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Implicit Sequence Learning in Children

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The main purpose of the present study was to examine whether implicit learning abilities, assessed by means of a serial reaction time task, are present to the same extent in 6- and 10-year-old children as in adults. We also wondered whether the knowledge acquired after one learning session is retained after a 1-week delay. And finally, we studied the explicit knowledge developed by the children in this task. Our results show no age-related difference in the serial reaction time performance, which is consistent with the idea that implicit learning abilities may be efficient early in development.

A new area of research has recently developed, concerning the ability to learn incidentally new complex information. In this area, called ‘‘implicit learning’’, the main accent is put on the fact that the study phase is incidental (i.e., subjects are unaware of the regularities governing the material), and that the learning leads to knowledge which it is difficult or impossible to access consciously and/or to report verbally (see Berry & Dienes, 1993; Seger, 1994). Another point is that implicit learning is often described as involving a phenomenon of abstraction (i.e., it depends not only on superficial features of the learning material); this abstraction process could concern the probabilistic relationships between elements or the ‘‘rules’’ governing the system. However, other authors

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have recently argued against the necessity to refer to any kind of implicit knowledge, and also that the principles governing more basic associative learning processes are often sufficient to account for the learning of the more complex structures involved in implicit learning situations (see Perruchet & Gallego, 1997, for more details about this view).

Different paradigms on implicit learning in adult subjects emerge from the literature. Probably the most investigated one concerns the artificial grammar learning task. In Reber's original study (Reber, 1967), subjects first had to learn letter strings generated by a finite-state grammar. After the study phase, they were informed that the letter strings had been composed on the basis of a complex system of rules. Finally, at the test phase, subjects had to classify new letter strings as grammatical, depending on whether or not the strings corresponded to the rules. In most experiments using this task, results show that subjects can classify grammatical and nongrammatical test strings at an above-chance level, although unable to report, sometimes even partially, the rules of the grammar (e.g., Mathews, Buss, Stanley, Blanchard-Fields, Cho, & Druhan, 1989; Meulemans & Van der Linden, 1997a; Reber & Lewis, 1977). So, it appears that subjects manifestly learned something from the task, without being able to report explicitly the rules underlying the grammar or to account for their performance (note, however, that there is no general agreement with regard to the very implicit nature of the acquired information in artificial grammar learning; see, for example, Shanks & St. John, 1994).

Another implicit learning paradigm is that of sequence learning or serial reaction time tasks (Nissen & Bullemer, 1987). In a classical serial reaction time task, a stimulus appears at one of four locations on a screen, and subjects have to respond as quickly as possible to each stimulus by pushing one of four keys, which corresponds to the position of the stimulus. In the original task designed by Nissen and Bullemer, subjects in a first group were confronted with sequences of stimuli appearing at random, while subjects in a second group had to respond to stimuli belonging to a repeating sequence running continuously. Sequence-specific learning in this task was observed when reaction times of the subjects in the second group (repeating condition), even though unaware of the presence of the repeating sequence, became faster than those of the subjects in the first group (random condition).

Implicit learning abilities have also been investigated in a neuropsychological perspective. It has been shown that amnesic patients, who are severely impaired in explicit memory tasks (such as recall or recognition), may show normal performance in various implicit learning situations (e.g., Knowlton & Squire, 1996; Nissen & Bullemer, 1987; Squire & Frambach, 1990). In the same manner, a few studies have shown that performances of elderly participants can be as good as those of young adult participants in implicit learning tasks. In a recent study, Cherry and Stadler (1995) studied young and elderly participants in a serial reaction time task. They showed that both groups performed at the same level for the learning of the sequence, although they also found individual differences in implicit learning. The higher ability older adults (selected on the basis of their educational and occupational levels) obtained results similar to young adults, while lower ability older adults showed less evidence of implicit learning. Other studies have found no age-related differences in sequence learning (e.g., Howard & Howard, 1992). With the artificial grammar learning paradigm, Meulemans and Van der Linden (1997b) have also shown that young and elderly participants could discriminate as readily between grammatical and nongrammatical items in the classification task.

Evidence in developmental psychology is more sparse. Reber (1993) reports two unpublished studies carried out in his laboratory: the first one suggests that children between 4 and 14 years of age can perform at a similar level in a modified form of the artificial-grammar learning paradigm (Roter, 1985, cited in Reber, 1993), and the second one shows that pre-school children could show a significant learning effect in an adapted form of the serial reaction time task. Lewicki, Hill, and Czyzewska (1992) also report an unpublished study (Czyzewska, Hill, & Lewicki, 1991, cited in Lewicki et al., 1992) in which evidence indicates that preschool children (4- to 5-year-olds) could implicitly acquire knowledge about a pattern in a visual search task where the location of a stimulus was determined by a set of rules. In the same research, Czyzewska et al. administered a task in which children learned a covariation between a general behavioural description concerning the level of activity of stimulus-persons (‘‘physically active’’ vs. ‘‘physically passive’’) and the color of their clothes. The authors showed normal implicit acquisition of information about covariations in 4- and 5-year-old children.

These results are consonant with the developmental invariance observed in research in the implicit memory area. Implicit memory refers to performance on tasks which do not require deliberate recollection of prior experience or of a prior event, but that, nonetheless, may reveal the influence of the prior experience (e.g., word completion and fragment identification). Global amnesia, ageing, and a number of variables (e.g., intention to learn, divided attention) have been found to affect performance on explicit memory tasks, while leaving implicit memory intact. Most of the research on the development of memory has focused on age differences in explicit memory tasks. In this perspective, a large number of studies have established that young children typically perform more poorly than adults on tasks such as recall and recognition (e.g., DiGiulio, Seidenberg, O’Leary, & Raz, 1994). By contrast, recent studies examining age differences in implicit memory tasks provide a different picture. Most of these studies have reported an absence of reliable differences in performance in implicit memory tasks between children of about 3 years and young adults (Carroll, Byrne, & Kirsner, 1985; DiGiulio et al., 1994; Ellis, Ellis, & Hosie, 1993; Greenbaum & Graf, 1989; Lorsbach & Worman, 1989; Naito, 1990; Parkin & Streete, 1988; Perrig & Perrig, 1993; Wippich, Mecklenbrauker, & Brausch, 1989).

However, some effects of age have also been reported in implicit tasks. The only published study (Maybery, Taylor, & O'Brien-Malone, 1995) in which children of different ages are compared in an implicit learning task showed an unexpected age-related effect. Maybery et al. adapted a matrix-learning task from Lewicki (1986a), and asked children from two age-groups (5–7 and 10–12 years old) to learn the covariation between the location of a picture in a 4 × 4 matrix and two other stimuli (the color of the matrix apparatus and the side of approach of the experimenter). Their results showed that the older children made more correct guesses concerning the location of the target-picture than the younger children (whose performance was not better than chance). Although this result was inconsistent with data previously obtained by Lewicki, who showed with the same task above-chance performance levels in a group of 4- to 5-year-old children, it does challenge Reber's claim that implicit learning is invariant with age. Likewise, improvement in performance with age on implicit memory tasks has been reported under some specific conditions, using a category exemplar generation task (Graf, 1990; Perruchet, Frazier, & Lautrey, 1995), thus strengthening the conclusion that the invariance of implicit task performance with age is far from being ubiquitous (see also Ausley & Guttentag, 1993).

