



Full Length Article

Explicit and implicit motor sequence learning in children and adults; the role of age and visual working memory



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ABSTRACT

This study investigated explicit and implicit motor learning, and the influence of visual working memory (VWM) and age. Sixty children and 28 adults learned a nine-button sequence task explicitly and implicitly. Performance in explicit and implicit learning improved with age. Learning curves were similar across ages for implicit learning. In explicit learning, learning curves differed across ages: younger children started slower, but their learning rate was higher compared to older children. Learning curves were similar across VWM scores, but performance in explicit learning was positively influenced by VWM scores. Further research and implications for education and rehabilitation are discussed.

1. Introduction

Motor skills can be learned explicitly and implicitly (Destrebecqz & Cleeremans, 2001; Nissen & Bullemer, 1987). Explicit learning makes use of declarative knowledge to build up a set of performance rules that guide motor performance or skills. Individuals are aware of the goal, the rules and the expected outcome of the task to learn. Implicit learning, on the other hand, is the ability to acquire a new skill without a corresponding increase in knowledge about the skill. Individuals perform a skill but are not aware of the regularities governing the skill. The procedural knowledge gained via implicit learning is therefore difficult or even impossible to access consciously and/or report verbally.

In general, the process of learning motor skills can be divided in three different phases (Fitts & Posner, 1967). The first phase is the cognitive phase, in which one tries to understand the motor skill, and discovers rules and strategies to manage the skill. Secondly, in the associative phase the chosen strategy for the motor skill is further refined. In the last phase, the autonomous phase, cognitive control decreases and the skill becomes automated. These three phases are not entirely distinct, but rather one phase merges gradually into the other phase (Fitts & Posner, 1967).

The cognitive phase requires a high level of cognitive activity to process the incoming sensory information, and to produce the appropriate (motor) outputs. Working memory and attention are such important cognitive processes (Halsband & Lange, 2006). In working memory, information is consciously retained, in order to subsequently manipulate this information and use it to guide behavior (Postle, 2006). Sensory stimuli (e.g. visual, spatial and proprioceptive information) have to be retained in working memory in order to produce adequate motor output. With practice (from the associative phase onwards), the dependence on cognitive

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processes diminishes (Deiber, Wise, Honda, Catalan, & Grafman, 1997; Halsband & Lange, 2006) and velocity and accuracy increase (Halsband & Lange, 2006). The cognitive phase is especially involved in explicit learning (Steenbergen, van der Kamp, Verneau, Jongbloed-Pereboom, & Masters, 2010). Implicit learning occurs in absence of the cognitive phase, and is therefore not or less dependent on working memory (Steenbergen et al., 2010).

Next to working memory, explicit learning is also dependent on other individual factors such as age (Meulemans, van der Linden, & Perruchet, 1998), and IQ (Reber, Walkenfeld, & Hernstadt, 1991). Implicit learning is relatively independent of these factors (Meulemans et al., 1998; Reber et al., 1991). Implicit learning has evolved earlier than explicit learning, and is therefore more stable and resilient to cognitive factors (Reber, 1992). Moreover, verbal skills need to develop in childhood, and therefore young children rely more on implicit processing (Thomas & Nelson, 2001). The robustness of implicit learning for age effects has been shown in children as well as in older adults for learning in both SRT tasks and gross motor skills (Meulemans et al., 1998; Steenbergen et al., 2010; Thomas & Nelson, 2001).

Explicit and implicit motor learning have often been examined in adults via serial reaction time (SRT) tasks (e.g. see Gheysen & Fias, 2012; Meulemans et al., 1998). In the explicit condition, participants are instructed that they have to learn a sequence or they receive explicit feedback on procedural errors, which leads them to focus on learning the sequence and to use working memory. In the implicit condition participants learn a sequence by performing it, often guided by visual or auditory cues without receiving any information that a specific sequence will be learned. They often do not become aware of the sequence, but they learn the regularity (e.g. Janacsek & Nemeth, 2012; Thomas & Nelson, 2001). To test if participants do not build up explicit knowledge while learning a sequence, some researchers tested afterwards whether participants gained explicit knowledge about the sequence (e.g. Meulemans et al., 1998; Vinck et al., 2012).

Although theory states that explicit learning is dependent on age and working memory while implicit learning is relatively independent of age and working memory, with vast empirical evidence to support this in adults (Gheysen & Fias, 2012), research in typically developing children is lacking. Children are developing, as are their brain systems that are crucial for motor learning, and this leads to differences in motor learning from adults (Savion-Lemieux, Bailey, & Penhune, 2009). Insight in these motor learning processes in children could in the future be used for teaching, sports, and rehabilitation purposes, in both typically developing children and in clinical groups of children. Furthermore, explicit and implicit motor learning are often not compared within the same subjects and the precise contribution of individual factors (and the combination of these factors) in SRT learning remains unclear. This study aimed to fill this knowledge gap and investigated both explicit and implicit motor learning in a SRT task in both typically developing children (5–6 years and 7–9 years) and adults. In the explicit condition, participants were instructed to discover a sequence on a button-box via trial and error. In the implicit condition, participants had to press the button that was lighted as quickly as possible, and sequence blocks were alternated with random blocks. Furthermore, we specifically studied the effects of age and visual working memory on explicit and implicit SRT learning. Visual working memory was examined because motor learning problems can be due to impairments in visual perception, visuomotor processing, and visual working memory (Shumway-Cook & Woollacott, 2011; Steenbergen et al., 2010), and the learning task is a visuomotor task in which participants were guided by visual cues. We hypothesized explicit learning to be dependent on age and visual working memory (i.e. positive effects of both age and visual working memory) and implicit learning to be independent of age and visual working memory.

