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EMPIRICAL ARTICLE

CHILD DEVELOPMENT

Goal-directedness enhances letter-speech sound learning and consolidation in an unknown orthography

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Abstract

This study examined how top-down control influenced letter-speech sound (L-SS) learning, the initial phase of learning to read. In 2020, 107 Dutch children (53 boys, M_{age} = 106.845 months) learned eight L-SS correspondences, either preceded by goal-directed or implicit instructions. Symbol knowledge and artificial word-reading ability were assessed immediately after learning and on the subsequent day to examine the effect of sleep. Goal-directed children were faster and more efficient in learning a new script and had better learning outcomes compared to children who were not instructed about the goal of the task. This study demonstrates that directing children toward the goal can promote L-SS learning and consolidation, giving insights into how top-down control influences the initial phase of reading acquisition.

Learning to read is essential for participation in society. Although our brain is not hardwired for reading, the vast majority of the population learns how to read relatively effortlessly. Previous studies have suggested that learning to read is a complex behavior that develops from dynamic interactions between multiple processes (Pennington, 2006; van Bergen et al., 2014; Verwimp et al., 2021), but these processes have commonly been studied in isolation. It, therefore, remains unclear how top-down processes and subsequent consolidation contribute to the initial phases of reading acquisition. To fill this gap, this study employed an artificial letter-speech sound (L-SS) association task in a sample of 107 elementary school children to examine the effect of revealing and directing a child toward the goal of the task on the initial learning and consolidation of new L-SS correspondences, aiming to provide a better understanding of the processes that influence the first stage of learning to read.

Learning to read

Learning to read is a complex multisensory process, which entails learning the underlying regularities of a writing system. In an alphabetic writing system, one of the regularities that has to be learned is how letters map onto units of speech (e.g., the letter A maps onto the sound /a/). How fast one can learn these mappings depends on the orthographic transparency of a given script, that is, the degree of regularity in L-SS correspondences (Seymour et al., 2003). In more transparent languages, such as Dutch, it takes approximately 1 year of formal reading instruction to acquire the knowledge of these correspondences (Vaessen & Blomert, 2010).

Accurate reading can be obtained relatively fast, but mere knowledge of these correspondences is not sufficient for fluent reading. Brain potential and neuroimaging studies have shown that once L-SS correspondences become highly overlearned, the visual

Abbreviations: ANOVAs, analyses of variance; FDR, false discovery rate; LSS, letter-speech sound; MANOVA, multivariate analysis of variance; OMT, one-minute reading test.

symbol automatically elicits an auditory referent (Blau et al., 2010; van Atteveldt et al., 2007). As a result, brain regions that are involved in multisensory processing and speech sound processing respond differently to congruent pairs (e.g., a—/a/) compared to incongruent pairs (e.g., a—/t/), referred to as the congruency effect. The emergence of this automatic neural sensitivity for congruent and incongruent pairs has been argued to be a fundamental building block for successful fluent reading and appears to be persistently less automatic in individuals with reading difficulties (Blomert, 2011; Dehaene et al., 2015; Žarić et al., 2014). Understanding the mechanisms underlying the formation of these associations is thus of great importance for two main reasons. First, to understand individual differences in reading development, and second, to ultimately assist all readers to become proficient, as instructional support can be better matched to individual needs.

Influence of instructions in a learning context

Although there has been substantial interest in how we acquire L-SS mappings (Karipidis et al., 2021; Xia et al., 2022), it remains heavily debated whether individuals are able to learn these regularities without explicitly drawing attention to that what has to be learned. One approach advocates that learning to read should be accompanied by explicit, systematic instructions (Castles et al., 2018; Rastle et al., 2021). When expertise grows, this gradually shifts toward an implicit form of learning in which associating a letter with its speech sound becomes automatic without the need for explicit instructions. An alternative approach advocates that many complex behaviors, like reading, should be learned in a minimally guided environment, in which learners should discover essential information on their own based on repeated exposure and incidental experience (e.g., Bruner, 1961; Krahenbuhl, 2016).

Based on this latter approach, policymakers and educators are investing more into technology-based interventions that use playful, repetitive practice to obtain automatized skills (e.g., GraphoGame; Saine et al., 2011). Although these technology-based interventions are thought to be more motivational and engaging, questions are raised regarding their compatibility with learning (Graesser et al., 2009), as they often direct learners by performance prompts (e.g., perform better than others or obtain a higher score to reach the next level). However, prompting learners to develop specific skills or master new knowledge has been found to promote better learning, as our brain can better select the inputs that are most pertinent to our behavioral goal at that time (Talsma et al., 2010). Accordingly, instructions that reveal or direct one to the goal of the task (hereafter referred to as goal-directed instructions) may facilitate the development of new knowledge and consequently foster the transfer of learning, whereas instructions that lack the rationale behind that what needs to be learned (hereafter referred to as implicit instructions) may complicate filtering out irrelevant distractors, hindering the establishment and consolidation of newly learned information (Erhel & Jamet, 2016).

Although cross-modal integration (i.e., integration of information from two or more different sensory modalities) has often been characterized as an implicit, automatic process, recent findings point toward the role of higher-level cognitive functions, such as top-down control (i.e., the mechanism of attentional filtering to minimize distraction of irrelevant stimuli; Talsma et al., 2010; van Atteveldt et al., 2007). Selectively directing attention to relevant graphemes and phonemes is thought to facilitate the formation of integrated representations, which are consequently stored in multisensory brain regions through repeated practice and offline sleep consolidation for fast and automatic retrieval (Klinzing et al., 2019; Stein & Stanford, 2008). Remarkably, it remains largely unclear how top-down control contributes to successful integration of letters and speech sounds and subsequent consolidation in the general population, as these processes are commonly examined in isolation. More insight into these processes is highly relevant for effective reading instruction and therapeutic remediation strategies.

Artificial learning design

Revealing the goal of a task and explaining in what context the new knowledge can be used (i.e., goal-directed instructions) is expected to influence the learning rate of the child when learning to associate letters and speech sounds. However, as most studies do not directly address the actual process of learning L-SS mappings, little is known about how goal-directed instructions influence the learning of new L-SS correspondences and how this contributes to the offline consolidation of this new knowledge. Although the studies previously discussed provided insights into L-SS learning, results are commonly influenced by prior letter knowledge and reading experience, as native graphemes and phonemes were used. To control for this, recent studies have developed an artificial L-SS training paradigm, in which participants had to learn how unknown symbols correspond to known speech sounds (e.g., Aravena et al., 2013; Karipidis et al., 2017; Rastle et al., 2021). Such a design allows for a more controlled mapping of the initial phase of learning to read. Moreover, the fact that such a paradigm is devoted to learning rather than to the level of skill already obtained makes it a useful tool to predict individual differences in reading performance and future gains in reading intervention (Aravena et al., 2018; Horbach et al., 2018).