The developmental dissociation between implicit and explicit memory processes could also be considered in the light of the view that age-related differences in memory performance are specifically observed in tasks involving strategic processes such as, for example, verbal mediation and rehearsal (for reviews, see Bjorklund & Douglas, 1997; Kail, 1990). In the implicit-learning research area, the aim is to study basic learning phenomena in situations where subjects do not use explicit mnemonic strategies simply because they often do not even know that they are learning something. Studies on implicit learning are also in keeping with a more ancient tradition in which age-related differences were studied in incidental versus intentional learning (e.g., Maccoby & Hagen, 1965; Newman, 1990). The characteristic of incidental learning tasks is that no learning instruction is given to the subjects when they are presented with the learning material. Studies have shown that age-related differences in a free-recall test are smaller when the encoding is incidental than when subjects are explicitly told to memorize the items (and this is especially true for very young children; see Newman, 1990). The incidental aspect of the learning phase has often been cited among the criteria defining the implicit learning area (e.g., Seger, 1994). Indeed, researches in implicit learning are specifically interested with the human ability to learn incidentally new complex information. However, the term ''incidental learning'' covers other research traditions as well, like, for example, studies on implicit memory.

Although the theoretical conclusions which will be drawn from age-related dissociations between explicit and implicit learning processes will depend on the theoretical perspective adopted, there is a general agreement on the idea that implicit learning processes play an important role in cognitive development. According to Karmiloff-Smith (1992, 1994), cognitive development consists of a succession of stages involving the setting up of different levels of representation. The initial phase of this process is typically procedural in the sense that representations are at first automatic and unconscious; but these representations, which are by nature implicit, nonetheless enable the children to interact efficiently with their environment. Other authors consider, on the contrary, that implicit learning processes do not imply the elaboration of abstract implicit representations, and can be easily accounted for by the intervention of elementary associative processes (Perruchet & Vinter, 1997; see also Perruchet & Gallego, 1997).

Whatever the theoretical perspective adopted, the paucity of the developmental data appears especially damaging in regard to the common assertion that implicit learning plays a fundamental role in early cognitive (and probably also emotional and social) development (e.g., Reber, 1993). It looks somewhat paradoxical to confer such a function to a mechanism the properties of which have been almost exclusively explored in adults. The purpose of the present study was to investigate whether implicit learning abilities, assessed by means of a serial reaction time task, are present in 6- and 10-year-old children to the same extent as in adults.

In the serial reaction time literature, a critical methodology issue concerns the way control performances are obtained to assess the genuine effect of practice on the repeating sequence. Although a few studies have included an independent group of subjects submitted to random sequences, most studies use a within-subject design in which subjects trained with the repeating sequence are transferred to a random block of trials at the end of training. Learning is measured by the resulting increase of reaction time. In the following experiment, we used a control procedure which retains the advantages associated with a within-subject design, but where random trials are intermixed with the repeating sequence within each training block, as in Curran (1997) and Perruchet, Bigand, and Benoit-Gonin (1997). Stadler (1993) showed that learning occurs in these conditions, and it turns out that this procedure provides a control which is endowed with several advantages with regard to the conventional method. Among the advantages pointed out by Curran (1997), two of them are specially relevant for our purpose. Firstly, due to the mixing of the repeating sequence with random trials, the explicit discovery of the task structure is made less probable. This feature is important whenever children are compared with adults on nominally implicit tasks. Secondly, this procedure, because it provides much more control data than the conventional procedure, allows the assessment of the effect of training for each location in the repeating sequence. This is important, because, beyond the question of the overall level of learning, it is interesting to examine, at a more qualitative level, to what extent children and adults are sensitive to the same structural constraints. And finally, another distinct advantage of this procedure is that it avoids the problem of confounding the random condition with the

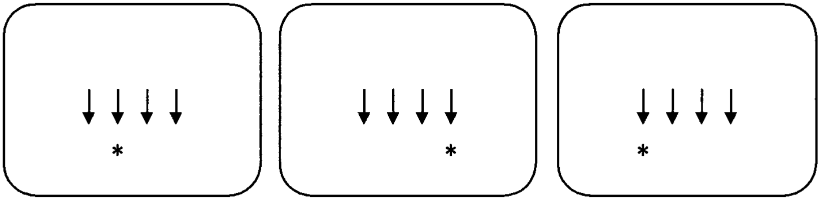

FIG. 1. Stimulus location for the three first stimuli of the repeating sequence (i.e., positions B-D-A).

last sequence condition, thus avoiding confounding performance on the control condition with fatigue and other sources of negative transfer.

In addition to this general purpose, we also explored whether children's performance was still sensitive to the repeated sequence after a one-week delay, as adults' performances have been reported to be (e.g., Nissen, Willingham, & Hartman, 1989). Finally, we examined the explicit knowledge acquired by the children in this task. Is this explicit knowledge better after two learning sessions than after one session? Does the explicit knowledge assessment show the age effect classically observed in explicit memory tasks?

METHOD

Subjects

Three groups of right-handed subjects participated in the experiment: a first group of 32 children aged between 6 and 7 years (18 boys and 14 girls; the ''6-year-old'' Group); a second group of 32 children aged between 10 and 11 years (15 boys and 17 girls; the ''10-year-old'' Group), and a comparison group of 32 university undergraduates aged between 18 and 27 years (10 men and 22 women; the ''Adults'' Group). All children were recruited from the same school and were from white, predominantly upperclass, backgrounds. None of the children had fallen behind their age group at school.

Materials

The serial reaction time task was administered on an IBM PC computer. The subject sat in front of the computer, and had to respond as quickly as possible to a stimulus (an asterisk) appearing at one of four locations on the screen by pushing one of four keys (keys ''X,'' ''C,'' ''N,'' '','' on a French AZERTY keyboard[1]), which corresponded to the position of the asterisk on the screen (see Figure 1). Four arrows, each indicating a stimulus location, remained displayed on the screen throughout the session. The appearance of the next stimulus followed each correct key press after a delay (response-stimulus interval) of 250 ms. Each block of trials consisted in sequences composed of random trials

[1] On a English QWERTY keyboard, the keys would be ''X,'' ''C,'' ''N,'' and ''M.''

alternating with a repeating sequence of 10 trials. The sequence was B-D-A-C-D-B-A-D-C-A, with ‘‘A’’ being the left key and ‘‘D’’ the right key. The location of the target in the random sequence was determined randomly, except that two asterisks could not appear in the same position consecutively. In addition, in each block, the four positions appeared in the same proportion as in the repeating sequences (i.e., A and D, 30%; and B and C, 20%). In this way, the learning of the sequence could not be attributable to other characteristics than its repetition, such as the unequal distribution of the four positions.

For the recognition task, 16 sequences of 4 stimuli were constructed (see Appendix): 8 sequences belonging to the repeating sequence in the learning phase (‘‘OLD’’ sequences) and 8 sequences which had never been presented during the learning phase (‘‘NEW’’ sequences). Old and New 4-trial sequences were yoked, so that the sequences from any pair differed only by their last trial.

The program controlled both stimulus presentation and data recording (stimulus position, reaction time, response correctness).

Procedure

Learning phase. The subjects were told:

> You will see 4 arrows on the screen. A little star will appear underneath these arrows. Sometimes underneath the first one, sometimes underneath the second one, and so on. You will have to push as quickly as possible on the corresponding key as soon as the star appears. When the star is underneath the first arrow, you push on the first key, and so on, but always pushing on the key corresponding to the arrow. If you make a mistake, the computer will make a noise. This is not serious, you simply push on the right key, and then the next star will appear. You must answer as quickly as possible, but try to make as few mistakes as possible.