2. Method

2.1. Participants

In total, 60 typically developing children were included in this study, of whom 39 children were aged 5–6 years, and 21 children were aged 7–9 years. Twenty-eight adult students (18–21 years) were included. Children were recruited and tested at four primary schools, while students were recruited and tested at the University lab. All participants had a normal IQ ($IQ \geq 85$, tested with the Wechsler non-verbal test; Wechsler & Naglieri, 2008), were born at term, had no neurological or physical disorders, and had no behavioral problems.

2.2. Procedure

The study was approved by the Ethical Committee of the Faculty of Social Sciences. Part of the children (20) also served as a matched control group in a study on motor learning and preterm birth (Jongbloed-Pereboom, Janssen, Steiner, Steenbergen, & Nijhuis-van der Sanden, 2017; study approved by the local Medical Ethical Committee in the university medical center). Only children with an $IQ \geq 85$ were included in the study (tested with the Wechsler non-verbal test; Wechsler & Naglieri, 2008). Participants or their parents gave informed consent and filled in a questionnaire about their own or their child's health to assess whether there were any medical or psychological conditions that could affect performance of the learning task. All participants performed both conditions of the learning task in a counterbalanced design in which the two conditions were tested on two different occasions, three weeks apart. Two different sequences were used during the explicit and implicit learning task, which had the same trajectory length. At the end of the experimental sessions, visual working memory, and manual dexterity were assessed. These two sessions lasted about 2 h in total.



Fig. 1. Set-up of the learning task.

2.3. Materials

2.3.1. Learning task

Explicit and implicit motor learning was tested with a serial reaction time task on a custom-made button-box with nine buttons (3×3). A nine-button sequence was learned on the box; each button was pressed once in the sequence. The button-box (see Fig. 1) was 33×33 cm with buttons of 7×7 cm. The distance between buttons was 3 cm. All buttons could be lighted. In-house custom software written in Presentation® was used to create and control the lightening of the buttons. A computer (Windows XP) recorded all generated responses from the button-box.

All participants started with a short practice session, in which they were familiarized with pushing the buttons on the button-box. Participants had to press the button that was lighted. They were instructed to perform the task with their dominant hand. After the practice session, participants proceeded with either the explicit or implicit condition. In the explicit condition participants were instructed to discover the sequence via trial and error. If a participant pressed the correct button, it was lighted, and the participant could move on to the next button in the sequence. If an incorrect button was pressed, it was not lighted, and the participant continued to seek the correct button. Participants performed five sequence blocks. A test block consisted of five sequences (5×9 buttons). In the implicit condition, participants had to press the button that was lighted as quickly as possible. Five sequence blocks were alternated with three random blocks to prevent explicit learning (see Table 1). After the test, participants played a short game with the test administrator, and then the experiment continued with a retention test of three sequence blocks. In the implicit retention test, the sequence blocks were again alternated with random blocks. After the implicit retention test, participants were tested for explicit recall of the sequence by asking them if they had noticed a sequence. If so, they were asked to reproduce the sequence.

2.3.2. Visual working memory

The Automated Working Memory Assessment (AWMA) is a computerized tool for assessing short-term and working memory in persons aged 4–22 years (Alloway, 2007). The three subtests to assess visuospatial working memory were used: Odd-One-Out, Mr. X, and Spatial Recall. The raw scores were converted into standardized scores, and a composite score for visual working memory ($M = 100$, $SD = 15$). The test-retest reliability of the three subtests is 0.88, 0.84, and 0.79, respectively, for children and adolescents between 4.10 years to 22.5 years (Alloway, 2007).

2.3.3. Manual dexterity

The Movement Assessment Battery for Children – Second Edition (Dutch version MABC-2-NL; Henderson, Sugden, Barnett, & Smits-Engelsman, 2010) was used to assess manual dexterity in children with three different subtests. For ages 3–6 (age band 1) the MABC-2 NL contained the subtests Posting Coins, Threading Beads, and Drawing Trail 1, for ages 7–10 (age band 2) it contained the subtests Placing Pegs, Threading Lace, and Drawing Trail 2. Raw scores were converted into a standard score ($M = 10$, $SD = 3$) for

Table 1

Learning task – alternating random and repeated sequence blocks.

Explicit	Test	S1	S2	S3	S4	S5			
	Retention	S6	S7	S8					
Implicit	Test	R1	S1	S2	R2	S3	S4	R3	S5
	Retention	R4	S6	S7	R5	S8			

S = repeated sequence block (1–8), $5 \times$ sequence of 9 buttons.

R = random sequence block (1–5), R1 and R4 = 2×9 buttons, R2, R3, and R5 = 5×9 buttons.

the subtests and total manual dexterity score. The MABC-2 NL is valid and reliable (Henderson et al., 2010). Scores were transformed into Z-scores.

For adult students, the Box and Block Test (Mathiowetz, Volland, Kashman, & Weber, 1985) was used to assess gross manual dexterity. Participants were asked to move as many blocks as possible with their dominant hand from one compartment to another in 60 s. The number of blocks transported was the outcome score of the test. The Box and Block Test has good reliability (Mathiowetz et al., 1985). Scores were transformed into Z-scores.

2.4. Analysis

SPSS version 23.0 was used for all statistical analyses. Descriptive statistics of participant characteristics and outcomes on visual working memory and manual dexterity were first analysed for children and adults. During the learning task, movement time and number of errors were recorded. In Matlab (Mathworks, 2010), movement time was calculated by summing the duration to press a button of all 9 subsequent button presses of a sequence. The number of errors was calculated by summing the number of errors that were made during the sequence of 9 buttons. If participants were distracted during a sequence or in case of a technical malfunction, which resulted in extreme high movement time or high amount of errors (< 1% of the data), this was noted during the experiment and these outliers were removed from the data and imputed with the mean value of the two surrounding trials. For each participant mean movement time and mean number of errors per sequence block were calculated.

