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Are implicit learning abilities sensitive to the type of material to be processed? Study on typical readers and children with dyslexia

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This study aims to examine the impact of the linguistic nature of the material to be tracked in a serial reaction time task on the performance of typical readers and children with dyslexia. In doing so, we wished to detect eventual differences in the mobilisation of implicit learning skills between typical readers according to their experience with the written word (8- vs 10-year-olds) on the one hand, and between typical readers and children with dyslexia, on the other hand. Experiment 1 confirms the efficiency of implicit sequence learning in typical readers regardless of the nature of the item being tracked. Experiment 2 indicates that the sequence learning of children with dyslexia is sensitive to the nature of the target. Children with dyslexia show differences in the evolution of response times according to the nature of the item to be tracked.

Learning to read requires a combination of two complementary types of learning. Explicit learning is essential for acquiring the rules of conversion between phonemes and graphemes. It allows children to memorise a certain number of rules and principles that they can consciously use when needed. Implicit learning begins even before starting school. It develops through repeated contact with the written word. Thus, before starting to learn to read, the child unconsciously acquires a certain number of principles that facilitate his/her entry into the world of written language (Gombert, 2003). The dyslexic child's difficulties are often approached from the angle of an explicit learning deficit. Actually, the presence of a deficit in children with dyslexia on the level of phonological consciousness, that is to say, in the explicit manipulation of the language's sounds, is quasi-accepted. What, however, is the situation concerning implicit learning?

Implicit learning refers to knowledge acquired by a subject unconsciously. Although all the proposed definitions agree on certain points: (1) the subject is unaware that learning is taking place; (2) the knowledge acquired is therefore difficult to access consciously; (3) it is difficult to verbalise (Berry & Dienes, 1993; Seger, 1994), the definitions of implicit learning are as numerous as the methods of its study. According to Perruchet and Gallego (1997), implicit learning describes an adaptive mode via which the subjects' behaviour shows sensitivity to a situation's structure, without this adaptation being imputable to intentional exploitation of explicit knowledge of this structure. In other words, the subjects would be capable of appropriating more or less complex structures through repeated exposure to these latter. The case of acquiring a mother tongue is often evoked to illustrate this learning mode and to underscore its precocity (Lewicki, Hill & Czyzewska, 1992). In fact, young children manage to appropriate and make use of complex structures in their mother tongue, without even being able to verbalise what they learn.

A precursor in this thinking, Reber (1967) developed the 'artificial grammar' (AG) paradigm. Thanks to the results of his first experiments, Reber (1967, 1976) shows that participants are sensitive to the regularity of a grammar whose structure they are unfamiliar with, and they are even capable of acquiring a knowledge of this structure without necessarily being able to verbalise it. Other paradigms have appeared, such as control of dynamic system (CDS) (Broadbent, 1977), probability learning (Reber & Millward, 1971) and also, the serial reaction time (SRT) task (Nissen & Bullemer, 1987). The SRT task is interesting because it allows the study of learning and memory mechanisms, on the one hand, and motor behaviour, on the other (Curran, 1998). In this type of task, the subject is instructed to track a target appearing in one of four squares on a computer screen, using a keyboard or a peripheral (mouse, joystick or switch). In their experiment, Nissen and Bullemer (1987) compared the performances of two groups of participants. The first group had to track an asterisk moving randomly among the four squares, while the second group tracked an asterisk that followed a sequence of 10 trials that were continuously repeated. The results obtained revealed that, for both groups, reaction times (RTs) decreased as testing proceeded, but the decrease was greater for the second group (repeating sequences). This paradigm is one of the most frequently used, as it allows, with a simple manipulation, the measurement of incidental learning, while precluding attempts at strategies.

In the field of investigating implicit learning in dyslexia, research projects using the SRT paradigm are the most numerous and detailed. They have asked the following question: do subjects presenting written language difficulties have the same implicit learning abilities as typical readers? (Howard, Howard, Japikse & Eden, 2006; Kelly, Griffiths & Frith, 2002; Stoodley, Harrison & Stein, 2006; Vicari, Marotta, Menghini, Molinari & Petrosini, 2003; Vicari et al., 2005; Waber et al., 2003) Their results however remain contradictory.

Three studies on children (Vicari et al., 2003, 2005; Waber et al., 2003) used an adaptation (in order to make it more attractive) of an SRT task originally developed by Nissen and Bullemer (1987). Postulating implicit sequence-learning efficiency in children with dyslexia, Waber et al. (2003) used an SRT task in which children were to track an asterisk moving from one to another of three possible locations on a computer screen. Waber et al. (2003) aimed to evaluate the performance of children presenting written language disorders using an SRT task to measure the eventual links to their reading skills and their level of cognitive abilities. Their results showed identical implicit learning skills, regardless of their reading performances and of the cognitive abilities of the children undergoing study. On the contrary, Vicari et al.'s (2003) study on dyslexic children and adolescents revealed opposite results. In their research, they presented an SRT task to two groups of children (dyslexic vs typical readers). The children were instructed to strike a key as soon as a green circle appeared in the centre of the computer screen. The target moved only horizontally from one square to another, as in the study by Waber et al. (2003), but changed colour from one time to the next. This study's results showed an implicit sequence-learning inefficiency in children with dyslexia. An analysis of methodologies helps us to understand the divergence of viewpoints. Concerning the population studied, whereas Vicari et al. (2003) carried out a study on participants diagnosed as having dyslexia, Waber et al. (2003) selected a very wide sample of children with reading problems. In the same way, the complementary tests presented to the children were not identical and do not allow us to consider these two groups of children to be analogous. Concerning the SRT task, the same method was chosen; however, the targets' presentation design is different. As we explained earlier, the task presented by Waber et al. (2003) was to track an asterisk moving around three stationary, horizontal locations on a computer screen. On the other hand, the task used by Vicari et al. (2003) differs from classic SRT tasks because the target to be tracked is static in the centre of the screen and only its colour changes. Thus, it is possible that the sequence learning does not concern the same processes. In fact, in the task used by Waber et al. (2003), sequence learning involves learning the movement of the target from one location to another. Moreover, learning may be both perceptive and motor because the child uses three distinct keys for tracking. On the contrary, in the study by Vicari et al. (2003), the target is static and only the colour sequence is learned. Thus, implicit learning is strictly perceptive.