The subject had to place his middle finger and his forefinger of each hand on the four response keys, and was asked to keep his fingers on the keys during the task.

The 32 subjects of each age group were divided into two subgroups: a first subgroup of 16 subjects (Condition A) was administered the serial reaction time task during one session, immediately followed by the recognition task, and a second subgroup of 16 subjects (Condition B) was administered the serial reaction time task during two sessions separated by a 1-week interval. For this second group, the recognition task was carried out after completion of the second learning session.

A learning session comprised 5 blocks of 84 trials. Each block started with 4 random trials, followed by the presentation of the repeating sequence (10 trials), after which 6 random trials were again presented, and so on. Hence, one block comprised 5 presentations of the repeating sequence, each of these presentations being followed by 6 random trials. Actually, because of their unpredictability, the two first stimuli of the repeating sequence were considered in the analysis as belonging to the random sequences (note that the status of the two first trials of the repeating sequence is questionable, but had learning occurred in these trials, it would have improved the performance on the random sequence, and hence decreased the chance of evidencing learning). Hence, the repeating and random sequences considered for the analyses comprised the same number of stimuli (8 in each).

Recognition task. At the end of the first learning session for subjects in Condition A, and at the end of the second learning session for subjects in Condition B, the subjects were informed of the presence of a repeating sequence, and were administered the recognition task. They had to say if the four-stimulus sequence they were presented belonged to the repeating sequence or not by choosing between five possibilities on a 1–5 scale: ''I am sure I never saw it,'' ''I believe I never saw it,'' ''I don't know,'' ''I believe I saw it,'' ''I am sure I saw it.'' Each asterisk appeared for one second on the screen, and there was an interval of two seconds between two asterisks. Just like in the learning task, the subject could push on the corresponding key (and all subjects did so); each sequence could be seen as often as desired.

In each block, learning was measured by using the median of the reaction times (for correct responses only) for both the repeating sequence and the random sequences. In order to take into account the different reaction time levels between the three groups, sequence-specific learning was also calculated by using the ratio (R5 − S5)/(R5 + S5), R5 being the median reaction time for the random sequences in Block 5, and S5 being the median reaction time for the repeating sequence in Block 5. A measure of response accuracy was also used, by calculating the number of false responses in each block for the two types of sequences.

RESULTS

Learning

An analysis of variance (ANOVA) with Group as between-subject variable, and Trial type (repeating or random sequences) and Block as repeated measures was calculated on the median reaction times for both types of sequences for the first session, including all subjects (32 in each group; see Fig. 2). With a significance level which was set at .05 for all statistical analyses, the ANOVA showed an effect of Group, $F(2,93) = 208.4$, an effect of Trial type, $F(1,93) = 70.03$, and an effect of Block, $F(4,372) = 20.98$. Interestingly, there was no interaction between the Group and Trial-type variables, $F(2,93) = 2.28$, indicating that the difference in reaction times between repeating and random sequences could be observed in a similar fashion in the three groups of subjects. On the other hand, there was an interaction between Group and Block, $F(8,372) = 8.52$, indicating (Newman–Keuls post-hoc test) that the global reaction time improvement from Block 1 to Block 5 only appeared in the 6-year-olds group. Sequence-specific learning appeared in the interaction between Trial type and Block, $F(4,372) = 6.21$: the difference in reaction times between block 5 and block 1 was larger for repeating-sequence than for random-sequence trials. This se-

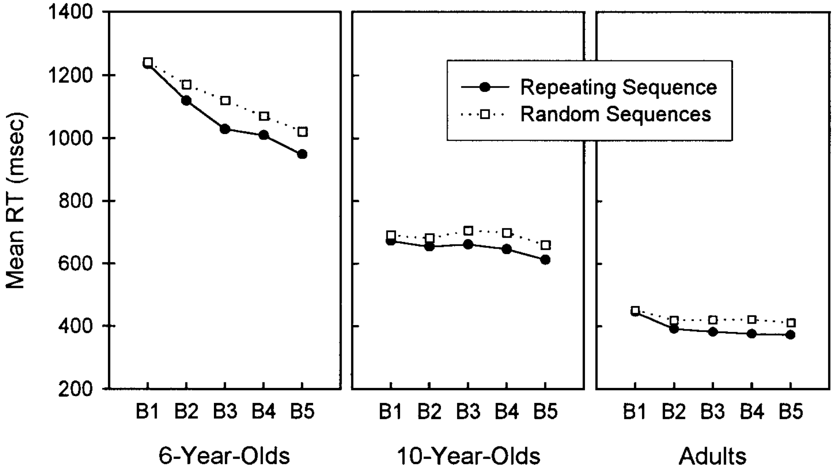

FIG. 2. Mean reaction time performance as a function of group, block and type of sequence (repeating vs. random).

quence-specific learning effect was the same for the three groups (no triple-interaction), $F(8,372) = 0.82$.

In order to minimize the impact of the much slower reaction times of the children, a one-way ANOVA was also carried out, using the ratio [(R5 − S5)/(R5 + S5)] as the dependent variable. The result confirmed that of the general ANOVA: there was no difference between the three groups of subjects concerning the magnitude of the ratio, $F(2,93) = 1.04$. In other words, the adults' mean ratio was not significantly higher than that of children, indicating that children showed the same sequence learning as the adults.

Another measure of learning was the number of errors in each block, both for trials belonging to the repeating sequence and for those belonging to the random sequences. A 3 × 2 × 5 ANOVA showed a significant effect of the Group variable, $F(2,93) = 19.57$, and of the type of stimulus (belonging to the random sequences or the repeating sequence), $F(1,93) = 44.26$. There was no effect of the Block variable. Finally, the only significant interaction concerned the variables Group and Type of stimulus, $F(2,93) = 4.72$, indicating that more errors were made for the stimuli belonging to the random sequences than for those belonging to the repeating sequence, and that the difference between repeating and random sequences was larger for the young than for the older subjects (Fig. 3).

Serial Order

Another way to compare sequence-specific learning is to investigate whether subjects in the three groups learned the same part(s) of the sequence. In order to avoid any confusion between sequence learning and a possible motor effect

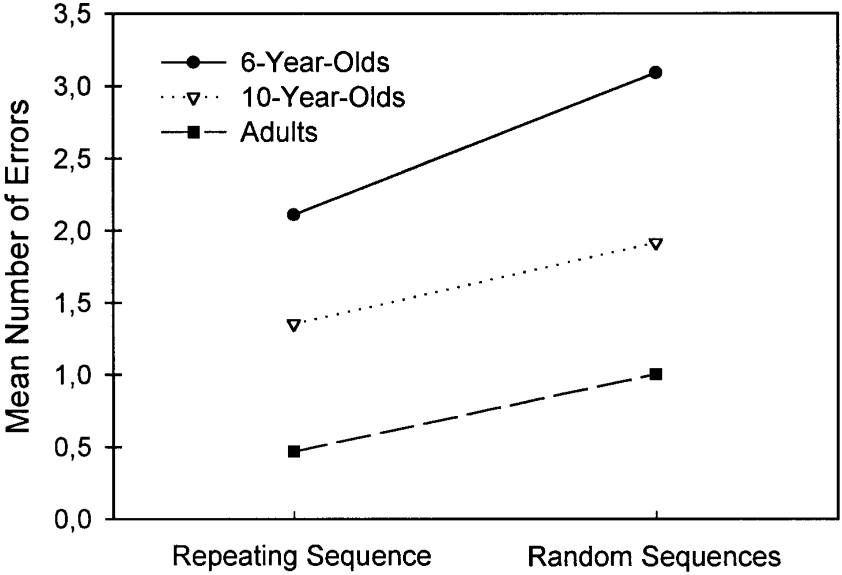

FIG. 3. Mean number of errors in the first learning session as a function of group and type of sequence (repeating vs. random).