As a measure of implicit learning, movement time of the last random sequence block (R5) was compared with the last repeated sequence block of the retention (S8) with a repeated measures (RM) ANOVA with age group as between subjects factor (see Table 1 for task design). In case of significant differences between groups, a post-hoc LSD test was conducted. For implicit learning, explicit awareness at the end of the implicit condition was assessed. If several participants were aware of the sequence, we further analysed if this affected task performance and learning with a RM ANOVA.

To compare both conditions and to compare results of children and adults, a RM ANOVA (2 conditions (implicit, explicit) by 5 blocks by 3 age groups (5–6 years 7–9 years, and adults) was conducted on movement time for the test phase. Visual working memory and manual dexterity were added to the analysis as covariates. Post-hoc tests (LSD) were used to further examine age effects and effects of block. Next, a RM ANOVA was conducted for retention (2 conditions by 3 blocks by 3 age groups), again with visual working memory and manual dexterity as covariates. For the number of errors, the analysis was repeated, but for the explicit condition only (participants produced almost no errors in the implicit condition): for the test phase 5 blocks by 3 age groups, and for retention 3 blocks by 3 age groups, both with visual working memory and manual dexterity added as covariates. Again, post-hoc tests (LSD) were used to further examine effects of age and block.

When sphericity could not be assumed, results of the Greenhouse-Geisser test were reported. Statistical significance (α) was set at $p < 0.05$. Effect sizes for the RM ANOVA's (partial eta squared, η^2) were interpreted according to Cohen's guidelines: 0.01 = small, 0.06 = medium, 0.14 = large (Cohen, 1988).

3. Results

Descriptive statistics of the participating children and adults are shown in Table 2. Gender was equally divided across groups, and hand dominance was similar to what is previously reported in a typical population (Perelle & Ehrman, 1994). The MABC-2-NL manual dexterity test was not different from the standard score. The manual dexterity test score for adults, the Box and Block Test score, was significantly lower than the mean of the norm scores (Mathiowetz et al., 1985), $t(27) = -7.52$, $p < .001$. The scores on AWMA visual working memory were significantly higher than the standard score for all three groups, for children 5–6 years ($t(38) = 9.21$, $p < .001$), children 7–9 years ($t(20) = 6.53$, $p < .001$), and adults ($t(27) = 6.08$, $p < .001$).

To examine implicit learning, we performed a RM ANOVA between mean movement time of random block 5 (R5) and sequence block 8 (S8). The random block was performed slower than the sequence block, indicating that the sequence was indeed learned (F

Table 2
Group characteristics.

	Children 5–6 years	Children 7–9 years	Adults
N	39	21	28
Gender (Male/Female)	20/19	8/13	13/15
Age in years, M (SD)	6.3 (0.5)	8.1 (0.7)	20.3 (1.0)
Dominant hand (Left/Right)	3/36	3/18	3/25
Manual dexterity			
MABC-2 Manual Dexterity, M (SD)	9.2 (2.5)	10.05 (3.1) [*]	–
Box and Block Test score, M (SD)	–	–	72.5 (9.9) [*]
AWMA visual working memory total score, M (SD)	120.6 (13.9) [*]	117.3 (12.1) [*]	116.6 (14.4) [*]
Awareness of implicit sequence (n)	5	4	13

^{*} The MABC-2 Manual dexterity test was not different from the standard score. The manual dexterity test score for adults, the Box and Block Test score, was significantly lower than the mean of the norm scores (Mathiowetz et al., 1985), $t(27) = -7.52$, $p < 0.001$. The scores on AWMA visual working memory were significantly higher than the standard score, both for children of 5–6 years of age ($t(38) = 9.21$, $p < 0.001$), children of 7–9 years of age ($t(20) = 6.53$, $p < 0.001$), and adults ($t(27) = 6.08$, $p < 0.001$).

(1,85) = 6.88, $p < .05$, $\eta^2 = 0.08$). Post-hoc analysis indicated that children performed both blocks slower than adults and that younger children performed slower than older children: 5–6 years vs 7–9 years ($p < .01$), 5–6 years vs adults ($p < .001$), 7–9 years vs adults ($p < .001$). There was no block \times age group interaction.

Following the implicit retention test, 24 participants (5 children 5–6 years, 4 children 7–9 years, and 15 adults) were explicitly aware of the sequence in the implicit condition: 4 children (2 5–6 years, 2 7–9 years) and 6 adults were aware of the fact that there was a sequence but could not reproduce (part of) the pattern, 4 children (3 5–6 years, 1 7–9 years) and 8 adults could reproduce at least 2 continuous buttons of the pattern in order correctly and 1 7–9 year-old child and 1 adult could reproduce all buttons of the sequence. Awareness was not influenced by the order in which participants performed the implicit condition within the experiment. If participants were aware of the implicit sequence, they performed the implicit condition significantly faster than participants who were unaware of the sequence, $F(1,86) = 11.70$, $p < .01$, $\eta^2 = 0.12$. There was no difference in the learning curve: there was not a block \times awareness (yes/no) interaction.

3.1. Movement time

3.1.1. Test

To compare both conditions during the test phase, and to compare results across age groups, a 2 (condition) by 5 (block) by 3 (group) RM ANOVA was conducted on movement time with visual working memory and manual dexterity as covariates. Detailed statistical information of the RM ANOVA is given in Table 3. The effect of condition was significant, movement time was shorter in the implicit than in the explicit condition. The effect of block was significant: movement time decreased during the test. Post-hoc analysis showed that from block 1 to 4 movement time was significantly lower (all $p < .001$), the difference between block 4 and 5 was no longer significant ($p = 0.07$). The effect of age was significant, in that younger children performed slower than older children and adults, the post-hoc test showed that 5–6-year-old children performed slower than older children and adults (both $p < .001$). Seven-to-nine-year-old children performed slower than adults ($p < .05$). The effect of visual working memory was significant, participants with better visual working memory scores performed faster. All the significant effects were large effects (≥ 14 , range 0.14–0.44, see Table 3). Manual dexterity was not a significant factor.