With adults, results that are just as contradictory have been underlined. Kelly et al. (2002) presented an SRT task to dyslexic adults and adults who are typical readers. Participants were instructed to track a complex form (an alien). Two complex forms were proposed, in two different colours, making a total of four different targets. Results of their study showed efficient implicit sequence learning in both subject groups. The study made by Stoodley, Fawcett, Nicolson and Stein (2006) showed contradictory results. Stoodley et al. (2006) gave their study participants an SRT task in which they were instructed to track a number (1, 2, 3, 4) appearing in one of four locations on a computer screen. Results underlined an implicit sequence-learning inefficiency in the dyslexic adults, compared with the typical readers. Here again, a methodological and statistical analysis seems to give several elements for understanding these conflicting results. In fact, the statistical analysis by Stoodley et al. (2006) gives few details. The authors conclude implicit learning is absent by highlighting longer RTs in children with dyslexia than in the typical readers while tracking the repeating series. To us, this interaction does not seem sufficient to validate or invalidate sequence-learning efficiency. Concerning the SRT task, we find differences in the choice of the number of tracking trials proposed (300 trials, Stoodley et al., 2006 vs 1216 trials, Kelly et al., 2002). In fact, the learning differences can be explained by the low number of presentations in the sequence in the study by Stoodley et al. (2006) (10 sequence presentations), in comparison with that by Kelly et al. (2002) (104 or 117 sequence presentations according to the participants).

Studies in dual task sought to confirm the presence of an automation deficit in children with dyslexia. These difficulties could explain the different results shown with the SRT task. For example, the balance task has been used in order to characterise the difficulties related to dyslexia (Nicolson & Fawcett, 1990, 1995). This task has been tested in two situations: (1) single-task condition and (2) dual-task condition, where the balance task was associated with another task (e.g. auditory judgement task, Yap & van der Leij, 1994). The authors showed that for children with dyslexia, a basic skill such as balance is disrupted by another task performed in parallel. Another study carried out by Stoodley et al. (2006) shows the implications for the role of the cerebellum and processing speed in dyslexia. Indeed, in this study, Stoodley et al. (2006) compared the performance of adults with dyslexia and control adults on rapid pointing and balancing measures. The results showed that there were no differences between the two groups of participants on the balancing tasks or when the speed and accuracy of pointing were analysed separately. But, when the speed and accuracy of pointing were combined, the dyslexic participants showed poorer performance than the controls.

As we have seen, the conclusions relative to implicit sequence-learning efficiency or inefficiency are not yet accordant. Differences in choice of populations studied, choice of method used, as well as in choice of statistical treatment are just so many elements of a possible explanation for the diverging results to which we have referred. To our knowledge, no study using an SRT paradigm, and carried out among subjects affected by written language learning disorders, has attempted to characterise the subjects' performance according to the nature of the target to be tracked. In the research described above, the target is always symbolic in nature. In the majority of cases, it is a question of tracking a coloured geometric form (squares, circles) (e.g. Vicari et al., 2003). However, we can also observe other target types such as a complex form (e.g. Kelly et al., 2002), an asterisk (e.g. Waber et al., 2003) or a number (e.g. Stoodley et al., 2006). It is curious that none of these studies has sought to manipulate the nature of the target in order to make it more or less linguistic. This choice is all the more surprising when one is interested in subjects presenting written language learning difficulties. In fact, could not the nature of the stimuli in the learning process, according to their structural characteristics, have an influence on the establishment of implicit sequence learning?

Considering these studies, it is difficult to ascertain the efficiency or inefficiency of implicit sequence learning, in subjects presenting written language disabilities. Studies in this area have been characterised by variability in methodology. The discrepancies in results among these different studies could be accounted for according to the following variables: (1) the nature of the population studied (dyslexic children and adolescents, dyslexic adults or children who are poor readers); (2) the nature of the matches made (dyslexic/non-dyslexic, according to reading age or chronological age); and (3) the nature of the item to be tracked (asterisk, coloured circles, picture of a dog, etc.).

To our knowledge, no study in SRT carried out on subjects with written language learning difficulties has sought to characterise their performances according to the nature of items being tracked. To date, experiments conducted on populations with or without learning problems have given different items to be tracked without questioning their nature's impact on the collected data. Is implicit learning independent of the nature of the stimuli involved, or does it, in fact, depend on our familiarity with the type of stimuli and on our ability to handle them? Could the implicit sequence learning in children with dyslexia be affected if the nature of the tracked items requires an important processing effort?