Previous artificial learning studies have shown benefits of explicit instructions in learning a new script (Aravena et al., 2013; Rastle et al., 2021). In the study of

Rastle et al. (2021), adults learned to read words printed in two unknown, artificial alphabets. One group received explicit instructions on the underlying regularities of the writing system whereas the other group had to discover these regularities through text experience alone. The authors found that in contrast to the explicitly instructed participants, only 20% of participants in the discovery-learning group obtained high levels of task performance, even after 18 h of training. In the study of Aravena et al. (2013), an artificial L-SS training paradigm was used to learn correspondences between visual Hebrew symbols and Dutch speech sounds. They found that explicit instructions were more efficient in initial L-SS binding, especially when a new orthographic rule had to be learned. In addition, they showed that children with dyslexia were as accurate as typically developed readers but were more prone to errors when applying this knowledge in an under-time pressure reading task. However, different game designs were used in the different conditions, allowing for the possibility that differences between the conditions are partially caused by the different game designs. Moreover, to address the actual process of these mappings, it is highly relevant to examine the learning curve during the training rather than only the behavioral outcome after the learning phase.

Current study

To address these issues, this study used a computerized artificial L-SS learning task similar to that of Aravena et al. (2013), aiming to mimic the initial formation of the neurocognitive reading network. Given that most experiments have been performed in adults (e.g., Rastle et al., 2021) or made group comparisons between individuals with and without dyslexia (e.g., Aravena et al., 2013), this study was performed in children with a wide range of reading levels to get more insight into individual differences in reading development.

The goal of this study was twofold: First, we wanted to examine whether goal-directed instructions influenced the learning and consolidation of L-SS correspondences. We provided the two groups with the same learning conditions, but either preceded by instructions that revealed the goal of the task and directed children toward that goal (i.e., goal-directed instructions) or instructions that prompted children to discover the goal of the task on their own (i.e., implicit instructions). Accuracy and reaction time were measured during the learning phase, allowing us to map the learning curve. Afterward, the instrumental use of the artificial correspondences was examined in a reading task within the artificial script. A congruency task in which children were required to rate an audiovisual presentation as congruent or incongruent served as a measure of L-SS integration. Contrary to most studies, the influence of the instructions on the retention of the L-SS knowledge was assessed 24 h after the learning task.

For this part, the following research questions were assessed: (I) Are children who are directed toward the goal of the task faster in learning the L-SS correspondences? (II) Does this instruction manipulation result in better knowledge of the newly learned script? (III) Does the instruction manipulation lead to differences in the consolidation of newly learned L-SS correspondences? and (IV) Are L-SS correspondences better integrated in children who were directed toward the goal of the task?

We hypothesized that both groups would improve in accuracy and reaction time during the L-SS learning task, but that children who received goal-directed instructions would be faster in learning a new script, resulting in a steeper learning curve. As a consequence, we expected that symbols and speech sounds would be better integrated in participants who received goal-directed instructions, reflected in the performance on the reading task, in which symbols and speech sounds needed to be integrated to use these correspondences under time pressure. In the congruency task, we expected that children who received implicit instructions would show no or a weak conflict-related reaction time. This is, we expected no difference in reaction time between congruent and incongruent trials, which may be interpreted as a weaker L-SS integration. Last, given that overnight sleep has been proposed to benefit integrating newly encoded information and memory consolidation (Klinzing et al., 2019), we expected that the new correspondences would be better integrated in both groups on the subsequent day and therefore would lead to a better performance in the reading task. However, working on the assumption that goal-directed instructions affect the quality of processing during the learning phase, we hypothesized that this increase in reading performance would be most apparent in children who received goal-directed instructions.

In the second part of this study, we wanted to establish how valid and reliable such an artificial learning design is. For this we examined whether indexes of our L-SS task were related to the reading performance in the Dutch script. In addition, children were tested with an alternative version of the task containing different L-SS correspondences, approximately 3 weeks after the first version to assess test–retest reliability.

Taken together, this study aims to provide a better understanding of how top-down control influences L-SS learning and subsequent consolidation, potentially of great importance for effective reading instruction and therapeutic remediation strategies.

METHODS

Participants and procedure

Participants were recruited through two primary schools in Amsterdam (the Netherlands) to participate in an artificial L-SS learning task to mimic the initial formation of the neurocognitive reading network. Amsterdam is highly diverse in cultures and ethnicities, but as current research questions did not address socio-demographics, this information was not collected or used to recruit participants. Parents were informed through a digital letter about the goal of the study. To capture the wide range of individual differences in reading levels, all children were eligible to participate when they were native Dutch speakers (both mono- and multilingual) in grade 3 or 4 (approximately aged between 8 and 10), without severe (uncorrected) visual and/or hearing problems. No further exclusion criteria were applied. A total of 107 elementary school children (53 boys) aged between 92 and 136 months (M = 106.845, SD = 8.876) took part in this study after obtaining active informed consent of the parents. Data were collected over a 4-day period (see Figure 1). On the first day, children completed the computerized artificial learning task, which consisted of three blocks that were devoted to learning the L-SS correspondences, and one testing block (i.e., congruency task). The artificial learning task took approximately 30 min in total and was conducted individually. Afterward, all children completed three tasks that were related to the new artificial script: a productive symbol knowledge task and two one-minute reading tests (OMTs) within the artificial script (real words and pseudowords). To assess word reading skills in the native language, a OMT within the Dutch script was conducted as well. Last, all children who were tested on the same day (with a maximum of 12) were positioned in a quiet room at the children's school and received 20 min to fill in all 20 items of the Raven's Colored Progressive