The condition \times block interaction was also significant. In Fig. 2a and c it is depicted that in the explicit condition participants started off slowly and showed a steep learning curve, whereas the implicit condition was performed fast across blocks (as a result of the presentation of the lighted buttons). Furthermore, there were significant condition \times age group, and block \times age group interactions, and a significant three-way condition \times block \times age group interaction. Children showed larger differences in movement time between the explicit and implicit condition, and across blocks than adults. Moreover, children showed a larger decrease in the explicit condition than adults than in the implicit condition (see Fig. 2). The condition \times visual working memory interaction was also significant. Participants with better visual working memory scores performed better in the explicit condition, but not in the implicit condition (see Fig. 3). We found no block \times visual working memory or condition \times block \times visual working memory interactions. All the significant interaction effects had large effect sizes (range 0.14–0.43, see Table 3). There were no significant interactions with manual dexterity.

3.1.2. Retention

For the retention phase, a 2 (condition) by 3 (block) by 3 (group) RM ANOVA was conducted on movement time with visual working memory and manual dexterity as covariates. Overall, results were similar to the test phase. Again, the effects of condition and block were significant, that is, movement time was shorter in the implicit than in the explicit condition and movement time decreased during the experiment. More specific, movement time decreased significantly from block 6 to 7 ($p < 0.01$), but not from block 7 to 8 ($p = 0.1$). The effect of age was significant and similar to the test phase; younger children performed slower than older children ($p < 0.01$) and adults ($p < 0.001$), and older children also performed slower than adults ($p < 0.001$). Participants with higher visual working memory scores performed significantly faster than participants with lower visual working memory scores. These significant effects had medium to large effect sizes, ranging from 0.12 to 0.30 (see Table 3). Again, manual dexterity was not a significant factor.

The condition \times block interaction was again significant. In the explicit condition participants show a learning curve during retention. In the implicit condition, a learning curve was absent, and movement time did not improve across blocks (Fig. 2a and c). Furthermore, there were significant condition \times age group, and block \times age group interactions, and a significant three-way condition \times block \times age group interaction. Children showed larger differences in movement time between the explicit and implicit condition. Across blocks, movement time decreased in the explicit condition specifically for the youngest children and adults, not for the older children. In the implicit condition, movement time increased for the youngest children (see Fig. 2). The condition \times visual working memory interaction was also significant, as was the block \times visual working memory interaction, and the three-way condition \times block \times visual working memory interaction. Participants with better visual working memory scores performed better in the explicit condition, this was not the case in the implicit condition. Moreover, participants with better visual working memory showed less improvement in movement time during retention in the explicit condition (see Fig. 3). The significant interaction effects had medium to large effect sizes (range 0.08–0.24, see Table 3). There were no significant interactions with manual dexterity.

Table 3
Results of the repeated measures ANOVA's.

Outcome Measure	Effect	F (df)	p	η^2
<i>Movement time</i>				
Test	Condition	64.09 (1, 83)	< 0.001	0.44
	Block ^a	13.29 (2.76, 229.19)	< 0.001	0.14
	Age group ^{aa}	36.13 (2, 83)	< 0.001	0.47
	Visual working memory	20.68 (1, 83)	< 0.001	0.20
	Manual Dexterity	n.s.		
	Condition × Block	13.41 (2.78, 230.29)	< 0.001	0.14
	Condition × Age group	30.75 (2, 83)	< 0.001	0.43
	Condition × Visual working memory	20.99 (1, 83)	< 0.001	0.20
	Condition × Manual Dexterity	n.s.		
	Block × Age group	8.03 (5.52, 229.19)	< 0.001	0.16
	Block × Visual working memory	n.s.		
	Block × Manual Dexterity	n.s.		
	Condition × Block × Age group	13.41 (2.78, 230.29)	< 0.001	0.17
	Condition × Block × Visual working memory	n.s.		
	Condition × Block × Manual Dexterity	n.s.		
Retention	Condition	36.16 (1, 83)	< 0.001	0.30
	Block ^b	11.07 (1.38, 114.46)	< 0.001	0.12
	Age group ^{bb}	9.76 (2, 83)	< 0.001	0.19
	Visual working memory	25.01 (1, 83)	< 0.001	0.23
	Manual Dexterity	n.s.		
	Condition × Block	11.29 (1.41, 116.74)	< 0.001	0.12
	Condition × Age group	5.85 (2, 83)	< 0.01	0.12
	Condition × Visual working memory	25.59 (1, 83)	< 0.001	0.24
	Condition × Manual Dexterity	n.s.		
	Block × Age group	5.30 (2.76, 114.46)	< 0.01	0.11
	Block × Visual working memory	7.41 (1.38, 114.46)	< 0.01	0.08
	Block × Manual Dexterity	n.s.		
	Condition × Block × Age group	4.84 (2.81, 116.74)	< 0.01	0.10
	Condition × Block × Visual working memory	7.31 (1.41, 116.74)	< 0.01	0.08
	Condition × Block × Manual Dexterity	n.s.		
<i>Number of errors</i>				
Test	Block ^c	19.20 (2.31, 192.10)	< 0.001	0.19
	Age group ^{cc}	20.94 (2, 83)	< 0.001	0.34
	Visual working memory	20.33 (1, 83)	< 0.001	0.20
	Manual Dexterity	n.s.		
	Block × Age group	6.27 (4.63, 192.10)	< 0.001	0.13
	Block × Visual working memory	n.s.		
	Block × Manual Dexterity	n.s.		
Retention	Block ^d	6.44 (1.66, 137.52)	< 0.01	0.07
	Age group ^{dd}	6.43 (2, 83)	< 0.01	0.13
	Visual working memory	18.53 (1, 83)	< 0.001	0.18
	Manual Dexterity	n.s.		
	Block × Age group	n.s.		
	Block × Visual working memory	5.39 (1.66, 137.52)	< 0.01	0.06
Block × Manual Dexterity	n.s.			

n.s.: non-significant.