This article aims to characterise implicit sequence learning by varying the nature of the target to be tracked in order to render it more or less linguistic. Participants include: (1) typical readers with a 2-year difference in experience of the written word; and (2) typical readers and children with dyslexia of the same chronological age, but different reading ages. In studies carried out among the general public as well as among subjects presenting written language disorders, the target tracked in an SRT task is always of a symbolic nature. It is usually an asterisk (e.g. Waber et al., 2003), as in the original study by Nissen and Bullemer (1987), but sometimes it is a more complex target (a dog, Thomas & Nelson, 2001; a coloured circle, Vicari et al., 2003; an alien, Kelly et al., 2002). These studies did not attempt to take into account the fact that implicit learning differences could be due to the choice of the target itself.

Experiment 1 aims to examine the impact of the nature of the target tracked in an SRT task on implicit sequence-learning skills in typical readers with a 2-year difference in experience of the written word. In these children, presenting no written language disorders, tracking a linguistic or nonlinguistic target should not generate any implicit sequence-learning differences. Our hypothesis is as follows: implicit sequence learning will be efficient in 8-year-old children and in 10-year-old children regardless of the nature of the target tracked in the SRT task. Experiment 2 has two goals: (1) to participate in the current discussion concerning efficiency or inefficiency of implicit sequence learning in dyslexic subjects; (2) to characterise the dyslexic subjects' sensitivity to the more or less linguistic nature of the target tracked in an SRT task, in comparison with typical readers. Our hypothesis is as follows: in the dyslexic subjects, implicit sequence learning will be perturbed to a greater extent when tracking a linguistic target (the latter requiring so much attention that it is cognitively more costly) than when tracking a nonlinguistic target. No difference should appear in the implicit learning skills of the typical readers.

Experiment 1

Method

Participants

Forty children participated in the experiment. Twenty children were in third-year elementary and 20 children were in fifth-year. All pupils were recruited from the same school in Toulouse (France). Children were included in the study if a satisfactory reading age (chronological age = reading age) was met. Background information on the participants is presented in Table 1. Reading level was evaluated using the Alouette test (Lefavrais, 1967). Each child has a maximum of 3 minutes in which to read a 265-word text aloud. The number of errors and the reading time are recorded. Thanks to these elements, it is possible to determine the reading age and an equivalent in terms of grade.

Materials

SRT task. The SRT task was given on a laptop computer. For this task, the child sits facing the computer screen and has to respond as quickly as possible, by pressing a key on the keyboard, when a target item appears in one of the four locations displayed on the screen. The four keys selected are 'W', 'X', 'N', ',' on a French AZERTY keyboard; they are covered with four black stickers to avoid all risk of linguistic-type interference. The rest of the keyboard is masked so as to leave only the four necessary keys visible.

Table 1. Chronological and reading ages in typical readers.

	Third-year elementary	Fifth-year elementary
N	20	20
Chronological age	8.52	10.42
	min: 8.08 – max: 9.5; $\sigma = 0.71$	min: 9.75 – max: 12; $\sigma = 0.33$
Reading age	8.54	10.28
	min: 7.75 – max: 9; $\sigma = 0.62$	min: 9.17 – max: 10.5; $\sigma = 0.11$
t	0.21, *ns*	1.52, *ns*

Task design. Four target items were chosen on the basis of their more or less linguistic nature: 'symbol (###)', 'letter (eee)', 'nonword (uco)', 'word (ami [friend])'. The test is divided into four parts, each one corresponding to the tracking of one of the four targets.

In each part, the child receives five blocks of stimuli (270 trials). Each block corresponds to the following chain: 4R+6S+4R+6S+4R+6S+4R+6S+4R+6S+4R. There is a pause of a few seconds after each repetition. The chain is composed of random series (R) and repeating sequence (S) in alternation. A random series corresponds to four successive appearances of the target item in one of the four squares at random. A repeating sequence corresponds to six successive appearances of the target item, but in a predefined order. The random and repeating sequences both fulfil certain criteria: (1) the stimulus cannot appear twice consecutively in the same square; and (2) there are as many 'right-hand' as 'left-hand' responses.

As did Waber et al. (2003), we used six successive appearances of the target item, instead of 12, as is generally the case with adults. A sequence of 12 appearances proves to be too long and too difficult for children, leading to a lack of motivation, fatigue and/or indifference.

In order to associate a different repeating sequence with each of the four parts of the experiment, four predefined series were created. The order in which the four parts of the experiment appeared, corresponding to the four different targets to be tracked, was randomised for each subject.

Procedure

This test was individual. It takes place in the presence of the same experimenter in an especially reserved room. The instructions given for the experiment are as follows:

> You see four squares on the screen. Something will appear in one of them. Sometimes it will be the first square, sometimes in the second one, etc. You must press the key that corresponds to the square as quickly as possible. If it is in the first square, press this key, here (key is pointed out to subject). If it is in the second, you press this key, here (key is pointed out), if it is in the third square, press this one and if it is in the fourth one, press this key. It is not difficult; you just press the correct key. You must press it as quickly as possible and make the fewest mistakes possible.

The child is seated facing the computer. He/she is asked to place his/her index and middle finger of each hand on the 'response' keys and to leave them in position until the testing is completed. A first phase composed of 50 appearances of a black star in the centre of the boxes precedes the experiment to familiarise the subject with the task. The signal 'Prêt?' (Ready?) appears on the screen at the beginning of the experiment, then before starting each repetition of the chain. The target appears 250 ms after a key is pressed. The RT between the appearance of the target and the child's motor response on the keyboard is automatically recorded.