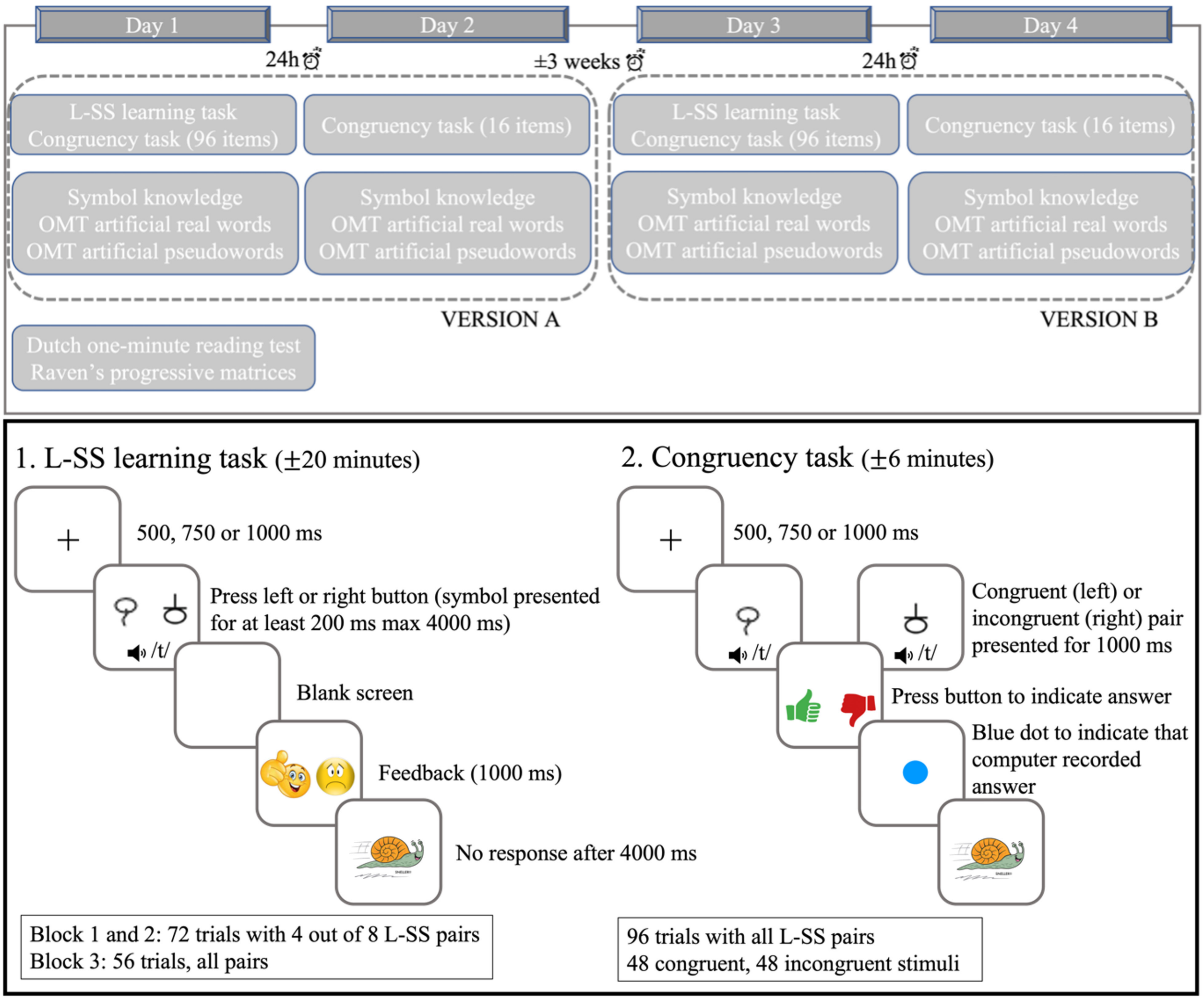

FIGURE 1 Overview of experimental design. OMT, one-minute reading test. Children had to learn eight new letter-speech sound (L-SS) correspondences with eight artificial symbols from the Brussels Artificial Character Set-1 alphabet (Vidal et al., 2017) that were matched to a Dutch phoneme. Consequently, they had to indicate whether the presented audiovisual stimulus was congruent or incongruent. The L-SS and congruency task were exactly the same for both conditions but were preceded by either goal-directed or implicit instructions to manipulate goal-directedness. The learning task was followed by three tasks that were related to the artificial script. A shortened version of the congruency task and the L-SS learning-related tasks were repeated on the subsequent day to assess retention. An alternative version of the learning task (Version B) was conducted in the same sample approximately 3 weeks later to measure test–retest reliability.

Matrices (Raven et al., 1984). On the second day, to assess the retention of the L-SS knowledge, a shortened version of the congruency task, the symbol knowledge task, and the two word reading tasks within the artificial script were conducted. This took approximately 10 min. After approximately 3 weeks, an alternative version of the learning task (Version B; mapping new symbols onto new speech sounds) was conducted in the same sample to examine the test–retest reliability of this Dutch artificial L-SS learning paradigm, followed by a retention session on the subsequent day as well. All data were collected within a period of 3 months (September 2020–November 2020). This study was approved by the ethics committee of the University of Amsterdam. Analyses were either pre-registered at OSF (https://osf.io/2cge6) or described as exploratory in the current study.

Artificial L-SS learning task

This study used an adaptation of the training paradigm used in Aravena et al. (2013), Fraga González et al. (2015), and Guerra (2022). All children completed a computerized artificial L-SS learning task, programmed in Psychopy2 (Peirce et al., 2019). The goal of the task was to learn eight new L-SS correspondences that consisted of eight unknown characters from the Brussels Artificial Character Set-1 alphabet (Vidal et al., 2017) that were linked to eight Dutch speech sounds (for an overview of all L-SS correspondences, see Table 1). Phonemes for Version A and B were selected such that enough words could be created for the subsequent artificial reading tests, with each version containing four consonants, two vowels, and two diphthongs. In addition, the mean phoneme duration was kept constant between the two versions. The learning experiment comprised four blocks, of which the first three aimed at learning the correspondences and the last block aimed at testing the correspondence knowledge. For the first three blocks, each trial started with a fixation cross presented with equiprobable durations of 500, 750, or 1000 ms, followed by the audiovisual presentation. Each speech sound was accompanied by two black artificial characters that appeared on a white background, one on the left-hand and one on the right-hand side of the screen. Children had to press the left or right button to indicate whether the left or right character corresponded to the speech sound (50% chance level). The position of the corresponding symbol was randomly determined at each trial. Each trial was followed by feedback such that children could learn the correct correspondences during the task. When no response was given after 4000 ms, children were encouraged to respond faster with an image of a snail. In the first block, four out of eight L-SS pairs were presented. The other four pairs were presented in the second block. The pairs that were presented in either the first or second block were kept constant across children, with each speech sound occurring 18 times. In the third block, all eight L-SS pairs were presented, with each speech sound occurring 7 times. In the fourth block (i.e., congruency task), either congruent (learned correspondence) or incongruent (new correspondence) L-SS pairs were presented on the screen. Children had to press the left or right button to indicate whether the pair was congruent or incongruent. As this block served as a testing block rather than a learning block, children received no feedback. However, children saw a blue dot in the middle of the screen every time they pressed a button, such that they knew that the computer had recorded their answer. The order of items was randomized for all blocks as well as which symbol was presented as the non-corresponding distractor, without presenting the same speech sound twice in a row. Figure 1 shows an overview of a trial in the learning and congruency task.

Task instructions were given verbally in a standardized manner prior to the learning task. In the goal-directed condition, the participants received information about the goal of the task, that is, learning as many symbols as possible to crack a secret code in the end. Participants

TABLE 1 Letter-speech sound combinations adapted from the Brussels Artificial Character Set-1 alphabet (Vidal et al., 2017) for Version A and B separately.

Version A								
Letter								
Speech sound (IPA)	[aʊ]	[t]	[z]	[ɛɪ]	[ɛ]	[n]	[f]	[ɔ]
Phoneme duration (ms)	505	194	516	527	387	734	303	383
Version B								
Letter								
Speech sound (IPA)	[ɑ]	[Ø:]	[ɪ]	[u]	[p]	[r]	[s]	[ʋ]
Phoneme duration (ms)	386	515	486	369	314	549	491	392

Abbreviation: IPA, International Phonetic Alphabet.

in the implicit condition were told to play a computer game of which the goal would become clear during the task itself. The message participants saw on the screen during breaks was also manipulated; children who received goal-directed instructions were prompted to learn more symbols to be able to crack the code, whereas children in the implicit condition just received the message to press the spacebar to continue. All participants were told which two keys to use during the task and received the same computerized feedback when pressing the right or wrong answer during the learning phase. Participants were randomly allocated to one out of two experimental conditions.

Outcome measures

L-SS learning during the training

Both accuracy and reaction time of L-SS learning were recorded during the training. The accuracy score was determined by the total number of correct responses divided by the total number of items (%). Reaction time was defined as the average reaction time of the correct responses.