^a Post-hoc test: from block 1 to 4 movement time was lower (all $p < .001$), between block 4 and 5 the difference was no longer significant ($p < 0.1$).

^b Post-hoc test: from block 6 to 7 movement time was lower ($p < .01$), between block 7 and 8 the difference was not significant ($p = 0.07$).

^c Post-hoc test: from block 1 to 5 the number of errors decreased (block 1–4 $p < .001$, block 4–5 $p < .05$).

^d Post-hoc test: no significant differences between block 6, 7 and 8.

^{aa} Post-hoc test: 5–6-year-old children performed slower 7–9-year-olds and adults (both $p < .001$), 7–9-year-olds performed slower than adults ($p < .05$).

^{bb} Post-hoc test: 5–6-year-old children performed slower 7–9-year-olds ($p < .01$) and adults ($p < .001$), 7–9-year-olds performed slower than adults ($p < .001$).

^{cc} Post-hoc test: 5–6-year-old children made more errors than 7–9-year-olds ($p < .01$) and adults ($p < .001$).

^{dd} Post-hoc test: 5–6-year-old children made more errors than adults ($p < .05$).

3.2. Number of errors

3.2.1. Test

To test the number of errors in the explicit condition during the test phase, a 5 (block) by 3 (age groups) RM ANOVA was conducted with visual working memory and manual dexterity as covariates. Details of the RM ANOVA are given in Table 3. The number of errors decreased significantly over blocks in the explicit condition for all participants. Post-hoc analysis showed that from

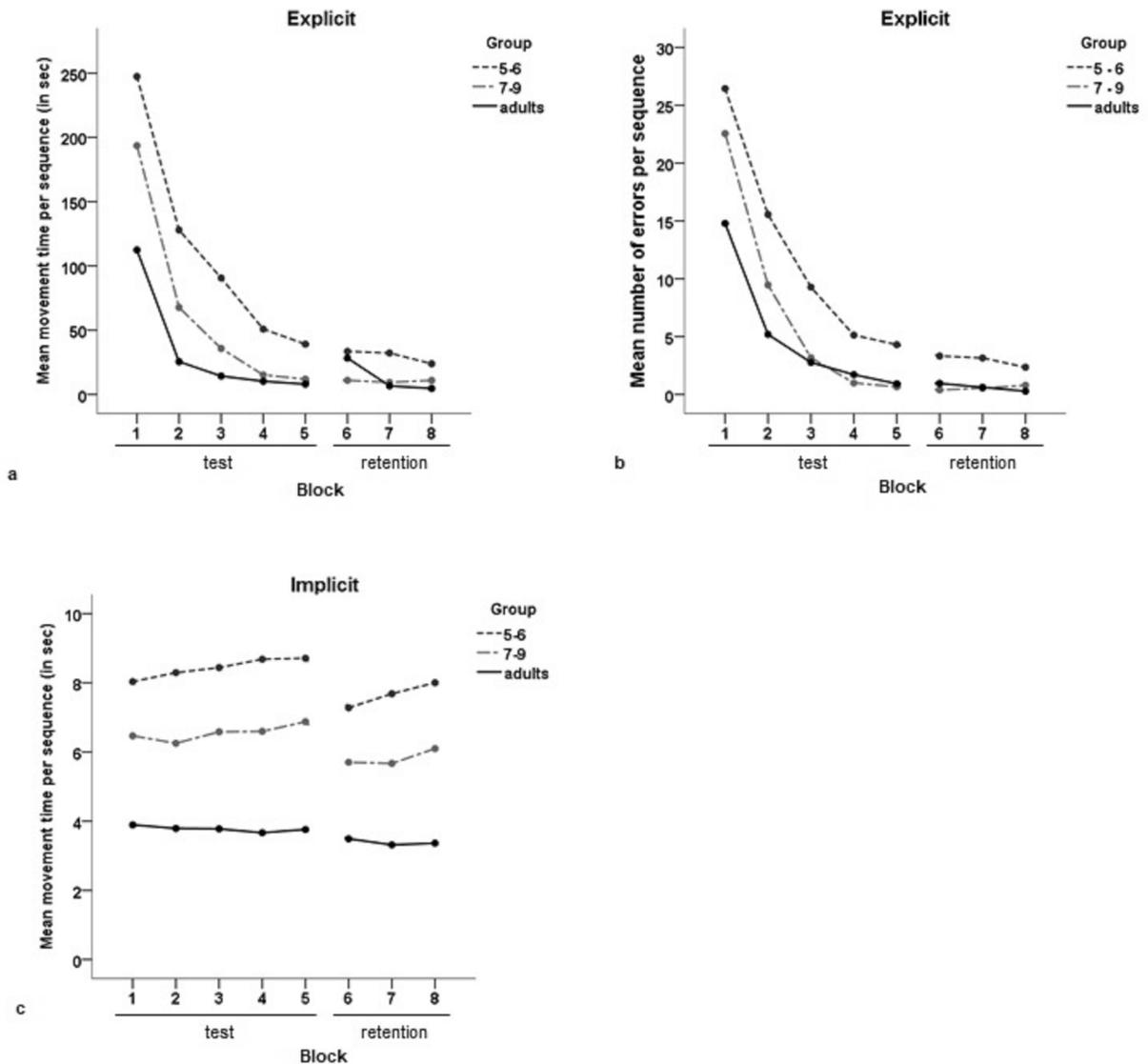


Fig. 2. Learning for the serial reaction time task across age groups: a) mean movement time per sequence for the explicit condition, b) mean number of errors per sequence for the explicit condition, and c) mean movement time per sequence for the implicit condition. The mean number or errors for the implicit condition are not shown, participants made minimal amount of errors in this condition.