(Nissen & Bullemer, 1987), we corrected, for the five blocks of the first session, the median reaction time for each stimulus in the repeating sequence by the median reaction time for its corresponding stimulus in the random sequences (i.e., the stimulus located at the same position on the screen). In other words, we subtracted each median reaction time for the stimuli belonging to the repeating sequence from its corresponding median reaction times for random stimuli. Figure 4 shows the corrected reaction times for each stimulus of the repeating sequence according to its serial order. An ANOVA with Group as between-subject variable and Serial order (including the 8 stimuli composing the repeating sequence) as within-subject variable, showed no effect of Group, $F(2,93) = 1.95$, an effect of Serial order, $F(7,651) = 80.35$, and a significant interaction between Group and Serial order, $F(14,651) = 13.10$, indicating that the Serial order effect is particularly marked in the 6-year-old group.

However, it appears in Fig. 4 that the three groups learned the same parts of the sequence. This result was confirmed by correlated rank analyses conducted between the three groups on the corrected serial position data. These correlations were all highly significant: between the 6-year-old and the 10-year-old groups ($r = .93$), between the 6-year-old and Adult groups ($r = .98$), and between the 10-year-old and Adult groups ($r = .98$). In the three groups, learning concerned especially positions 3, 5, and 7. Interestingly, these positions are the ones when the subjects had to respond with the other finger of the same hand as in the preceding trial. It could be

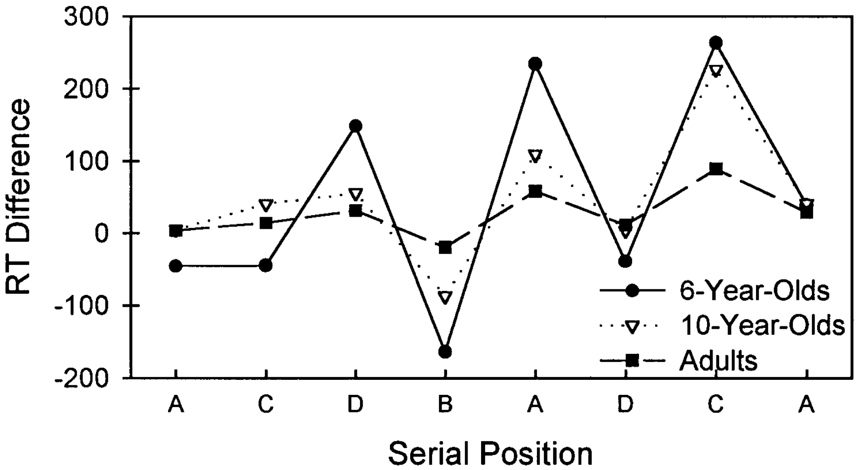

FIG. 4. Mean reaction time according to serial position as a function of group in the first learning session, corrected for the baseline reaction time to the stimulus (see text).

that this kind of regularity constitutes a part of what subjects actually learn in a sequence; what is shown in the analysis is that this observation concerned the two groups of children as well as the adult group.

It could be argued that the faster reaction times when the subjects had to respond with the other finger of the same hand as in the preceding trial results from a simple motor facilitation due to the fact that these movements would be easier than others. Two series of data run counter this argument. First, the motor facilitation interpretation is not consistent with data previously obtained by Rabbitt and Vyas (1970), who found that reaction times in a task including only random stimuli were fastest when subjects had to respond with the same finger of the other hand than that used for the previous trial [HF-hF], slower when the response implied the other finger of the same hand [HF-Hf], and slowest when they had to respond with the other finger of the other hand [HF-hf]. As shown in Fig. 4, no learning can be observed in the present study for the HF-hF alternations, while HF-Hf alternations seem to give rise to faster reaction times in the repeating sequence.

Secondly, the effect of motor facilitation in our experiment should concern random as well as repeated parts of the sequence. In order to compare reaction times for the HF-Hf alternations between random and repeating sequences, we computed an ANOVA with Group (6-year-old, 10-year-old, Adults) as the between-subject variable, and Type of sequence (random vs. repeated sequences) and Type of alternation (different hand-same finger [HF-hF] vs. same hand-different finger [HF-Hf] vs. different hand-different finger [HF-hf]) as repeated measure factors. The ANOVA showed significant effects for the three variables, an interaction between Type of sequence and Type of alternation, $F(2,186)$ =

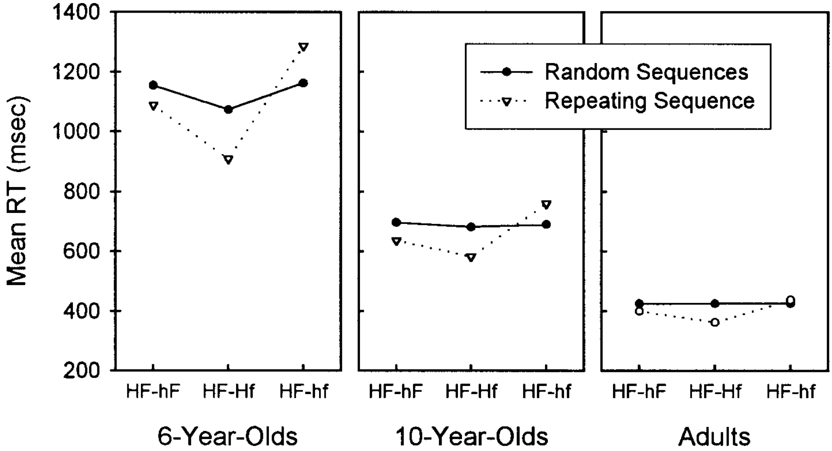

FIG. 5. Mean reaction time by type of finger alternation (HF-hF = different hand, same finger; HF-Hf = same hand, different finger; HF-hf = different hand, different finger) as a function of group in the first learning session.

93.25, and an interaction between the three variables, $F(4,186) = 11.17$. On the whole, the fastest reaction times concerned the HF-Hf alternations. However, the HF-Hf alternations were faster than the other ones in the repeating sequence, but post-hoc statistical analysis (Newman–Keuls tests) actually showed no reaction time difference between the three alternations in the random sequences, except for the 6-year-old children, who showed a faster reaction time for the HF-Hf alternations (see Fig. 5). In the same line, reaction times for HF-Hf alternations were shorter for the alternations within the repeating sequence than for the alternations within the random sequences, $F(1,93) = 233.66$.