Passive L-SS integration

Both accuracy and reaction time were assessed as a proxy of passive L-SS integration during the congruency task, in which children had to indicate whether a presented L-SS pair was correct (learned) or incorrect (not learned). Accuracy scores and reaction times were computed for congruent and incongruent items separately. Accuracy was determined by the total number of correct responses divided by the total number of the items (%) and reaction time by the average reaction time of correct responses. A shortened version of this task (16 trials) was repeated on the subsequent day to assess the influence of sleep on the passive L-SS integration.

Productive symbol knowledge

The experimenter presented children with a form containing the eight artificial symbols. While pointing at one of the symbols, children were asked to name the letter out loud. Children repeated the symbol knowledge task as a measure of retention on the subsequent day. The score was determined by the number of speech sounds that were named correctly (maximum score = 8).

Word reading rate in artificial orthography

Two lists of 14 monosyllabic words within the artificial orthography were constructed with increasing difficulty: one resulting in real Dutch words when all symbols were correctly decoded, one resulting in pseudowords (see Table S4). The words were arranged in one column on two different papers. Children needed to read as many words as possible within 1 min. The score was determined as the number of words read correctly within 1 min (for both versions maximum = 14).

Word reading in Dutch

The 1-min test was used as a measure of word reading skills in Dutch (Brus & Voeten, 1973). Children needed to read as many words as possible within a time-limit of 1 min. The score was determined by the number of words read correctly within 1 min (maximum = 116).

Non-verbal IQ

Non-verbal IQ was assessed with a time-limited version of the Raven's Colored Progressive Matrices (Hamel & Schmittmann, 2006; Raven et al., 1984). Raw data were used as a measure of non-verbal IQ (maximum = 36).

Data analysis

Before the statistical analyses, reaction times were outlier-corrected using a two-step procedure; First, values below 100 ms were considered unconscious (i.e., guessing behavior) and therefore removed. Second, reaction times deviating more than 3 SDs from the individual mean of each subject were excluded. Based on this procedure a maximum of three trials per block per participant were removed. Only trials with correct answers were included in the reaction time analysis. Furthermore, children were only included when they had all data available that were needed to answer a certain research question. As a result, for the first research question, three children had to be excluded as they had missing data due to technical issues. For the second research question, 16 additional children had to be excluded as consolidation data were missing due to technical problems of one computer. For the third and the last research question, no children had to be excluded.

For the first part of this study, we aimed to examine how goal-directed instructions influenced the learning of new L-SS correspondences. To examine differences in learning progress between the two conditions, accuracy and reaction time during the learning task were averaged across 4 bins of 18 trials for Block 1 and 2, and of 14 trials for Block 3. The percentage of correct answers and reaction time was computed per block for each bin and submitted to a repeated-measures multivariate analysis of variance (MANOVA) with Group (Goal-directed vs. Implicit) as between-subjects factor and Time (Bin 1 vs. Bin 2 vs. Bin 3 vs. Bin 4) as within-subjects factor. Participants were removed from the analysis if a certain bin did not have at least one value left ($n = 1$). To examine the influence of instruction on the passive L-SS integration immediately after learning and on the subsequent day, accuracy and reaction times following either congruent or incongruent trials on Day 1 and Day 2 were compared between children who received goal-directed or implicit instructions with a factorial MANOVA, with Group (Goal-directed vs. Implicit) as between-subjects factor and Congruency (congruent trials vs. incongruent) and Day (Day 1 vs. Day 2) as within-subjects factors. To examine differences in L-SS knowledge immediately after the learning task and on the subsequent day, a factorial MANOVA was conducted with symbol knowledge and word reading rate within the artificial orthography (real words and pseudowords) as dependent variables, Condition as between-subjects variable and Day (Day 1 vs. Day 2) as within-subjects variable.

For the second part of this study, we aimed to examine the validity and reliability of this Dutch artificial L-SS learning paradigm. To examine the external validity, a one-tailed Pearson correlation test was conducted between reading rate in Dutch and reading rate in the artificial orthography (real words and pseudowords). As we wanted to compare reading fluency in both scripts and fluent reading requires the knowledge of all symbols, only children who obtained full mastery of the new symbols were included in this analysis ($n = 32$). Last, test–retest reliability was computed by correlating the outcome measures (i.e., symbol knowledge and the two reading tasks within the artificial script) of the original version of the task (Version A) to the outcome measures of the alternative version (Version B). Correlations between the two versions were computed for the outcomes immediately after the learning task (Day 1) as well as for the outcomes after one night of sleep (Day 2).

The significance level for all analyses was set at .05. Given the increased risk for type-1 error when conducting multiple tests, *p*-values were false discovery rate corrected (FDR; Benjamini & Hochberg, 1995) within each set of outcomes associated with a certain research question (for research question 1, 2 and 3 separately). Pairwise comparisons between levels of main effects were only performed when interactions involving our manipulation of interest were found to be significant after FDR correction. Partial Eta squared effect sizes were computed and reported as well.

RESULTS

Participant characteristics

The goal-directed condition comprised 54 participants with a mean age of 106.201 months (SD = 8.690) and the implicit condition comprised 53 participants with a mean age of 107.50 months (SD = 9.215). Participants' characteristics are shown in Table 2. No significant differences in age, intelligence, or reading fluency in Dutch were found between the two conditions. Although gender distribution was not significantly different between the two conditions, gender could still influence the results given possible attentional and motivational differences between girls and boys. Re-running the analyses with gender as an additional between-subject factor did not influence our main outcomes.

L-SS learning during the training

A 2 (condition) × 4 (time) repeated measures (RM) MANOVA with accuracy and reaction time as dependent variables were performed for Block 1, 2, and 3 separately. Mean accuracy scores and reaction times for each bin are shown in Table 3 for the two conditions separately and statistical values are reported in Table S1. For Block 1, we found a main effect of Condition, a main effect of Time, and a significant interaction effect between Condition and Time. For Block 2, we found a main effect of Time, a significant interaction effect between Condition and Time, but no main effect of Condition. For Block 3, there appeared a main effect of Condition, but no main effect of Time or interaction effect between Condition and Time. After FDR correction, only the main effect of Time and the interaction effect between

TABLE 2 Participant characteristics.

	Mean (SD)		
Characteristic	**GD group**	**Implicit group**	**Group comparison**[a]
n	54	53	
Gender (M:F)	23:31	31:22	$\chi^2(1) = 2.106$, $p = .147$
Age	106.201 (8.690)	107.500 (9.215)	$F(1, 105) = .544$, $p = .462$
IQ	31.500 (3.155)	31.170 (3.751)	$F(1, 105) = .243$, $p = .623$
Reading fluency Dutch	58.574 (14.565)	59.925 (13.701)	$F(1, 105) = .244$, $p = .622$

Abbreviation: GD, goal-directed.

[a]Nominal data were investigated using Pearson's chi-squared tests, continuous data were investigated using analyses of variance.

TABLE 3 Mean (SD) accuracy and reaction time (RT) of correct responses by condition and learning block for each bin.