With the above task accomplished, participants were asked to answer an interview, inspired by the explicit knowledge task of Howard and Howard (1997). In their task, participants completed a written end-of-session questionnaire. In our questionnaire, the experimenter asked children questions to be sure that they understand. The questions were simplified to better suit children.

1. Do you have anything to report regarding the game?
2. Did you notice anything special about the game?
3. Did you notice any pattern in the way the target was moving on the screen? (If the children answered yes, the experimenter probed for more specifics, and then asked the following.)
4. Did you attempt to take advantage of the patterns you noticed in order to help you to know what would happen next? If so, did this help?
5. In fact, there was some pattern to the sequences you observed; the target moved by moments following the same boxes on the screen. What do you think it was? Can you describe any pattern you think might have been there? (The experimenter encouraged the subject to describe any pattern whatsoever they noticed on the screen or on the keyboard, even if they were vague or unsure.)

Results

We analysed our data according to two dependent variables:

1. The median RT, corresponding to the time between the appearance of the target on the screen and the subject's correct response on the keyboard. The median is a more robust indicator than the mean when having outliers in the data (e.g. Gomez Beldarrain, Gafman, de Velasco, Pascual-Leone & Garcia-Monco, 2002).
2. The correct response rates, corresponding to the subject's correct motor response on the keyboard at the first go, when the target appears on the screen.

The temporal data relative to incorrect responses (tracking errors) have been removed from the analysis.

Mauchly's tests were calculated to test for the sphericity assumption. If the assumption of sphericity is rejected, we used the Greenhouse–Geisser correction. Each result is reported with a partial eta squared, η_p^2, as effect size. If $\eta_p^2 < .06$, the effect is small; if $.06 < \eta_p^2 < .14$, the effect is medium; if $\eta_p^2 > .14$, the effect is high (Cohen, 1988).

RT analysis

These data were submitted to Age (8- vs 10-year-olds) × Condition (random vs repeating) × Block (1–5) × Item (symbol, letter, nonword, word) mixed-design ANOVAs with repeated measures on the condition, block and item factors.

We observed an age effect, $F(1, 38) = 8.29$, $p < .01$, $\eta_p^2 = .18$. The RTs are longer in the 8-year-old (616.1 ms) than in the 10-year-old children (537.2 ms). Taking all the groups together, the RTs are longer in the random condition (584.6 ms) than in the repeating condition (568.7 ms), $F(1, 38) = 18.35$, $p < .001$, $\eta_p^2 = .33$; and they decrease as testing continues, $F(4, 152) = 2.4$, $p = .05$, $\eta_p^2 = .06$ (Block 1 = 595.9 ms; Block 2 = 590.9 ms; Block 3 = 573.9 ms; Block 4 = 562.1 ms; Block 5 = 560.3 ms).

The condition × block interaction is significant, $F(4, 152) = 6.83$, $p < .001$, $\eta_p^2 = .15$. It indicates that the RTs are shorter in the repeating condition than in the random condition and that the RTs decrease more in the repeating condition than in the random condition (cf. Figure 1). Associated with the absence of age × condition × block interaction, $F < 1$, *ns*, and the absence of age × condition × block × item, $F < 1$, *ns*, these

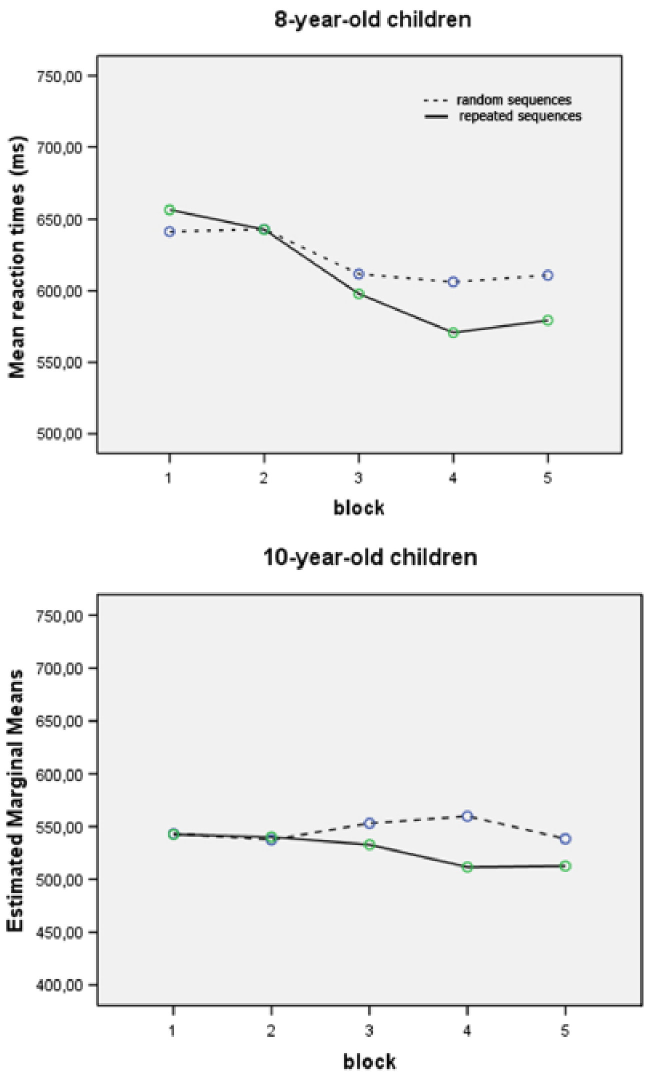

Figure 1. Sequence learning in 8- and 10-year-old children. Change, over the course of the task, of reaction times according to condition (random or repeated), as testing continues.

results confirm the presence of a sequence learning in the 8- and in the 10-year-old children, independently of the nature of the target to be tracked.

