, concessions must be made to accommodate the immature fine-motor coordination of young children. This issue is of similar concern with adult patient populations where group differences could be confounded by baseline differences, or overall slowness. Reaction times from Experiments 1 and 2 cannot be directly compared given baseline RT differences between age groups and between task variants. Although direct comparisons are not possible, measurements of the relative improvement from random motor responses to sequenced motor responses provide some comparison of the size of the learning effects across conditions and age groups. In Experiment 1, clear differences emerged in sequence-specific learning effect between children with explicit knowledge and those without. In addition, 7- and 10-year-olds evidenced a nonsignificant trend toward larger sequence effects with age (0.17 and 0.22, respectively). In contrast, the 4-year-olds in Experiment 2 showed sequence learning effects (0.08) that were smaller overall than either of the other age groups. This pattern of results suggests that implicit sequence learning may, in fact, show improvements with age, given that the magnitude of the sequence learning effect appears to increase from 4-year-olds to 7-year-olds to 10-year-olds. While many researchers have criticized raw RT comparisons between
groups with different baseline performance, some also point out potentially invalid assumptions made by proportional measures of RT differences (Chapman, Chapman, Curran, & Miller, 1994; Howard & Howard, 1992). A regression analysis procedure has been suggested as a means of dealing with group differences in overall slowness (Chapman et al., 1994), however, the lack of overlap in RTs between age groups in the current study would require significant extrapolation of the regression relationship, adding another potential source of error. The proportional measure reported here represents a middle ground in these options and is consistently reported by other groups investigating developmental questions.

Suggestions of developmental change from 4- to 10 years must be qualified by the acknowledgement that learning effects may differ between the linear and quadrant SRT task variants. There is evidence from adults to suggest that learning can transfer directly from a finger-response to a whole-hand motion (Grafton, Hazeltine, & Ivy, 1998), indicating that the motor differences between the task should not be significant using a relative measure of change. However, it is possible that the differential visual pattern inherent in the quadrant stimulus display used with 4-year-olds is somehow more difficult to learn. Although this does not seem intuitively likely given the exact replication of the sequence characteristics, it remains an empirical question for further study. In addition to these baseline differences in the task and motor performance, button-press tasks require the subject to symbolically represent the stimulus information and to map each stimulus to an arbitrary button response. This ability to represent relations among stimuli is still developing between 2 and 4 years of age (e.g., DeLoache, Kolstad, & Anderson, 1991). It is possible that one of the developmental changes affecting learning on the SRT task is the ability to symbolically represent the stimulus locations and map them to corresponding response buttons. However, since 4-year-olds demonstrated a high degree of accuracy in button-press responding, a representational explanation would have to involve some higher level cognitive interference that prevents learning despite accurate motor mapping.

**Individual Differences in Learning**

Individual differences are an important consideration in developmental investigations. To what extent does the pattern of results generalize to the general population of children? While the majority of 4- to 10-year-olds showed clear RT improvements across sequence trials, and RT impairments during random trials, there were some exceptions. All twenty 10-year-olds showed sequence-specific learning; however, three 7-year-olds (13%) evidenced questionable sequence learning. For the 4-year-olds, the percentage of nonlearners rose to 28% (11 of 40). Although Nissen and Bullemer (1987) did not report this result in their original article, such rates of nonlearners have been used as supporting evidence of a dysfunction in implicit processing. Knopman and Nissen (1987) reported that 9 of their 28 patients (32%) with probable Alzheimer’s disease failed to demonstrate sequence-specific learning despite eliminating data from those individuals
who performed at less than 70% accuracy by the fourth and fifth blocks of trials. These investigators reported similar rates of nonlearning (5 of 13, or 38%) in their study of patients with Huntington’s disease (Knopman & Nissen, 1991). The patients showing learning performed similarly to controls but showed smaller sequence learning effects at the end of the session, as well as overall slower RTs. Overall, learners and nonlearners in the Knopman and Nissen (1991) studies and in our experiments did not differ in their accuracy at the task. It is interesting to note the similarities in performance between adult patients and the 4-year-olds that we tested. Both had a high percentage of nonlearners despite adequate success at the RT task, and both demonstrated smaller sequence-specific learning effects than their comparison groups.

These individual difference effects also are echoed in the infant visual-expectancy literature. For example, although Smith et al. (1989) report greater-than-chance recall of locations in a 1-2-3-4 sequence by 5-month-olds, only 5 of 48 babies (10%) actually recalled all four steps in order. Similarly, 5-month-old infants in simple alternation paradigms as a group actually make anticipatory responses on only 14% of trials (Canfield et al., 1997). These results suggest that, although sequence learning looks similar across age groups using RT measures, some measure of individual differences or group variability may be informative. In particular, only 72% of our 4-year-olds demonstrated sequence-specific learning, whereas 87% of the 7-year-olds and 100% of the 10-year-olds showed significant sequence learning.

Conclusions

Overall, the current experiments provide supporting evidence of the utility of visuomotor sequence-learning paradigms for studying learning in preschool and school-age children. Our results are consistent with those reported by Meulemans et al. (1998) suggesting that RT measures of implicit learning do not differ significantly between age groups. However, our data suggest that other learning measures did differ by age. Children with complete explicit knowledge demonstrated larger sequence-specific learning effects than those with implicit knowledge alone, while partial awareness provided no learning benefit. This result fits cleanly with the observation from adult studies that incomplete explicit knowledge may actually impede task performance as subjects test strategies that they have formed about the paradigm. The degree of anticipatory responding also increased with age. Four-year-olds demonstrated very little anticipatory behavior and were not very accurate when anticipating. Both 7- and 10-year-olds showed more anticipatory responding, with explicitly-aware 10-year-olds showing the most anticipations. Despite the fact that all age groups performed above 80% accuracy, the younger age groups had more children who failed to demonstrate learning of the sequence based on RT measures. Interestingly, our attempt to manipulate implicit and explicit knowledge prior to the task was ineffective in producing implicitly- and explicitly-aware groups. Further developmental studies are needed to examine the effects of varying sequence complexity, symbolic rep-
resentational demands, and pretest explicit information on these age-related differences.

REFERENCES


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