Condition	Goal-directed group		Implicit group	
	Accuracy (%)	RT	Accuracy (%)	RT
Block 1				
Bin 1	49.14 (14.32)	0.890 (0.379)	47.60 (15.53)	0.994 (0.461)
Bin 2	58.55 (12.02)	0.767 (0.358)	58.17 (15.49)	0.770 (0.384)
Bin 3	65.81 (16.59)	0.739 (0.299)	56.43 (17.51)	0.699 (0.375)
Bin 4	68.70 (16.72)	0.701 (0.299)	56.32 (19.95)	0.734 (0.387)
Block 2				
Bin 1	56.09 (14.93)	0.685 (0.348)	56.86 (15.50)	0.610 (0.273)
Bin 2	64.10 (16.45)	0.639 (0.327)	61.66 (16.79)	0.596 (0.289)
Bin 3	73.08 18.16)	0.622 (0.291)	63.07 (19.96)	0.559 (0.285)
Bin 4	72.65 (17.73)	0.625 (0.258)	62.53 (20.09)	0.570 (0.220)
Block 3				
Bin 1	70.19 (20.39)	0.678 (0.353)	66.25 (19.59)	0.646 (0.274)
Bin 2	74.45 (19.41)	0.646 (0.288)	64.85 (21.61)	0.679 (0.334)
Bin 3	75.69 (17.34)	0.608 (0.276)	64.57 (21.66)	0.612 (0.297)
Bin 4	73.49 (16.09)	0.659 (0.278)	64.43 (19.61)	0.597 (0.258)

Condition and Time in the first and the second block remained significant ($ps<.003$). To interpret these effects, RM analyses of variance (ANOVAs) were conducted for accuracy and reaction time separately.

Accuracy

Children who received goal-directed instructions prior to the learning task were on average more accurate in responding compared to children who received implicit instructions. This effect was found for Block 1 and Block 3, but not for Block 2. For Time, we found a main effect for Block 1, as well as for Block 2, but not for Block 3, indicating that children learned the most during the first two blocks, in which all symbols were new. Last, significant interactions between Condition and Time were found for Block 1 and Block 2, but not for Block 3. Post-hoc tests showed that during Block 1, children who received goal-directed instructions started to differ from children who received implicit instructions from the third bin onwards ($ps<.007$). This is, children who received implicit instructions slightly increased in accuracy but tend to stagnate relatively close to the chance level, whereas children who were directed toward the goal increased further in accuracy until the last bin (see Figure 2). The same results appeared for Block 2.

Reaction time

For reaction time, no differences between the two conditions were found across all blocks. However, we found a main effect of Time in the first and the second block, but only the Time effect in Block 1 remained significant after FDR correction. No interaction effects were found ($ps>.219$) and therefore no follow-up tests were conducted.

To sum up, children who received goal-directed instructions prior to the training increased more in accuracy compared to the children who received implicit instructions in Block 1 and 2. Although children in the implicit group seemed to perform equally well in the first bins of the first two blocks, differences in learning performance became apparent in the later trials. In the third block, where all eight L-SS correspondences came together, children who received goal-directed instructions were on average more accurate compared to children who received implicit instructions. Regarding reaction time, children became faster in the first few trials, but then remained stable during the rest of the learning phase in both conditions. This suggests that this time effect is mainly due to becoming familiar with the task rather than a substantial influence of the instructions on the reaction time during the learning phase.

Passive L-SS integration immediately after and 1 day after training

A factorial MANOVA with accuracy and reaction time with Condition (Goal-directed vs. Implicit) as between-subjects variable and Congruency (congruent vs. incongruent trial) and Day (Day 1 vs. Day 2) as within-subjects variables was conducted. Results are visualized in Figure 3 and statistical values are reported in Table S2. This revealed a significant main effect of Condition,

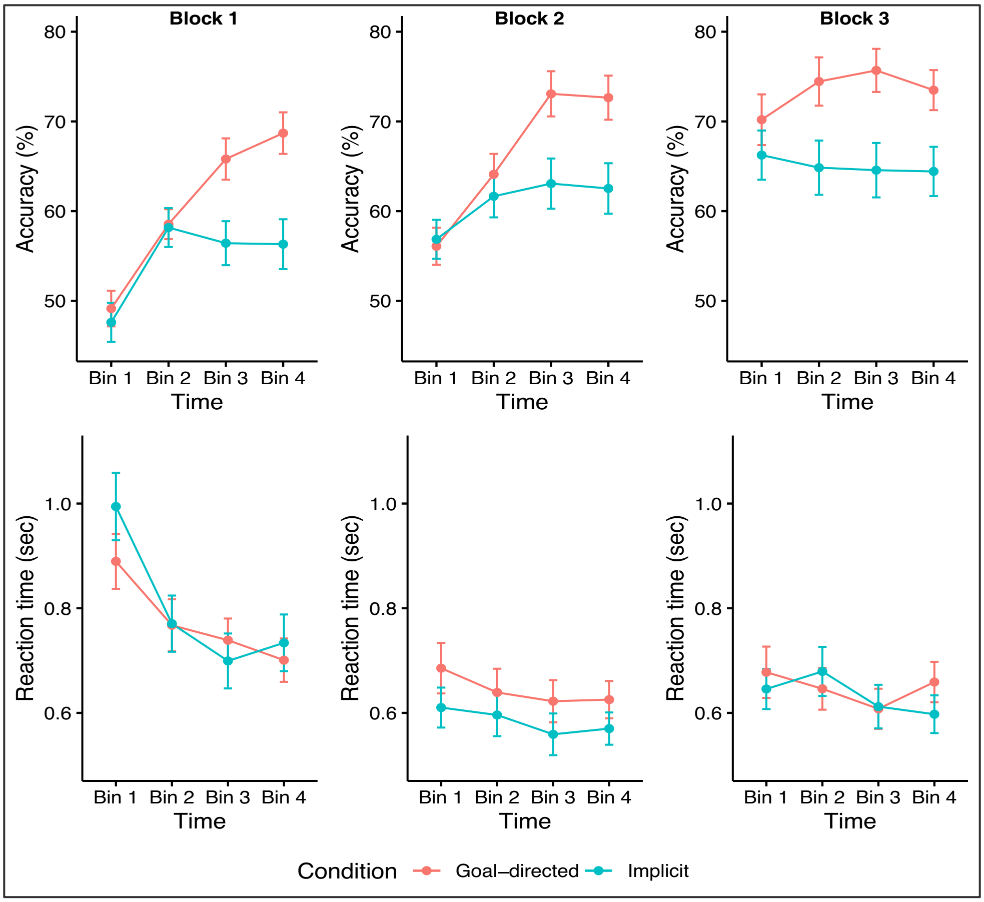

FIGURE 2 Learning curves during the letter-speech sound mapping task. Accuracy (percentage correct) and reaction time (in seconds) during the learning task for the goal-directed and implicit condition are presented separately, averaged across 4 bins of 18 trials for Block 1 and 2, and of 14 trials for Block 3 to map the learning curves. Children only learned four out of eight letter-speech sound (L-SS) pairs in the first block, and four new L-SS pairs in the second block, explaining why they start again around an accuracy level of 55% in the second block. In the third block, all eight L-SS pairs were presented together. Error bars represent standard errors.