In order to bring other explanatory elements to the particularities of implicit sequence learning, we carried out an analysis of the correct response rate (accuracy). A correct response corresponds to correct tracking, successful the first time, of the target. The wrong responses were removed from the analysis.

Accuracy rate analysis

These data were submitted to Age (8- vs 10-year-olds) × Condition (random vs repeating) × Block (1–5) × Item (symbol, letter, nonword, word) mixed-design ANOVAs with repeated measures on the condition, block and item factors.

The accuracy rate is significantly higher in the 10-year-old children (89.1%) than in the 8-year-old children (85.13%), $F(1, 38) = 13.6$, $p < .001$, $\eta_p^2 = .26$. All levels taken together, the accuracy rate is significantly higher in the repeating condition (87.9%) than in the random condition (86.3%), $F(1, 38) = 27.58$, $p < .001$, $\eta_p^2 = .07$. Finally, the children made fewer errors while tracking the items 'symbol' and 'word' (88.1% and 87.6%, respectively) than the items 'letter' and 'nonword' (86.3% and 86.4%, respectively), $F(3, 114) = 2.65$, $p = .05$, $\eta_p^2 = .07$.

The absence, in this analysis, of interaction involving the age factor indicates that, regardless of the children's age, the profile of correct responses does not vary significantly between the 8- and the 10-year-old children. Both groups of children make fewer tracking mistakes in the repeating condition, which would seem to indicate a sensitivity to regularities in the repeated sequence. However, this performance improvement does not increase as testing proceeds.

Questionnaire

The final interview, adapted from Howard and Howard (1997), showed an absence of the children's awareness of sequences. Most of the children stopped at question 3, 'Did you notice any pattern in the way the target was moving on the screen?' Most answered negatively. To make sure the question was well understood, we guided them by asking whether they believed the target moved erratically or following a specific pattern. To this very direct question, two children answered that they had identified specific patterns. When asked to describe the sequences they had perceived, both preferred to show the movements by pointing their finger at the screen. However, none managed to discern any pattern. It was our intention not to specify the number of elements constituting the repeated sequences. We wished to identify possible bigrams and trigrams belonging to sequences and which would be more striking than others. The sequences proposed by these two children did not belong to our set of patterns. Finally, on question 3, an 8-year-old child answered that the target kept moving faster. We explained that if the target seemed to be moving faster, it was because he kept giving faster answers. He said that sometimes the target almost had no time to appear because his fingers guessed in which box it would go next! However, we explained by moving on to question 5 – 'In fact, there was some pattern to the sequences you observed. The target moved at times following the same boxes on the screen. What do you think it was? Try to describe any pattern you think might have been there' – the child was incapable of identifying the movement. We conclude that learning in this task was implicit.

Discussion

Experiment 1 aimed to examine what impact the nature of the target being tracked in an SRT task could have on the implicit sequence-learning skills of typical readers with a 2-year difference in experience of the written word. Experiment 1 was carried out among children presenting no written language disorders. Thus, our hypothesis was the following: implicit sequence learning will be efficient in 8-year-old children (second grade) and in 10-year-old children (fourth grade) regardless of the nature of the target tracked (more or less linguistic) in an SRT task.

The results allow us to support our hypothesis. In fact, we show the presence of undifferentiated implicit sequence learning, regardless of the children's experience level of the written word. This implicit sequence learning is revealed by: (1) RTs that decrease more in the repeating condition than in the random condition as the blocks proceed (significant condition × block interaction); (2) the fact that this difference in the change, over the course of the task, of RTs according to condition and block does not depend on grade (absence of grade × condition × block interaction); (3) the absence of explicit knowledge as shown in the final questionnaire. Moreover, we underline efficient sequence learning, independent of the item tracked, revealed by a greater decrease of RTs in the repeating condition than in the random condition as the blocks proceed, regardless of the nature of the item tracked (absence of condition × block × item interaction). We nevertheless observe higher performances in terms of correct responses during tracking of 'symbol' and 'word' target items than during tracking of 'letter' and 'nonword' target items, independently of grade, condition or block. Tracking series of letters and nonwords thus seems to require a greater attention effort and therefore to generate more tracking errors by typical readers than symbols and words. These results are original because in the implicit sequence-learning literature, no study has sought to manipulate the more or less linguistic nature of the item tracked. Studies carried out on implicit reading have nevertheless underlined the differences in cerebral activation when different item types (false letters, nonwords, words) entered a subject's field of vision without his or her being involved in a reading task (e.g. Brunswick, McCrory, Price, Frith & Frith, 1999). Thus, treatment of a known word would be faster and higher performance than the treatment of less frequent linguistic items such as a series of letters or nonwords. Besides, tracking symbols would lead to a different, nonlinguistic, treatment that is relatively high performance in children who were typical readers.

Implicit sequence learning would thus be efficient in typical readers in an SRT task. Therefore, Experiment 1 concords with the majority of the works carried out in typical children (e.g. Meulemans, Van der Linden & Perruchet, 1998). Our experiment shows that implicit sequence learning would be independent of subjects' age, but also that it would be independent of the level of experience with the written word in children who present no specific written language disorders (second grade vs fourth grade). In the same manner, this study shows that, in typical readers, implicit sequence learning does not depend on the nature of the target tracked in an SRT task. These results are interesting, as the majority of studies done on dyslexic subjects tend to point up inefficiency in this type of learning. Therefore, the implicit learning deficit would not be due only to a difference in terms of reading level, because we have shown that children having approximately a 2-year reading age difference (8.54 vs 10.28) show implicit sequence learning, but it could depend on other factors that enter into play in this sort of task. These results lead us to continue our research by studying the relationship between the nature of the target tracked and the subjects' ability to manipulate these different items.