Although these results rule out an interpretation framed in terms of motor facilitation, it is worth stressing that they raise a problem about what subjects actually learned. At first glance, these results suggest that subjects learned something about the HF-Hf alternations themselves, such as their high frequency. However, this interpretation is dismissed by the fact that, on the whole, the most frequent alternations were not the HF-Hf, but rather the HF-hf alternations, for which the reaction times were the slowest. Moreover, this line of reasoning would have been appropriate only if the control sequences used in the above analyses had been practised by independent subjects. Now, it must be realised that a within-subject control procedure was used here. What is observed, in fact, is that HF-Hf alternations elicited shorter reaction times when they occurred in the context of the repeating sequence than when they occurred in the context of the random trials intermixed with the repeating sequences, in the same subjects. Hence the only possible conclusion is that subjects did not become sensitive to the overall probability of HF-Hf alternations, but rather learned about the

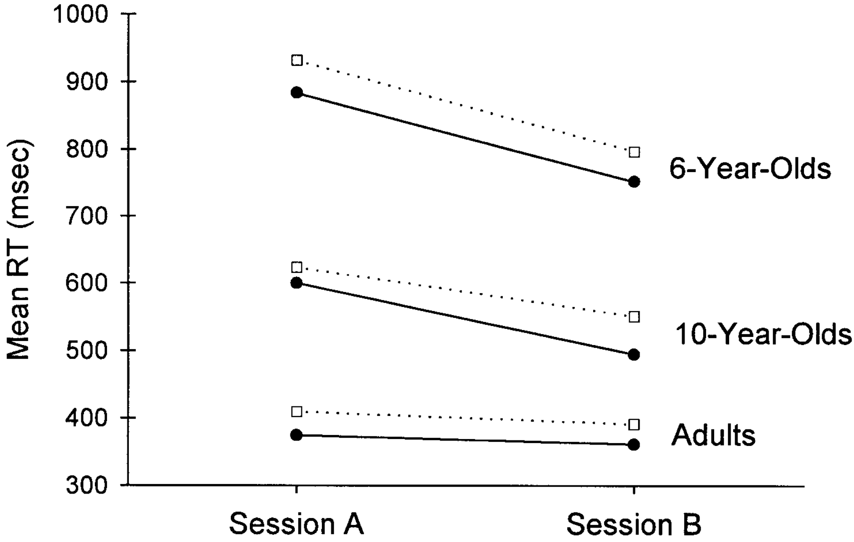

FIG. 6. Mean reaction time performance for the three age-groups at the end of the first session (block 5) and at the beginning of the second session (block 1) as a function of the type of sequence (the dotted lines representing RT's for the random sequences, and the solid lines the RT's for the repeating sequence).

probability of these alternations in a specific context.[2] We postpone to the discussion some suggestions about what this context may have been.

Retention

Concerning the performance of the subjects after a 1-week delay, an ANOVA with Group as between-subjects variable (including only the subjects who participated in both sessions), and Session (first vs. second) and Type of sequence (repeating vs. random) as within-subject variables was computed using the reaction times on the last block of the first session and those on the first block of the second session. Apart from the effect of the Group variable, $F(2,45) = 89.48$, reflecting the effect of age on the reaction time, there was a significant effect of the Session variable, $F(1,45) = 27.06$: the mean reaction time at the beginning of the second session was faster than the mean reaction time at the end of the first session (558 ms vs. 637 ms). The expected effect of the type of sequence was present, $F(1,45) = 40.88$, but it did not interact with any of the

[2] However, we do not assert that what subjects learned is really the ''motor'' aspect of these transitions. Indeed, Stadler (1989) has shown that, in sequence learning, changing the keys had little effect on performance, an observation which suggests that the learning concerns the target transitions on the screen more than the finger transitions. The reader should keep this in mind whenever we speak about finger transitions in the present article.

TABLE 1
Mean Recognition Ratings for Old and New Sequences

	Old		New	
	M	*SD*	*M*	*SD*
6-Year-old	3.17	0.57	3.03	0.59
10-Year-old	3.41	0.55	3.26	0.58
Adults	3.47	0.53	3.52	0.54

Note. The scale was ranging from 1 to 5 (from ''I am sure I never saw it'' to ''I am sure I saw it'').

other variables, showing that sequence-specific knowledge was not significantly different from one session to another, and that the three groups did not differ with regard to this latter observation (see Fig. 6). Finally, there was an interaction between the Group and Session variables, $F(2,45) = 5.03$, indicating that the reaction time improvement was significant for both the 6-year-old and the 10-year-old groups, but not for the Adults (maybe reflecting a floor effect).

Recognition

The recognition task was administered to half of the subjects after one learning session, and to the other half of the subjects after two learning sessions. In order to compare these two conditions in the three groups of subjects, the ANOVA comprised two between-subject variables (Group and Condition), and one within-subject variable (Old sequences vs. New sequences). The dependent variable was the mean response level for both types of sequences. The analysis shows an effect of Group, $F(2, 90) = 5.44$, indicating that the adults tended to respond more often that they saw the sequence (whether the sequence was ''OLD'' or not) than the children. Apart from this, no effect was significant; particularly, there was no effect of the OLD/NEW variable, and no interaction with the Group variable (see Table 1 for the mean recognition ratings of the three groups). In order to ensure that this absence of effect was not due to our sample size, we computed a power analysis on the data. With regard to the absence of Group $\times$ Type of sequence interaction, the largest effect size concerned the 6-year-old group (.27). In order to reach a power level of .80, a sample size of at least 213 would be needed in each group. However, it should be noted that, for the Adult group, the interaction which would be reached would be in the opposite direction: if anything, the adult subjects would recognize more often the NEW items than the OLD (see Table 1). Finally, there was no correlation between performance in the recognition task and sequence learning (calculated for each block by the difference between RT for random and repeating sequences).

Another analysis was realized in order to compare the responses for the Old and New sequences. For this analysis, these responses were converted to a

2-point scale: the responses ''I am sure I never saw it'' and ''I believe I never saw it'' were converted into ''NO'' responses, and ''I believe I saw it'' and ''I am sure I saw it'' into ''YES'' responses (the ''I don't know'' responses were excluded from this analysis). So, each subject had two scores for each item type (Old and New sequences). A first ANOVA was computed, with two between-subject variables (Group and Condition) and two within-subject variables (Type of sequence and Response). Because there was no effect of the Condition variable, two separate analyses were computed for each condition. For both conditions, there was no interaction between the Type of sequence and Response variables, $F\text{s}(1,45) < 1.85$. Moreover, there was no triple interaction for condition 1, $F(2,45) = 1.43$, and a tendency for condition 2, $F(2,45) = 2.59$, $p = .086$. However, the Newman–Keuls post-hoc test revealed no significant difference between the two types of sequences, neither for the ''YES'' responses nor the ''NO'' responses. These results confirm those of the previous ANOVA, showing that subjects could not discriminate between the old and new sequences in the recognition task.

Following the above analysis on the finger alternations, it could be that subjects learned information about the presence of HF-Hf alternations in the repeating sequence, in which case, the analysis made on the recognition task could be not relevant. Indeed, Jackson and Jackson (1995) argued that most of the explicit tests administered in serial reaction time studies (including the recognition tasks) require that subjects have acquired information about the serial-order of the sequence. If this is not what subjects actually learned, these explicit tests would not be appropriate for evaluating the explicit knowledge, in that they would not fit the Information Criterion proposed by Shanks and St. John (1994).