block 1 to 5 the number of errors decreased significantly (block 1–4 $p < .001$, block 4–5 $p < .05$). Overall, adults and older children made fewer errors than younger children. Post-hoc tests showed that 5–6-year-old children made more errors than 7–9-year-old children ($p < .01$), and adults ($p < .001$). Participants with higher visual working memory scores made less errors during learning. These significant effects had large effect sizes, ranging from 0.20 to 0.34 (see Table 3). Manual dexterity had no effect on the number of errors.

There was a significant block \times age group interaction ($\eta^2 = 0.13$): although younger children made more errors throughout the entire task, they started making many errors and then showed a steep learning curve (see Fig. 2b). For younger children, the number of errors decreased significantly across blocks in the explicit condition. Older children made fewer errors than younger children (see Fig. 2b). Finally, participants with better visual working memory made less errors during learning (block \times visual working memory interaction). There were no significant interactions with manual dexterity.

3.2.2. Retention

To test the number of errors in the explicit condition during retention, a 3 (block) by 3 (age groups) RM ANOVA was conducted with visual working memory and manual dexterity as covariates. The number of errors decreased significantly across blocks in the explicit condition for all participants. However, in the post-hoc analysis there were no significant differences between blocks. Age was again a significant factor, post-hoc tests of the age effect showed that 5–6-year-old children made more errors than adults ($p < .05$).

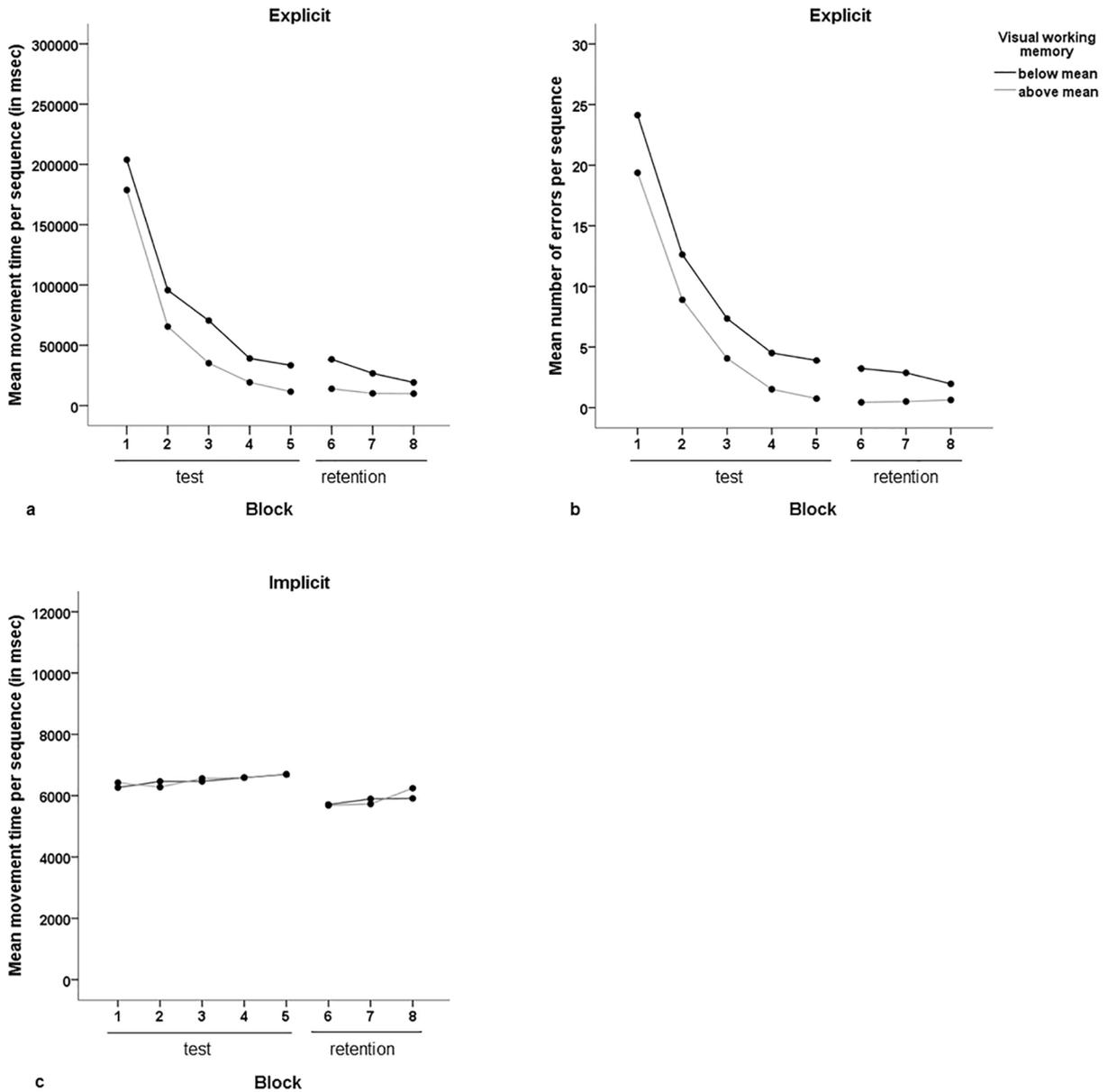


Fig. 3. Learning for the serial reaction time task across visual working memory scores: a) mean movement time per sequence for the explicit condition, b) mean number of errors per sequence for the explicit condition, and c) mean movement time per sequence for the implicit condition. The mean number or errors for the implicit condition are not shown, participants made minimal amount of errors in this condition.