Congruency, and Day, but no significant interaction effects (all *ps* > .071). Separate ANOVAs for accuracy and reaction time showed that children who received goal-directed instructions were on average more accurate (M = 81.76%) in the congruency task compared to the children who received implicit instructions (M = 70.93%). We found a significant main effect of Day, meaning that children were more accurate in the congruency task on the second day. No interaction effects including our manipulation of interest, that is, instruction, reached significance (all *ps* > .345) and therefore no follow-up tests were conducted. For reaction time, we found a significant main effect of Congruency, with children being faster in responding to congruent trials. This was especially true for children who received goal-directed instructions. In addition, children became faster in responding the next day, but this seemed to be especially true for the incongruent trials. However, these interaction effects did not remain significant after FDR correction and no main effect of Condition was found. Therefore, no follow-up tests were conducted.

Symbol knowledge and active L-SS integration immediately after and 1 day after training

A factorial MANOVA with symbol knowledge and reading within the artificial script (Real words and pseudowords) as dependent variables, Condition (Goal-directed vs. Implicit) as between-subjects variable and Day (Day 1 vs. Day 2) as within-subjects variable revealed a significant effect of Condition and Day (for statistical values see Table S3). Moreover, a significant interaction effect between Condition and Day was found. To interpret these effects, ANOVAs were conducted for symbol knowledge, reading artificial Dutch words and reading artificial pseudowords separately.

As shown in Table 4, children who received goal-directed instructions had a better knowledge of the newly learned symbols compared to those that received implicit instructions. Moreover, they seemed to be more fluent in using this knowledge in reading words within the artificial script (real words and pseudowords). A

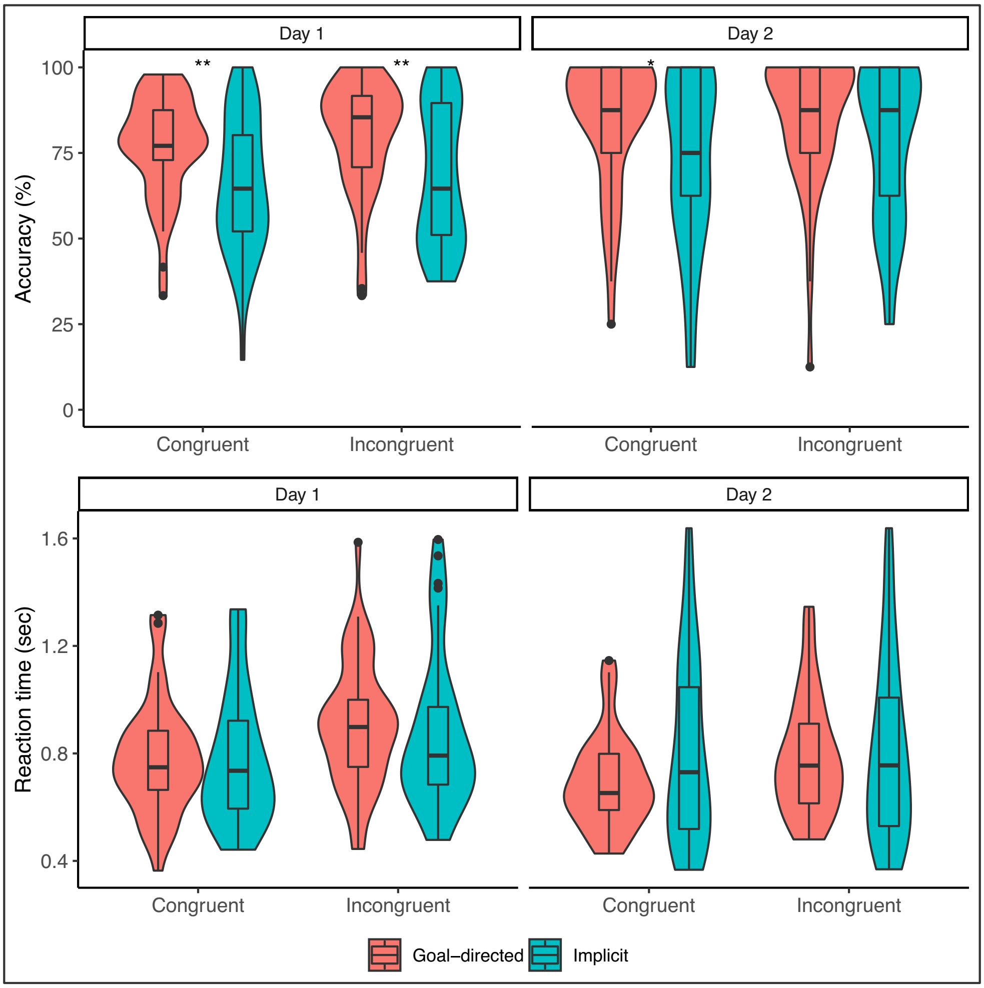

FIGURE 3 Performance during the congruency task. Accuracy and reaction time for congruent and incongruent trials during the congruency task immediately after the learning phase (Day 1) and after one night of sleep (Day 2) for both conditions separately. $^{**}p<.01$, $^{*}p<.05$.

TABLE 4 Means (SD) of outcome measures for both conditions separately.

	Goal-directed group		Implicit group	
Condition	**Day 1**	**Day 2**	**Day 1**	**Day 2**
Symbol knowledge	6.093 (2.121)	6.333 (2.101)	3.925 (3.018)	4.113 (2.991)
OMT real words	5.574 (4.657)	8.278 (5.304)	3.283 (4.469)	4.302 (5.033)
OMT pseudowords	4.741 (4.327)	6.981 (5.368)	3.019 (4.461)	3.736 (5.211)

Abbreviation: OMT, one-minute reading test.

significant main effect of Day indicated that children on average knew more symbols on the second day, and were more fluent in applying this knowledge after one night of sleep in both artificial reading tests. A significant interaction effect between Condition and Day for both reading tasks indicated that this time effect was most apparent in children who received goal-directed instructions compared to their implicitly instructed peers.

However, knowledge of the symbols is required to be able to decode the artificial words. Based on visual inspection of Figure 4, especially children who knew more than 5 symbols were able to decode the words within the artificial script. To this end, we conducted an exploratory analysis in which we only selected children who had learned 5 or more symbols on Day 1. In the goal-directed group, 79.63% of the children met this criterion, whereas only 43.40% of the implicitly