Experiment 2

In this study, we speak of 'developmental dyslexia' when a significant gap of at least 2 years between intellectual and reading levels interferes with scholastic success and/or daily activities. Thus, intellectual inefficiency, sensory deficit (visual or auditory), psychological, psychiatric or neurological problems, or inadequate or irregular scholastic education cannot explain this problem. It is a part of learning difficulties and is generally characterised by specific reading or spelling problems (Ramus, 2005). A large heterogeneity among the profiles of children with dyslexia can be observed. Research in the past decade has investigated several causal hypotheses (e.g. the hypothesis of magnocellular deficit, Stein, 2001, 2003; Stein & Talcott, 1999; Stein & Walsh, 1997, or the phonological deficit, Goswami, 2000; Ramus, 2003; Snowling, 2000).

The cerebellum deficit hypothesis suggests an impairment in automated learning and motor skills (Fawcett & Nicolson, 1999; Fawcett, Nicolson & Dean, 1996; Nicolson, Fawcett & Dean, 2001). This theory attempts to explain both the unconscious processes of automation and literacy problems in dyslexia (Fawcett & Nicolson, 2001).

In this experiment, we submitted children presenting written language learning disorders and typical readers, matched by chronological age, to the same SRT task.

Even if the experiment did not reveal a difference linked to the children's age, we chose to match them this way in order to avoid any risk of interference between our results and developmental factors. The greater fatiguability of children with dyslexia in this sort of task, which requires a high concentration level, necessitated simplifying the protocol (Goswami, 2003). We therefore retained only two types of target items to be tracked, 'symbol' and 'word', so as to decrease the testing time. The choice of retaining only these two items is justified by: (1) the maximum contrast between the word item (linguistic) and the symbol item (nonlinguistic); and (2) the improved performances in terms of correct responses by typical readers for these two item types.

Method

Participants

Forty-five children participated in Experiment 2. All were right-handed and were native speakers of French. Twenty typical readers were matched on the basis of their chronological age with 25 children with dyslexia. Reading age was calculated using the Alouette test (Lefavrais, 1967; cf. Table 2). Children with dyslexia were recruited among volunteers thanks to the association APEDYS Haute-Garonne (France). We relied on the children's complete medical record, established by health professionals (psychologists, neuropsychologists, doctors and speech therapists). The children showed deficits in reading both regular and irregular words. They had a typical oral expression level (L2MA, Chevrie-Muller, Simon & Fournier, 1997), and good visual skills. On the other hand, the majority presented some kind of orthographic difficulties (L2MA, Chevrie-Muller et al., 1997; ANALEC, Inizan, 1998). Chronological and reading ages in typical readers and children with dyslexia are presented in Table 2.

Table 2. Chronological and reading ages in typical readers and children with dyslexia.

	Typical readers	Children with dyslexia	t
N	20	25	
Chronological age (σ)	10.43 (0.41)	10.39 (0.86)	0.17, *ns*
Reading age (σ)	10.18 (0.43)	7.47 (0.62)	16.54^{**}
t	1.97, *ns*	12.60^{**}	

$^{**}p < .001$.

Results

In this analysis, we wish to test the existence of implicit sequence learning in children with dyslexia. We suggest that the success of implicit sequence learning depends on the nature of the tracked items. We assume that implicit sequence learning is efficient when associated with nonlinguistic item tracking. We believe that implicit sequence learning will be hindered by the cognitive cost of treating the linguistic item. We analysed the date according to two dependent variables: the median RT, corresponding to the response speed and the correct response rate.

RT analysis

The data were treated using a 2 (Group: typical readers vs children with dyslexia) $\times$ 2 (Condition: random vs repeating) $\times$ 5 (Block: 1–5) $\times$ 2 (Item: nonlinguistic vs linguistic) ANOVA with repeated measures of the latter three factors.

The RTs are longer in children with dyslexia (600 ms) than in the typical readers (528 ms), $F(1,43) = 6.19$, $p < .02$, $\eta_p^2 = .13$. We observe a condition effect, $F(1,43) = 33.72$, $p < .001$, $\eta_p^2 = .44$. Taking all the groups together, the RTs are longer in the random condition (573 ms) than in the repeating condition (555 ms).

The condition $\times$ block interaction is significant, $F(4,172) = 7.18$, $p < .001$, $\eta_p^2 = .14$. It indicates that the RTs are shorter in the repeating condition than in the random condition and that the RTs decrease more in the repeating condition than in the random condition. The interaction condition $\times$ item is significant, $F(1,43) = 4.18$, $p < .05$, $\eta_p^2 = .09$. Associated with the condition $\times$ block $\times$ item interaction, $F(1,172) = 4.87$, $p < .001$, $\eta_p^2 = .10$, this last result indicates that the RTs differ according to the condition and the item to be tracked, in the course of blocks. To investigate these interactions, we made a group-by-group analysis.