Participants with higher visual working memory scores made less errors during learning. These significant effects had medium to large effect sizes, ranging from 0.07 to 0.18 (see Table 3). Again, manual dexterity had no effect on the number of errors.

There was one significant interaction of block \times visual working memory ($\eta^2 = 0.06$). Participants with lower visual working memory scores showed a larger decrease in the number of errors during retention in the explicit condition, whereas participants with better visual working scores did not show learning anymore (a floor effect, see Fig. 3).

4. Discussion

This is the first study that investigated explicit and implicit motor sequence learning in both children and adults using a within subject design. We hypothesized explicit learning to be dependent on age and visual working memory and implicit learning to be independent of age and visual working memory. All participants learned the motor sequence explicitly and implicitly. We found differences between children and adults for both explicit and implicit performance. Adults and older children performed better than the youngest children (5 and 6 years), both in terms of movement time and accuracy. Moreover, adults and older children also started

at a higher level (lower movement time and less errors) than the youngest children. Learning curves were also different, but only for explicit learning: for the youngest children the curves were steeper, due to their lower level at the start of the test. Visual working memory positively influenced the results in the explicit condition. Participants with better visual working memory performed faster and more accurate. However, there was no effect of visual working memory on the learning curve during the test. In retention, visual working memory did affect explicit learning. Participants with better visual working memory reached a floor effect in the explicit condition, whereas participants with lower visual working memory scores did not (yet).

We expected an effect of age on explicit learning, but not on implicit learning and our results confirmed this expectation. During learning, age indeed moderated explicit learning. Adults and older children performed the sequences faster, predominantly in the explicit condition. In addition, they were more accurate than younger children. Our data showed that in the explicit condition younger children had a lower movement time and made more errors, while older children performed at an intermediate level, and adults performed best. However, the younger children did show the steepest learning curve for explicit learning. Their movement times and number of errors did decrease across all five test blocks, whereas older children and adults performed similar from block 4 to 5 and reached a floor effect. These findings may suggest that young children spent more time in the first, cognitive phase of learning (Fitts & Posner, 1967) compared to older participants. For implicit learning, we found an age effect that was restricted to performance only, i.e. younger participants had a larger movement time throughout the learning task. The rate of learning across the blocks, as shown by the learning curves, was not different for the age groups. These results are in line with previous studies on implicit learning (Meulemans et al., 1998; Savion-Lemieux et al., 2009; Thomas & Nelson, 2001).

The effects of visual working memory on motor learning were not completely in line with our expectations. We expected visual working memory to have an effect in the explicit condition, but not in the implicit condition. Participants with better visual working memory did perform better in the explicit condition, i.e. participants had a lower movement time and lower number of errors, but their learning curves were not different in the test phase. In retention, learning curves were different: participants with better visual working memory reached a floor effect in the explicit condition, whereas participants with lower visual working memory scores did not. For implicit learning, visual working memory did not influence either performance or learning. In a previous study of this task, in children born very preterm (reference blinded for review), we found positive effects of visual working memory in the explicit condition, and also small effects in the implicit condition. In that previous study, 15 percent of the participants were aware of a sequence in the implicit condition. Again, these effects of visual working memory were only effects at the level of performance, and not on the learning curves itself. It seems that explicit performance of this task is dependent on visual working memory capacity, whereas implicit performance is not, or to a lesser extent. To further unravel these visual working memory effects, it is necessary to include an implicit or non-verbal awareness task before the explicit verbal awareness task. Participants might be aware of a sequence, although they cannot articulate this yet.

Other studies have also focused on the effect of visual working memory on explicit and implicit sequence learning with mixed results (for a review see Janacsek & Nemeth, 2013). Janacsek and Nemeth (2013) argue that among other factors, the method of measuring working memory capacity is important in considering the results. In the present study, we measured visual working memory only, since the sequence is a series of stimuli of different locations. In future research it would be valuable to measure both visual and verbal working memory. During the explicit condition, several children counted the buttons in the pattern while they learned the pattern, suggesting that verbal working memory was also employed during the experiment. Furthermore, a dual-task, which loads working memory while performing the primary task, might also give additional information on the role of working memory in explicit and implicit sequence learning. This additional information could be used to tailor individual learning programs.

Unexpectedly, several participants were explicitly aware of the sequence in the implicit condition. Fifteen percent of the children was aware of the sequence, and almost half of the adults. There was no effect of order, participants were not more aware of the sequence if they first performed the explicit condition and then the implicit condition. The extent to which these participants were aware of the sequence differed, but still awareness had a strong effect on performance in the implicit condition. Although participants who were aware of the sequence performed faster throughout the motor sequence task than participants who were unaware, learning curves were not different for the two groups. It is theorized that implicit and explicit motor learning are separate processes (Destrebecqz & Cleeremans, 2001; Nissen & Bullemer, 1987; Steenbergen et al., 2010). However, if participants become explicitly aware during implicit learning, explicit processes can contribute to learning by selecting and sequencing of the spatial targets (Willingham, 1998). This beneficial effect of explicit awareness in implicit learning was also found in a study on implicit sequence learning in typically developing children (Thomas & Nelson, 2001) and children with spina bifida (Vinck et al., 2012).