In the present case, we should consider the sequences proposed in the recognition task, not according to whether they simply belonged or not to the repeating sequence, but according to the fact that they contained or not HF-Hf alternations (assuming that this was the information acquired by the subjects). Two different analyses were conducted: in a first analysis, we compared results obtained in the recognition task for the old sequences containing the HF-Hf alternations present in the repeating sequence (this concerned five sequences) with those obtained for the new sequences containing the same alternations (five sequences); in a second analysis, results for the same five old sequences were compared with results for all other sequences (i.e., old sequences which did not contain the HF-Hf alternations and new sequences containing or not the HF-Hf alternations). In the first analysis, there was no overall significant effect of the Old/New variable, $F(1,90) = .06$; on the other hand, there was a significant interaction between the Group and the Old/New variables, $F(2,90) = 3.44$. Post hoc tests (Newman–Keuls) showed no difference between Old and New sequences for 6-year-old and 10-year-old children, but a nearly significant difference for adults ($p = .06$). However, this latter effect indicated that the old sequences were less often accepted as being old by the subjects than the new ones. Concerning the second analysis, the pattern was about the same, except that there was only a marginal significant interaction between the Group and the Old/New variables ($p = .06$). This time, post hoc tests showed no difference between Old and New sequences for neither groups. Hence, even when considering the recognition task on the basis of what subjects could have actually learned in the learning task (the HF-Hf alternations present in the repeating sequence), no consistent evidence of explicit knowledge emerges from our data.

DISCUSSION

Different analyses were computed on the data in order to evaluate sequence-specific learning in 6- and 10-year-old children and in adults. These analyses all converge towards the same conclusion: the implicit learning of the sequence can be observed at the same level in the three groups. Hence, this study shows that 6-year-old children can learn the sequence as well as adults. Furthermore, the analysis made on the serial order learning of the sequence showed that all three groups learned the same parts of the sequence. From a more qualitative point of view, this latter finding can be considered as an additional argument supporting the idea that implicit learning abilities are present early in development. Concerning the serial order learning, our data also suggest that, in the three groups, reaction times improved most when, in the context of the repeating sequence, subjects had to respond with the other finger of the same hand after the preceding trial. Another important result of this study concerns the long-term retention of the sequence-specific knowledge. Indeed, the analysis revealed that children as well as adults retain their acquired knowledge after a 1-week delay. This finding is consistent with studies in adults which have shown that implicit learning effects persisted across delays of days and months (e.g., Allen & Reber, 1980; Nissen, Willingham, & Hartman, 1989). In our study, there was also a global improvement from session one to session two. This could actually be due to a tiredness effect: it could be that subjects became somewhat tired at the end of the first session, and hence their performance was slower.

Finally, the analysis of the recognition task showed performance levels which suggest that subjects did not acquire any explicit knowledge of the repeating sequence. At first approximation, this suggests that sequence learning indicated through reaction time measures is implicit and does not result in a conscious, verbalizable knowledge. The result of a dissociation between performance in the serial reaction time task and explicit knowledge in children may be considered as a new and important result, insofar as, to the best of our knowledge, our study is the first to investigate this issue. However, we also found this dissociation in adults, a result which is at odds with most of the data in the literature: at present, a large number of researchers in this domain consider that the implicit learning of the sequence is often accompanied by explicit knowledge. Obviously, we need to explain our atypical finding in adults before the evidence of a dissociation in children may be considered at its full value.

Although several early studies have claimed that learning occurs without subjects being aware of the repeating sequence (e.g., Cohen, Ivry, & Keele, 1990; Nissen & Bullemer, 1987; Willingham, Nissen, & Bullemer, 1989), subsequent investigations demonstrated that these apparent dissociations stemmed from various procedural biases (e.g., Perruchet & Amorim, 1992; Shanks & St. John, 1994). More recently, Shanks and Johnstone (1997) showed that the evidence for unconscious learning put forth by Reed and Johnson (1994) was also due to a flaw in their experimental design. Overall, there is wide evidence that some explicit knowledge may be observed after practice on a serial reaction time task, and especially with a recognition test, as used in the present experiment (e.g., Willingham, Greeley, & Bardone, 1993; Perruchet et al., 1997). Why was recognition in adults at chance level in the present experiment?

A first possibility is that this result points to a genuine implicit/explicit dissociation. The fact that children and adults learned to the same extent in the serial reaction time tasks is, in some ways, consistent with this possibility. Indeed, different studies (e.g., Curran, 1997; Curran & Keele, 1993; Hartman, Knopman, & Nissen, 1989; Willingham et al., 1989) have suggested that performance in sequence learning tasks could benefit from the explicit knowledge acquired by the subjects in the task: the more important the explicit knowledge, the greater the RT decrease for the repeating sequence. Following these results, one could have expected that, in the present study, performance in the serial reaction time task could have been better for adults than for children, because it is well known that adults generally perform better than children in explicit memory tasks. The fact that adults' performance in the serial reaction time task was no better than that of children suggests that no explicit knowledge was acquired by our subjects in the present study.

This atypical result could be due to some particularities of the procedure. A priori, a particularly important aspect concerns the nature of the repeating sequence. However, the sequence used here does not seem to differ by any relevant features, such as length or complexity of the statistical structure, from the ones used elsewhere. On the other hand, a characteristic of our procedure, departing from the standard one, was the intermixing of random trials between successive occurrences of the repeating sequence. It is possible that this feature prevents the formation of explicit knowledge without having any detrimental effects on reaction times. Note that this explanation suggests that the absence of any age effect observed in our study could be due, at least partially, to the difficulty of the task. If the statistical structure had been more salient, explicit knowledge may have developed and may have contributed to the RT acceleration, and one could expect this effect to be more important for adults than for children.

The hypothesis that the atypical procedure used here could be responsible for the lack of recognition finds partial support in Curran's (1997) results. Curran observed no significant recognition for fragments of the repeating sequences in young and elderly participants, although reaction times improved selectively on these sequences in the training phase. Notably, the control procedure used by Curran was similar to ours (except that random trials occurred only after two exposures to the repeating sequence instead of one). Moreover, the statistical structure of the repeating sequence used in the present experiment is more complex than that used in other studies (e.g., Perruchet et al., 1995). It is possible that the combined use of a within-subject within-block design with a relatively complex repeating sequence made the situation too difficult to allow for explicit knowledge to emerge.

Another possibility regarding our failure to reveal any explicit knowledge is that it is due to the inadequacy of our recognition task. We have to examine whether the test we used fulfils what Shanks and St. John (1994) called the *sensitivity* and the *information* criteria. Regarding the first criterion, there is a consensus on the idea that recognition is a sensitive measure. This consensus is even reinforced by one finding from Curran's (1997) study. Curran (1997, Experiment 2) compared several tests of explicit knowledge, and concluded that the fragment recognition test, as used in the present study, may be the most sensitive to partial levels of explicit knowledge. The issue pertaining to the information criterion is more problematic. As Shanks and St. John (1994, p. 373) pointed out, ''before concluding that subjects are unaware of the information they have learned and which is influencing their behaviour, the experimenter must be able to establish that the information he or she is looking for in the awareness test is indeed the information responsible for performance changes''. In an attempt to fulfil this criterion, the situation of the recognition task was close to that of the learning phase: the recognition sequences were presented in a very similar way to that of the stimuli in the learning phase, and subjects could respond to the stimuli by pushing the corresponding keys on the keyboard.

However, this does not necessarily entail that the to-be-recognized fragments displayed during the recognition test provided the same information as the training sequences. Analyses of reaction times revealed that subjects may have learned information about specific finger alternations embedded in the repeating sequence. More specifically, same hand-different finger [HF-Hf] alternations elicited shorter reaction times when they occurred in the context of the repeating sequence than when they occurred in the context of the random trials intermixed with the repeating sequences. Hence our conclusion was that subjects did not become sensitive to the overall probability of HF-Hf alternations, but rather learned about the occurrence of these alternations *in a specific context*. In our analysis of the recognition data, we also focused on the knowledge related to these specific finger alternations and found no indications of explicit knowledge; however, it is noteworthy that our fragment recognition task did not provided the specific context that seemed necessary for RT improvement.