In typical readers, as in Experiment 1, the analysis shows a significant effect of the condition factor, $F(1,19) = 8.2$, $p < .01$, $\eta_p^2 = .30$. RTs are significantly shorter in the repeating condition (533 ms) than in the random condition (555.5 ms). Analysis also shows the significance of condition $\times$ block interaction, principal indicator of sequence learning, $F(4,76) = 4.03$, $p < .01$, $\eta_p^2 = .18$. Associated with the absence of condition $\times$ block $\times$ item interaction, $F(4,76) = 1.21$, *ns*, this interaction reveals sequence learning regardless of the item type tracked in typical readers.

In children with dyslexia, the analysis reveals a significant effect for the condition factor, $F(1,24) = 35.11$, $p < .001$, $\eta_p^2 = .39$. The RTs are significantly shorter in the repeating condition (585.6 ms) than in the random condition (615.1 ms). The block factor is significant, $F(4,96) = 4.09$, $p < .001$, $\eta_p^2 = .15$. The analysis also reveals the presence of significant condition $\times$ block interaction, principal indicator of sequence learning, $F(4,96) = 4.49$, $p < .01$, $\eta_p^2 = .16$. Associated with the condition $\times$ block $\times$ item interaction, $F(4,96) = 5.21$, $p < .001$, $\eta_p^2 = .18$, this interaction reveals sequence learning differentiated according to the type of item tracked by children with dyslexia.

In order to explore the condition $\times$ block $\times$ item interaction, we made an item-by-item analysis. This analysis revealed that during the tracking of the symbol item, the effect of the condition factor is significant, $F(1,24) = 14.79$, $p < .001$, $\eta_p^2 = .38$. The condition $\times$ block interaction is significant, $F(4,96) = 6.5$, $p < .001$, $\eta_p^2 = .21$. During tracking of the word item, only the condition factor is insignificant, $F(1,24) = 5.95$, $p < .03$, $\eta_p^2 = .20$. The condition $\times$ block condition, principal indicator of sequence learning, is non-significant, $F < 1$, *ns* (cf. Figure 2).

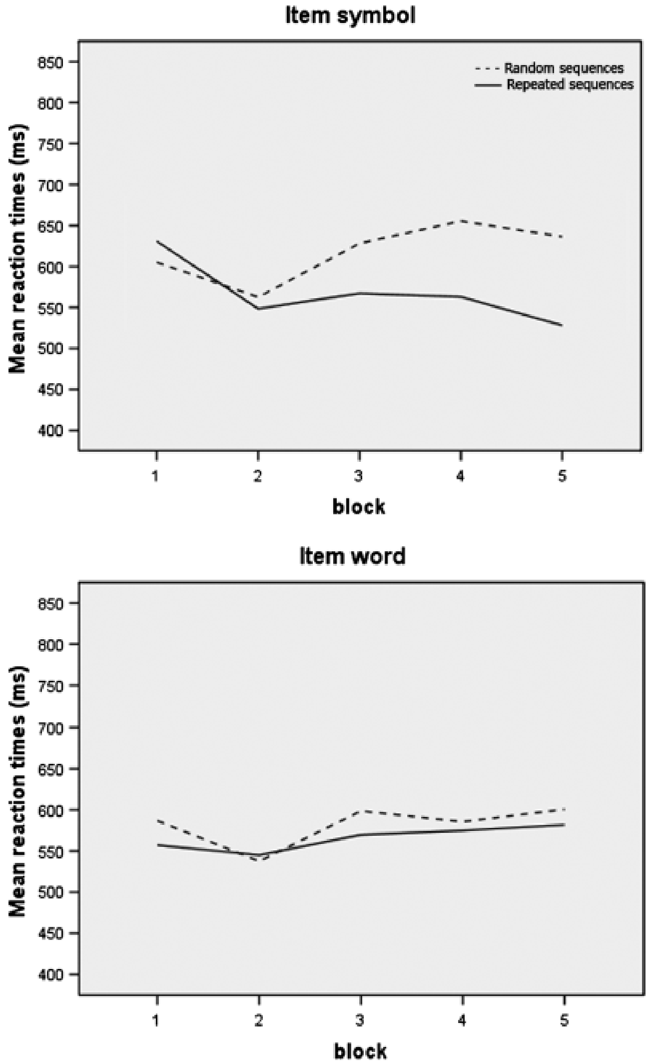

Figure 2. Change, over the course of the task, of reaction time according to condition during the tracking of the nonlinguistic (at the top of the figure) and the linguistic (at the bottom of the figure), in children with dyslexia.

Accuracy rate analysis

The data were processed with a 2 (Group: typical readers vs children with dyslexia) × 2 (Condition: random vs repeating) × 5 (Block: 1–5) × 2 (Item: nonlinguistic vs linguistic) ANOVA and repeated measures of the last three factors.

The global analysis indicates a higher accuracy rate in typical readers than in children with dyslexia, $F(1, 43) = 21.38$, $p < .001$, $\eta_p^2 = .33$, and a higher accuracy rate in the repeating condition than in the random condition, $F(1, 43) = 7.66$, $p < .01$, $\eta_p^2 = .15$. The block effect, $F(4, 172) = 2.45$, $p < .05$, $\eta_p^2 = .05$, indicates an accuracy variation as testing goes on. The analysis also reveals the presence of significant interactions: (1) the condition × block interaction, $F(4, 172) = 2.75$, $p < .03$, $\eta_p^2 = .16$; (2) the group × condition, $F(1, 43) = 5.38$, $p < .03$, $\eta_p^2 = .11$; (3) the group × condition × block, $F(4, 172) = 3.57$, $p < .01$, $\eta_p^2 = .08$; (4) the condition × block × item interaction, $F(4, 172) = 4.36$, $p < .01$, $\eta_p^2 = .09$. The above factors are also implicated in the group × condition × block × item interaction, $F(4, 172) = 4.13$, $p < .01$, $\eta_p^2 = .09$. This interaction indicates different accuracy rates, as the succession of blocks continues, according to the group, condition and the nature of the item being tracked.