Participants learned the sequences both in an explicit and implicit manner. The way in which these sequences will be consolidated (i.e. stabilization of a memory trace; Krakauer & Shadmehr, 2006) after explicit or implicit learning remains an important topic for further scrutiny. Within the present set-up, the retention test was assessed shortly after learning. In the literature there is no gold standard for the time in between learning and retention. We chose for a retention 10 min after learning for practical/logistical reasons. During these 10 min, participants were occupied with playing a game, keeping them from rehearsing the task in memory. An extra assessment, e.g. one week later, could give more insight into consolidation. When consolidation occurs, the memory trace may become resistant to interference and performance can even improve after initial learning (Janacsek & Nemeth, 2012; Krakauer & Shadmehr, 2006). From several studies it may be concluded that consolidation is different following explicit and implicit learning. In explicit learning, consolidation is dependent on sleep, while in implicit learning consolidation is time dependent. Furthermore, it seems that participants who become aware of a sequence during implicit learning, also adopt the explicit consolidation strategy. So even though awareness seems beneficial for implicit learning, it may not benefit consolidation. This difference in consolidation is also related to the brain structures involved, where sleep dependent consolidation relies more on evolutionary newer brain structures compared to time dependent consolidation (for a review see Janacsek & Nemeth, 2012). These differences may be advantageous in

implicit learning (without awareness during learning), and may further explain why implicit learning is more stable and resilient to cognitive factors as Reber (1992) described.

In the literature, several other benefits of implicit learning have also been described. These studies have not focused on SRT tasks, but on applied tasks such as throwing tasks. Implicit learning leads to better performance under stress or distraction (Maxwell, Masters, Kerr, & Weedon, 2001; Capio, Sit, Abernethy, & Masters, 2012). This could be beneficial for people with cognitive and/or attentional deficits. Moreover, a study of Capio, Poolton, Sit, Eguia, and Masters (2013) showed promising results in implicit and explicit motor learning in overhand throwing. That is, children with intellectual disabilities learned to throw more accurate and with better movement form in the implicit condition. Importantly, children in the implicit condition spent much more time throwing during free play in school (Capio et al., 2013). This result could also have important health benefits for children. Finally, an exploratory study of Van der Kamp, Steenbergen, and Masters (2017), showed that children with right unilateral cerebral palsy had more difficulty in explicit learning and not in implicit learning. It was hypothesized that these children have less conscious control of motor processes given their affected left hemisphere. In sum, implicit learning can be beneficial for different clinical groups of children.

The present study focused on motor sequence learning, to further explore the already existing knowledge on motor sequence learning and to extend this knowledge to learning of a basic motor task. However, motor sequence learning may not be similar to learning other motor skills (Krakauer & Shadmehr, 2006), such as writing or gross motor skills in sports. Moreover, there is a debate on what exactly is measured with such a motor sequence learning task: motor sequence learning or spatial sequence learning (perceptual) (Hikosaka, Nakamura, Sakai, & Nakahara, 2002; Robertson, 2007). The aim of our study was not to unravel these processes, but to study motor learning of a simple and controlled, gross manual motor task. Future studies should extend this research to clinical groups of children and other individual factors than age and visual working memory that are important in learning. In order to use the principles of the theory on implicit and explicit motor learning for teaching and rehabilitation purposes, research should focus on more relevant motor tasks and especially focus on learning in (clinical groups of) children.

This study has several limitations and elements of improvement. First, as already discussed, we measured visual working memory only, while other measures of working memory (verbal working memory or dual-tasks) might give additional information on the role of working memory in motor sequence learning. Second, learning effects in the implicit condition were not as pronounced as in the explicit condition, especially in children. It could be that the motor task was not motivating enough, or that children did not pay enough attention to the task at hand, which could result in less learning (Nissen & Bullemer, 1987). Furthermore, children might also have become tired during the test, since pressing the buttons requires force. We observed that several children had a tired arm after the implicit test. The task could be adapted on these aspects, e.g. by presenting the task on a touch screen with a puppet on the stimuli locations that children need to ‘chase’, to make it less forceful and possibly more motivating. Third, we only included an explicit awareness task at the end of the implicit condition. In future research, it would be interesting to include a more implicit awareness task after the retention test (as also discussed above). It would then be possible to further unravel awareness and visual working memory effects. Especially the youngest children might be aware of a sequence, although they cannot articulate this yet.

We noticed that scores on visual working memory were quite high in both adults and children, but with a normal standard deviation. For adults this was expected, since we included university students. For children, this was also observed in two other studies (Jongbloed-Pereboom et al., 2017; Jongbloed-Pereboom, Peeters, Overvelde, Nijhuis-van der Sanden, & Steenbergen, 2015). It seems that the UK norm scores are not suitable for young Dutch children. Then, for the adult manual dexterity score, we observed the opposite: the Box and Block Test score was lower than expected from norm scores (Mathiowetz et al., 1985). The norm scores for adults are 30 years old, and in two other studies diminished motor performance was also observed on this test (Jongbloed-Pereboom, Nijhuis-van der Sanden, & Steenbergen, 2013; Jongbloed-Pereboom, Spruijt, Nijhuis-van der Sanden, & Steenbergen, 2016). To be able to compare the scores of the different manual dexterity tests between children and adults we transformed these scores into Z-scores. By this transformation and because the standard deviation is normal, we do not expect that the deviation from the norm scores influenced the conclusions of this study.

5. Conclusion

To our knowledge, this was the first study to compare explicit and implicit sequence learning in both children and adults. To this purpose, we used a counterbalanced within-subjects design. As hypothesized, explicit learning was dependent on age, while implicit learning was not. In explicit learning, adults and older children performed better than the youngest children. Age did affect performance in implicit learning, but for the implicit condition learning curves were similar across groups. Visual working memory positively influenced the results in the explicit condition, not in the implicit condition. Participants with better visual working memory performed faster and more accurate in the explicit condition. However, there was no effect of visual working memory on the learning curve during the test. In retention, visual working memory did affect explicit learning. Further research is necessary to test if and how principles of implicit and explicit motor learning can be applied in education and rehabilitation.

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