Thus, what can be said about the information acquired by the subjects during the learning phase, and about the status of this information with regard to the implicit/explicit dimension? Actually, our data seems to confirm that subjects can detect some regularities in the stream of stimuli with which they are confronted. More specifically, it might be that subjects are sensitive to relatively complex information. Indeed, performance improvement observed in the present experiment *cannot* be due to some information regarding the presence or the frequency of a single stimulus or pairs of stimuli. Reaction times differed between the HF-Hf alternations included in the repeating sequence and the same alternations occurring in the random trials intermixed with the repeating sequence. This finding demonstrates that participants were sensitive to higher order information (for instance, to second-order dependency rules) than the simple presence or frequency of these alternations.

Be that as it may, the important point is the demonstration of the absence of any age-related effect in implicit sequence learning. This result is consistent with the idea that implicit learning processes would be present early in development, a postulate consonant with different current accounts of the cognitive development in children. The theoretical construction which is probably the most integrated from a developmental perspective is that proposed by Karmiloff-Smith (1992, 1994), who tries to reconcile the nativist and constructivist positions on cognitive development. According to her, cognitive development consists of a succession of stages which imply a mechanism of redescription of representations. Karmiloff-Smith proposes different levels of representation. The first level (implicit) encodes the representations in a procedural form. At this stage, children are mainly sensitive to the information coming from their external environment; this rather inflexible data-driven learning permits children nonetheless to interact efficiently with their environment. Then, different redescriptions can take place, leading to the elaboration of an explicit format of the representations (according to Karmiloff-Smith, the term ‘‘explicit’’ is not necessarily synonymous with ‘‘verbalisable’’); this explicit format has the advantage of being more flexible and manipulable by the cognitive system (e.g., usable for other purposes). In that context, from one redescription to another, the mental representations become more and more open to conscious thought. This process of *representational redescription,* which constitutes the foundation of Karmiloff-Smith’s theory, does not end up in the elaboration of a unique representational format, but leads to the existence of different representational levels for a particular knowledge. Within this theoretical framework, implicit memory and implicit learning phenomenons take place during the initial stage of the representation formation: these representations are procedural, automatic, rather inflexible and inaccessible to consciousness, but they permit children to reach a sufficient ‘‘behavioural mastery’’ of their environment. This initial phase would be typical of the early stages of cognitive development.

More recently, Perruchet and Vinter (1997; see also Perruchet & Gallego,

1997) have presented a radically different interpretation than that adopted by Karmiloff-Smith (1992). Perruchet and Vinter reject the idea by which the early ability to interact efficiently with the environment would depend on the building of implicit representations. According to Perruchet and Vinter, this aptitude can be accounted for by the ability of the young child to segment the stream of stimulations coming from the environment into discrete units, a process which can be explained by the simple implementation of elementary associative processes. Confronted with this stream of information, the child's attention can be captured by a set of stimuli sharing some specific properties (like their novel nature, or their movement), and the result of this associative process is the formation of the primitive subjective units, which will serve for the elaboration of units of higher level. According to Perruchet and Vinter, this hierarchical mechanism also accounts for more complex learning phenomena, which could be real-life situations as well as some implicit learning phenomena observed in the laboratory. On no account do the implicit learning processes involve abstraction mechanisms, which would depend on the conscious forms of thought.

To summarise, the results of the present study showed no age effect on implicit learning in a serial reaction time task. This result is consistent with the idea that implicit learning processes would be present early in development, a postulate consonant with different current accounts of the cognitive development in children. However, this result contrasts with the Maybery et al. (1995) study, which showed, on the contrary, an age-related improvement in an implicit learning task. The discrepancy between the two studies could be due to the fact that different implicit learning paradigms were used: Maybery et al. used a task adapted from the covariation learning paradigm developed by Lewicki (e.g., Lewicki, 1986b), whereas the present study used a serial reaction time task. Although the absence of implicit learning observed by Maybery et al. in young children could also have been due to some strategy biases (i.e., a tendency in the young children group to perseverate on the previous target-stimulus location), it is more likely that the two implicit learning tasks involve different processes, and that some of these processes could be more sensitive to age variations than others. Another possibility is that performance in the nominally implicit learning task has been affected by the explicit knowledge about the training situation. Maybery et al. provided some evidence that explicit knowledge was lacking, but this evidence was grounded on the results on a questionaire, which is known to be a specially unsensitive measure. If responses in the learning task may have been contaminated by explicit knowledge, this could explain that adults outperformed children. One of the critical issues of future research on implicit learning and development will be of assessing whether children really exhibit lesser capabilities than adults in a subset of implicit learning tasks, or whether the occasionally reported superiority of adults is due to the contamination by explicit factors.

APPENDIX

Recognition Sequences

Old	New
DBDA	DBDB
BDAC	BDAB
DACD	DACA
ACDB	ACDA
CDBA	CDBD
DBAD	DBAC
BADC	BADB
ADCA	ADCD

REFERENCES

Allen, R., & Reber, A. S. (1980). Very long term memory for tacit knowledge. *Cognition,* **8,** 175–185.

Ausley, J. A., & Guttentag, R. E. (1993). Direct and indirect assessments of memory: Implications for the study of memory development during childhood. In M. Howe & R. Pasnak (Eds.), *Emerging themes in cognitive development* (pp. 234–264). New York: Springer-Verlag.

Berry, D. C., & Dienes, Z. (1993). *Implicit learning: Theoretical and empirical issues.* Hillsdale, NJ: Erlbaum.

Bjorklund, D. F., & Douglas, R. N. (1997). The development of memory strategies. In N. Cowan (Ed.), *The development of memory in childhood* (pp. 201–246). Hove, UK: Psychology Press.

Carroll, M., Byrne, B., & Kirsner, K. (1985). Autobiographical memory and perceptual learning: A developmental study using picture recognition, naming latency, and perceptual identification. *Memory and Cognition,* **13,** 273–279.

Cherry, K. E., & Stadler, M. A. (1995). Implicit learning of a nonverbal sequence in younger and older adults. *Psychology and Aging,* **10,** 379–394.

Cohen, A., Ivry, R. I., & Keele, S. W. (1990). Attention and structure in sequence learning. *Journal of Experimental Psychology: Learning, Memory, and Cognition,* **16,** 17–30.

Curran, T. (1997). Effects of aging on implicit sequence learning: Accounting for sequence structure and explicit knowledge. *Psychological Research,* **60,** 24–41.

Curran, T., & Keele, S. W. (1993). Attentional and nonattentional forms of sequence learning *Journal of Experimental Psychology: Learning, Memory, and Cognition,* **19,** 189–202.

DiGiulio, D. V., Seidenberg, M., O'Leary, D. S., & Raz, N. (1994). Procedural and declarative memory: A developmental study. *Brain and Cognition,* **25,** 79–91.

Ellis, H. D., Ellis, D. M., & Hosie, J. A. (1993). Priming effects in children's face recognition. *British Journal of Psychology,* **84,** 101–110.

Graf, P. (1990). Life-span changes in implicit and explicit memory. *Bulletin of the Psychonomic Society,* **28,** 353–358.

Greenbaum, J. L., & Graf, P. (1989). Preschool period development of implicit and explicit remembering. *Bulletin of the Psychonomic Society,* **27,** 417–420.

Hartman, M., Knopman, D. S., & Nissen, M. J. (1989). Implicit learning of new verbal associations. *Journal of Experimental Psychology: Learning, Memory, and Cognition,* **15,** 1070–1082.