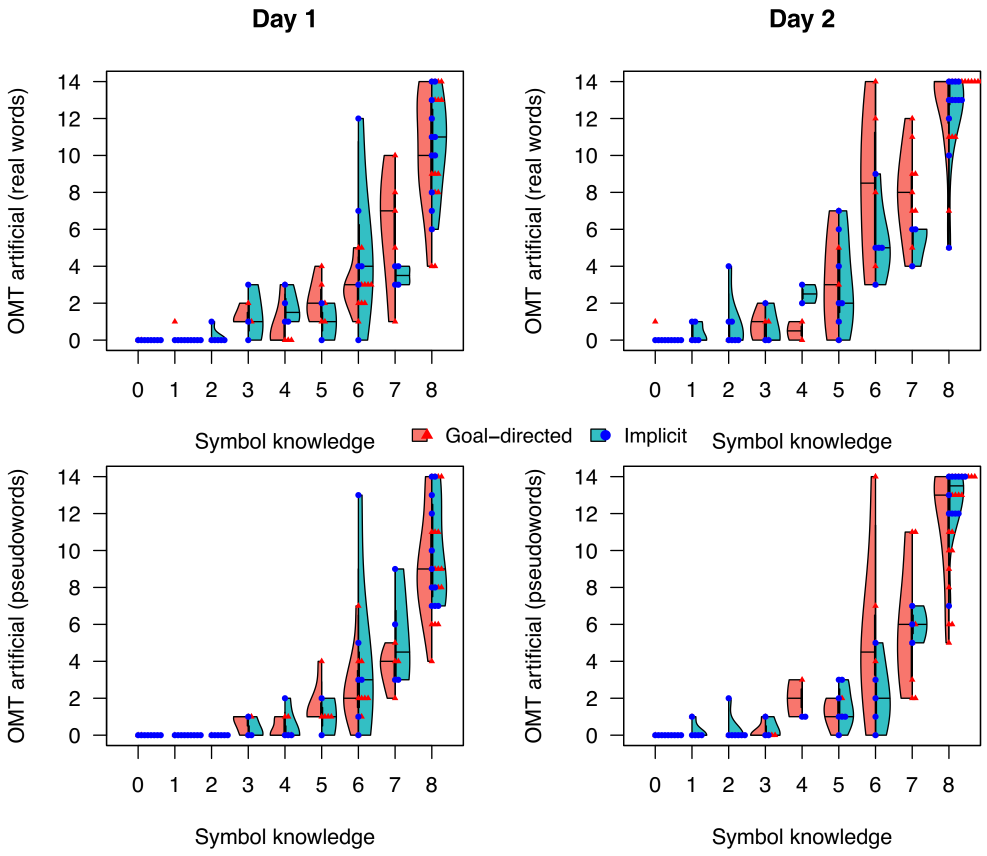

FIGURE 4 Reading scores in the artificial script in relation to symbol knowledge. Scores on the one-minute reading tests (OMT) within the artificial script resulting in real, Dutch words (top) or pseudowords (bottom). Results are visualized for the two conditions separately and show that especially children who knew more than 5 symbols were able to decode the words within the artificial script. On average, children became better in applying the learned knowledge after one night of sleep (Day 2; right) compared to immediately after the learning phase (Day 1; left).

instructed children met this criterion. An analysis of variance within this subgroup with reading within the artificial script (Real words and pseudowords) as dependent variable, Condition (Goal-directed vs. Implicit) as between-subjects variable and Day (Day 1 vs. Day 2) as within-subjects variable revealed again a significant main effect of Day. This is, children in both conditions profited from one night of sleep. By visual inspection of Figure 4, this seemed to be especially true for the goal-directed group, but this interaction effect between Day and Condition did not reach statistical significance (see Table S3).

In sum, children who received goal-directed instructions on average learned more symbols than their implicitly instructed peers. Although there seemed to be a difference between the conditions in applying the new knowledge in a time-limited reading task as well, these results were mainly driven by the differences in symbol knowledge. As can be seen in Figure 4, especially children who learned more than 5 symbols obtained better scores on the reading tasks, for both the implicit and the goal-directed condition. In both groups, children became more fluent in applying this knowledge after 1 day of sleep. Although this time effect seemed to be more pronounced for children who were directed toward the goal during the learning phase, this effect was non-significant.

External validity and reliability of the artificial learning paradigm in Dutch

External validity

To examine the external validity of our results, we compared reading fluency within the artificial script immediately after the learning task (Day 1) with the typical reading skills assessed with the OMT. As fluent reading requires knowledge of the symbols, only children who obtained full mastery of the new symbols were included in this analysis ($n = 32$). A one-tailed Pearson correlation test revealed a moderate correlation between reading rate in Dutch and reading rate in the artificial orthography for both real words ($r = .551$, $t(30) = 3.612$, $p < .001$) and pseudowords ($r = .410$, $t(30) = 2.459$, $p = .010$), shown in Figure 5. These results indicated that children who were better readers in Dutch tended to read better in the new artificial script as well, validating generalizations of our findings to reading in Dutch.

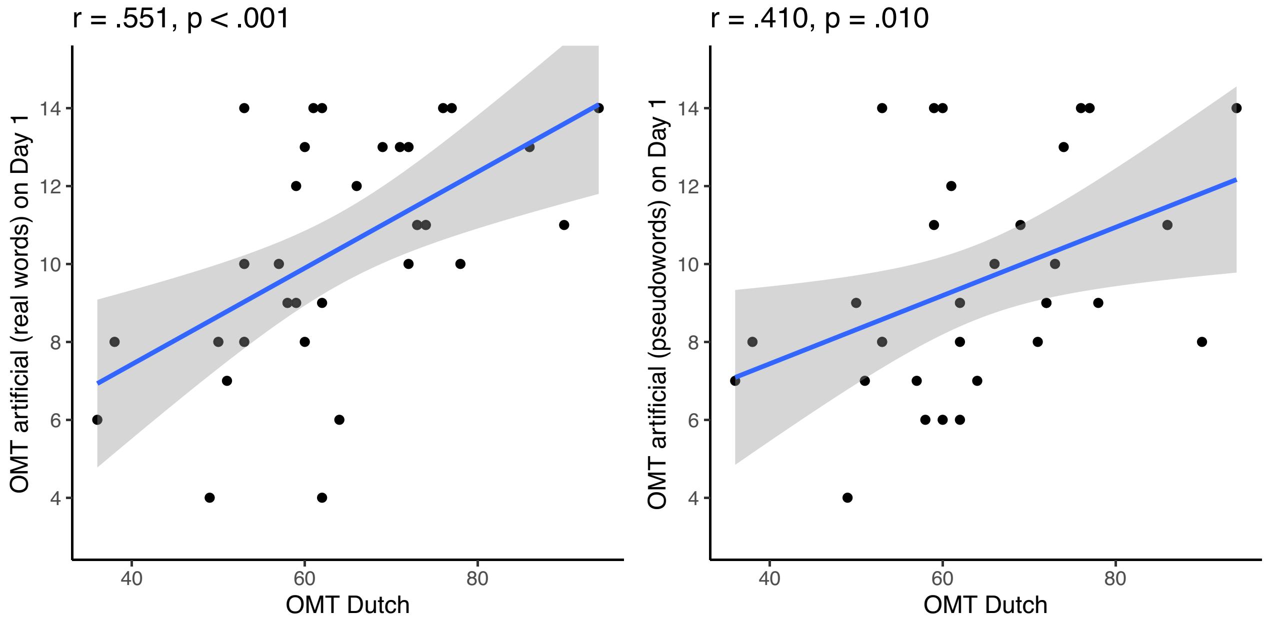

FIGURE 5 Correlations Between Reading Rate in Dutch and the Artificial Orthography. OMT, one-minute reading test. Correlations with the artificial orthography resulting in Dutch words (left) and pseudowords (right) immediately after the letter-speech sound learning task (Day 1).