Secondary analyses were carried out in order to interpret the results obtained in the global analysis.

In typical readers, one single effect is significant: the condition effect showing a higher accuracy rate in the repeating condition than in the random condition, $F(1, 19) = 6.5$, $p < .03$, $\eta_p^2 = .24$. This result is compatible with that of the correct response rate analysis in Experiment 1.

In children with dyslexia, the block effect indicates an accuracy variation as testing goes on, $F(4, 96) = 4.31$, $p < .01$, $\eta_p^2 = .15$. The item effect, $F(1, 24) = 4.77$, $p < .04$, $\eta_p^2 = .17$, associated with a significant condition × block × item interaction, $F(4, 96) = 11.17$, $p < .001$, $\eta_p^2 = .32$, reveals performances dependent on the condition and the nature of the tracked item.

The per-item analyses do not allow us to draw a clear profile because the condition × block interaction is significant during linguistic item tracking, $F(4, 96) = 6.01$, $p < .001$, $\eta_p^2 = .20$, as well as nonlinguistic item tracking, $F(4, 96) = 12.25$, $p < .001$, $\eta_p^2 = .34$. In both cases, the differences between random condition and repeating condition are visible during the first blocks. From the third, the accuracy rate aligns itself in both experimental conditions.

Questionnaire

Just as in Experiment 1, most of the children stopped at the third question, 'Did you notice any pattern in the way the target was moving on the screen?' Two typical-reader children answered 'yes' to question 3. In question 4 – Did you attempt to take advantage of the patterns you noticed in order to help you to know what would happen next? If so, did this help? – only one of them maintained that he was 'pushing the same keys faster and faster'; the second answered negatively. In question 5, both children were delighted to explain the sequence they discovered. Both preferred using the screen to point out the movement; however, none of them discovered the correct structure of the sequence. Among the group with dyslexia, all answered negatively to question 3, 'Did you notice any pattern in the way the target was moving on the screen?' As in Experiment 1, the final interview showed the absence of the children's awareness of sequences.

Discussion

In Experiment 2, we tested the assumption that implicit sequence learning will be efficient in children with dyslexia, when it comes to tracking nonlinguistic items.

Results show that implicit sequence learning is efficient (underlined by the presence of a condition × block interaction) in children who are typical readers, and this regardless of the nature of the tracked items. In other words, the 10-year-old children presenting no difficulties with written language do not seem sensitive to the more or less linguistic nature of the target in an SRT task.

In the global analysis, Experiment 2 underlined the longer RT in children with dyslexia, despite a chronological age equivalent to that of typical readers. This result is confirmed by the accuracy rate analysis. Indeed, typical readers performed better than the children with dyslexia did. These results seem compatible with the hypothesis of a cerebellum-type deficit, which points out a deficit in the automation process and motor skills (Fawcett & Nicolson, 1999). On the other hand, all groups taken together, the accuracy rate tends to increase block after block. This is an interesting point, as few articles have revealed performance increases (in time or accuracy) in children with dyslexia (e.g. Vicari et al., 2003).

Unlike in typical readers, the item is implicated in the interaction condition × block × item in the RT analysis in children with dyslexia. This fact is interesting because it shows the presence of sensitivity to the nature of the tracked item for children with dyslexia. Analysis of the accuracy rate is also based on our hypothesis according to which sequence learning could be dependent on the nature of the item being tracked in an SRT task. It reveals a higher accuracy rate in the repeating condition than in the random condition as the succession of blocks continues, and this only during tracking of a nonlinguistic item. Interpretations of this result can be found in the dual-task work which underline a deficit in this type of task (e.g. Stoodley et al., 2006). In fact, being exposed to linguistic material could disrupt the sequence learning in an SRT task. Another explanation can be found in the field of rapid automatised naming (RAN). Studies showed a deficit in RAN of letters (e.g. Wolf & Bowers, 1999). In our task, although the participants did not name the stimuli, it is possible that an interpretation from this perspective might also fit the findings. In fact, dealing with words seems to require an additional and more intense effort on the part of children with dyslexia, and this could thus affect implicit sequence learning.

Conclusion

The aim of this study was to reveal differences in the implicit sequence-learning abilities of typical readers and children with dyslexia. To do this, we manipulated the more or less linguistic nature of the targets to be tracked in an SRT task.

Experiment 1 showed the presence of implicit sequence learning in both 8- and 10-year-old children. This result is compatible with Reber's (1993) postulate according to which implicit learning would not be dependent on the subject's age. In this study, we went further, by showing an implicit sequence-learning efficiency in typical readers, regardless of their level of experience with written language and, equally, regardless of the nature of the item to be tracked.

Experiment 2 pointed up differentiated learning according to the nature of the target tracked. While this element seems to have no influence on implicit sequence learning in the typical reader child, this is not the case in the child presenting written language difficulties. Indeed, our experiment allowed us to bring to light differentiated profiles of performance according to the nature of the material to be processed. The use of a linguistic item in an SRT task seems to influence the implementation of sequence learning, just as if the subject were in a dual-task situation.

These first results require confirmation. In the future, research aiming to characterise implicit learning using SRT tasks should better justify the choice of items to be tracked, particularly when the study is carried out in populations with written language learning difficulties.

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