Howard, D. V., & Howard, J. H. (1992). Adult age differences in the rate of learning serial patterns: evidence from direct and indirect tests. *Psychology and Aging,* **7,** 232–241.

Jackson, G. M., & Jackson, S. R. (1995). Do measures of explicit learning actually measure what is being learnt in the serial reaction time task? A critique of current methods. *Psyche,* **2(20)** [On Line]. Available: http://psyche.cs.monash.edu.au:80/volume2-1/psyche-95-2-20-implicit-1-jackson.html

Kail, R. V. (1990). *The development of memory in children.* New York: Freeman.

Karmiloff-Smith, A. (1992). *Beyond modularity: A developmental perspective on cognitive science.* Cambridge, MA: The MIT Press.

Karmiloff-Smith, A. (1994). Précis of Beyond modularity: A developmental perspective on cognitive science. *Behavioral and Brain Sciences,* **17,** 693–745.

Knowlton, B. J., & Squire, L. R. (1996). Artificial grammar learning depends on implicit acquisition of both abstract and exemplar-specific information. *Journal of Experimental Psychology: Learning, Memory, and Cognition,* **22,** 169–181.

Lewicki, P. (1986a). *Nonconscious social information processing.* Orlando: Academic.

Lewicki, P. (1986b). Processing information about covariations that cannot be articulated. *Journal of Experimental Psychology: Learning, Memory, and Cognition,* **12,** 135–146.

Lewicki, P., Hill, T., & Czyzewska, M. (1992). Nonconscious acquisition of information. *American Psychologist,* **47,** 796–801.

Lorsbach, T. C., & Worman, L. J. (1989). The development of explicit and implicit forms of memory in learning disabled and nondisabled children. *Contemporary Educational Psychology,* **14,** 67–76.

Maccoby, E. E., & Hagen, J. W. (1965). Effects of distraction upon central versus incidental recall: Developmental trends. *Journal of Experimental Child Psychology,* **2,** 280–289.

Mathews, R. C., Buss, R. R., Stanley, W. B., Blanchard-Fields, F., Ryeul Cho, J., & Druhan, B. (1989). Role of implicit and explicit processes in learning from examples: A synergistic effect. *Journal of Experimental Psychology: Learning, Memory, and Cognition,* **15,** 1083–1100.

Maybery, M., Taylor, M., & O'Brien-Malone, A. (1995). Implicit learning: Sensitive to age but not IQ. *Australian Journal of Psychology,* **47,** 8–17.

Meulemans, T., & Van der Linden, M. (1997a). Associative chunk strength in artificial grammar learning. *Journal of Experimental Psychology: Learning, Memory, and Cognition,* **23,** 1007–1028.

Meulemans, T., & Van der Linden, M. (1997b). Does the artificial grammar learning paradigm involve the acquisition of complex information? *Psychologica Belgica,* **37,** 69–88.

Naito, M. (1990). Repetition priming in children and adults: Age-related dissociation between implicit and explicit memory. *Journal of Experimental Child Psychology,* **50,** 462–484.

Newman, L. S. (1990). Intentional and unintentional memory in young children: Remembering vs. playing. *Journal of Experimental Child Psychology,* **50,** 243–258.

Nissen, M. J., & Bullemer, P. (1987). Attentional requirements of learning: Evidence from performance measures. *Cognitive Psychology,* **19,** 1–32.

Nissen, M. J., Willingham, D., & Hartman, M. (1989). Explicit and implicit remembering: When is learning preserved in amnesia? *Neuropsychologia,* **27,** 341–352.

Parkin, A. J., & Streete, S. (1988). Implicit and explicit memory in young children and adults. *British Journal of Psychology,* **79,** 361–369.

Perrig, W. J., & Perrig, P. (1993). Implizites gedachtnis: Unwillkurlich, entwicklungsresistent und altersunabhangig? *Zeitschrift fur Entwicklungs und Padagogische Psychologie,* **25,** 29–47.

Perruchet, P., & Amorim, M. A. (1992). Conscious knowledge and changes in performance in sequence learning: Evidence against dissociation. *Journal of Experimental Psychology: Learning, Memory, and Cognition,* **18,** 785–800.

Perruchet, P., & Gallego, J. (1997). A subjective unit formation account of implicit learning. In D. Berry (Ed.), *How implicit is implicit learning?* (pp. 124–161). Oxford: Oxford University Press.

Perruchet, P., Bigand, E., & Benoit-Gonin, F. (1997). The emergence of explicit knowledge during the early phase of learning in sequential reaction time tasks. *Psychological Research,* **60,** 4–13.

Perruchet, P., Frazier, N., & Lautrey, J. (1995). Conceptual implicit memory: A developmental study. *Psychological Research,* **57,** 220–228.

Perruchet, P., & Vinter, A. (1997). Learning and development: The implicit knowledge assumption reconsidered. In M. A. Stadler & P. A. Frensch (Eds.), *Handbook of implicit learning* (pp. 495–531). Thousand Oaks, CA: Sage Publications.

Rabbitt, P. M. A., & Vyas, S. M. (1970). An elementary preliminary taxonomy for some errors in laboratory choice RT tasks. *Acta Psychologica,* **33,** 56–76.

Reber, A. S. (1967). Implicit learning of artificial grammars. *Journal of Verbal Learning and Verbal Behavior,* **6,** 855–863.

Reber, A. S. (1993). *Implicit learning and tacit knowledge: An essay on the cognitive unconscious.* New York: Oxford University Press.

Reber, A. S., & Lewis, S. (1977). Implicit learning: an analysis of the form and structure of a body of tacit knowledge. *Cognition,* **5,** 331–363.

Reed, J., & Johnson, P. (1994). Assessing implicit learning with indirect tests: Determining what is learned about sequence structure. *Journal of Experimental Psychology: Learning, Memory, and Cognition,* **20,** 585–594.

Seger, C. A. (1994). Implicit learning. *Psychological Bulletin,* **115,** 163–196.

Shanks, D. R., & Johnstone, T. (1997). Implicit knowledge in sequential learning tasks. In M. A. Stadler and P. A. Frensch (Eds.), *Handbook of implicit learning* (pp. 533–572). Thousand Oaks, CA: Sage Publications.

Shanks, D. R., & St. John, M. F. (1994). Characteristics of dissociable human learning systems. *Behavioral and Brain Sciences,* **17,** 367–447.

Squire, L. R., & Frambach, M. (1990). Cognitive skill learning in amnesia. *Psychobiology,* **18,** 109–117.

Stadler, M. A. (1993). Implicit serial learning: Questions inspired by Hebb (1961). *Memory & Cognition,* **21,** 819–827.

Willingham, D. B., Greeley, T., & Bardone, A. M. (1993). Dissociation in a serial response time task using a recognition measure: Comment on Perruchet and Amorim (1992). *Journal of Experimental Psychology: Learning, Memory, and Cognition,* **19,** 1424–1430.

Willingham, D. B., Nissen, M. J., & Bullemer, P. (1989). On the development of procedural knowledge. *Journal of Experimental Psychology: Learning, Memory, and Cognition,* **15,** 1047–1060.

Wippich, W., Mecklenbrauker, S., & Brausch, A. (1989). Implizites und explizites Gedachtnis bei kindern: Bleiben bei indirekten Behaltensprufungen Altersunterschiede aus? *Zeitschrift fur Entwicklungs und Padagogische Psychologie,* **21,** 294–306.

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