Test–retest reliability

To examine the reliability of our artificial learning task, an alternative version of the task (Version B) was conducted in the same sample approximately 3 weeks later (M_{days} = 25.53, SD_{days} = 6.71). We conducted a one-tailed Pearson correlation test between the outcome measures from the original version and the alternative version of the task. For symbol knowledge assessed immediately after the learning phase, we found a significant correlation between the two versions (r = .560, t(104) = 6.900, p < .001). That is, children with better scores on the original version of the task also obtained better scores in the alternative version. Correlations between word reading fluency within the artificial script after learning symbols were much lower (r = .289, t(104) = 3.082, p = .003 for Dutch words, r = .301, t(104) = 3.224, p = .002 for pseudowords). Correlating the outcome scores between the two versions after one night of sleep (Day 2) revealed a significant correlation for symbol knowledge (r = .388, t(104) = 4.296, p < .001). Moreover, correlating the word reading fluency tasks within the artificial script on Day 2 for the original version and the alternative version of the task revealed significant correlations for both Dutch words (r = .405, t(104) = 4.515, p < .001) and pseudowords (r = .421, t(104) = 4.727, p < .001). Correlations between the learning blocks of the original and the alternative version of the task are presented in Supporting Information (Table S5).

DISCUSSION

This study aimed to shed a light on the role of top-down control in associative cross-modal learning and subsequent consolidation by manipulating the manner of instruction. We found that children who were directed toward the goal of the task were faster and more efficient in learning a new script and had a better learning outcome compared to their peers that had to rely on implicit instructions, suggesting that L-SS learning is more than merely mapping letters onto speech sounds using associative, statistical processes. Our results contribute to the long-standing debate on the role of top-down processes in acquiring new knowledge such as L-SS correspondences.

The results of the current study demonstrate the benefit of directing children toward the goal of the task prior to the learning process. More specifically, we found that goal-directed instructions significantly influenced the rate at which children learned new L-SS mappings. Differences in learning performance already became apparent in the second half of the first two blocks and persisted in the third block of the learning task in which all eight L-SS correspondences were presented. Although accuracy in implicitly instructed peers seemed to increase during the first trials of the learning phase, implicit learners stagnated around an accuracy level of 65%. These results suggest that implicitly instructed children were able to learn the new knowledge to some extent, but that learning was faster and more efficient when the learning process was preceded by clear, explicit instructions.

Regarding response latencies, we did not find any evidence for differences between the two conditions during the learning phase. Previous studies showed that the quality of audio-visual integration of L-SS correspondences in the brain is reflected in the time course of the neural activation of target units, and consequently manifests in the behavioral response latencies during identification (Blomert, 2011). However, in the first phase of learning to read, decoding is effortful and non-automatic, which is gradually replaced by fluent and effortless reading after much exposure and reading practice (Karipidis et al., 2021; Romanovska & Bonte, 2021). As automatic integration of letters and speech sounds might take up to 2 years of reading instruction, our 20-min learning task might not be sufficient to elicit differences in response times. In the congruency task, in which children had to indicate whether a congruent or incongruent trial was presented, children were faster in identifying congruent trials. Although most studies examined this congruency effect on a neural rather than on a behavioral level (e.g., Xu et al., 2018; Žarić et al., 2014), this is in line with some older studies (Dijkstra et al., 1993; Herdman et al., 2006) that interpreted this effect as multisensory facilitation during processing congruent grapheme-phoneme stimuli.

Instruction manipulation led to differences in symbol knowledge immediately after the learning phase, with children who received goal-directed instructions on average knowing more symbols than their implicitly instructed peers. The difference in applying this new knowledge in a time-limited reading task seemed to be mainly driven by the differences in symbol knowledge. Especially children who had learned more than five symbols obtained better scores on the reading tasks, suggesting a certain threshold that was needed to read the monosyllabic words. Hence, our results suggest that goal-directed instructions were beneficial for faster and more efficient learning and led to a better knowledge of the symbols, but we did not find statistical evidence for better application of the knowledge on top of the symbol knowledge effect.

To get more insight into how top-down control influenced the consolidation of newly learned L-SS correspondences, we examined the effect of one night of sleep on the outcome measures. In the passive L-SS integration task, both children who received goal-directed instructions and their implicitly instructed peers were more accurate in deciding which trials were congruent or incongruent on the second day. In addition, they became faster in making this decision. Although especially children who received goal-directed instructions were the ones that became faster, there was no significant effect of the instruction manipulation on the accuracy. However, as children who received goal-directed instructions already reached high accuracy levels on the first day, immediately after the learning phase, they could not increase as much compared to their implicitly instructed peers on the second day, possibly explaining why we failed to find this effect. For the active L-SS integration task, in which children needed to read words that were written within the artificial script, children read significantly more words on the second day. One explanation might be that children remembered words from the previous session and therefore were more fluent on the subsequent day. However, as we also found evidence for decreased response times during the congruency task after one night of sleep, these results can be explained by the consolidation of the new knowledge rather than a word recognition effect. This is, memory for newly learned information is enhanced following a period of sleep, making it easier to retrieve information (Klinzing et al., 2019; Mazza et al., 2016) and therefore resulting in improved performance in the next session. Recent findings of Wang et al. (2022) showed that even short naps facilitated the acquisition and application of L-SS mappings in preschool children. In our study, both conditions benefitted from offline sleep consolidation, but this effect seemed to be pronounced for the goal-directed group. This finding suggests that goal-directedness might help with better integration of letters and speech sounds after already one night of sleep. Bitan and Booth (2012) reported similar findings, namely, that participants whose attention was directed toward the correspondence between individual artificial letters and their corresponding Latin phonemes benefited the most from offline improvement.

The second aim of our study was to examine the external validity and test–retest reliability of the used artificial learning paradigm. We found that children who were better readers in Dutch tended to be more fluent in decoding the new artificial script as well. This was especially true for decoding the artificial words that resulted in a real Dutch word. The same result was found in the study of Aravena et al. (2013), implying that our findings can be applied to reading in the Dutch language and highlighting the applicability of artificial script learning paradigms in studying individual differences in early reading development. To examine the reliability of our artificial learning task, we computed correlations between the outcome measures of the original version of the task and the alternative version that was conducted approximately 3 weeks later. We found significant correlations between the two versions for symbol knowledge, the reading outcomes on Day 1 and the reading outcomes on Day 2. However, the correlation between the two reading tasks on Day 1, immediately after learning, was rather low. Skimming the data revealed high variability in children's outcomes. Some children learned more symbols after the alternative version and obtained higher reading scores after learning the second script and likewise, children who learned fewer symbols obtained lower reading scores in the alternative version. Others learned as many symbols in the alternative version as in the original version and obtained similar reading scores in both versions. As argued before, knowledge of the symbols is needed to accurately decode the words, and especially children who learned more than 5 symbols were able to decode the words. As a result, although symbol knowledge in both versions was moderately correlated, reading scores might have increased exponentially as a result of an increase in symbol knowledge. For example, children who had learned two symbols in the original version and three symbols in the alternative version did most likely obtain similar reading scores in both versions, whereas children who had learned five symbols in the original version and six symbols in the alternative version most likely increased exponentially in their reading outcome, therefore returning low correlations between the two versions. Another explanation might be that some children remembered the task and therefore were faster in applying the new knowledge the second time and therefore obtained higher reading scores. Last, although symbols and speech sounds were carefully matched (i.e., diphthongs and monotones in both versions), the two versions might differ in difficulty. As we wanted to construct artificial combinations that resulted in real Dutch (or pseudo)words, the word lists slightly differed in positions of vowels, consonants, and diphthongs, possibly resulting in differences in how easy these could be decoded. These observations are merely anecdotal and therefore need further research to be confirmed. A future study might want to examine the test–retest reliability with the same version and a longer period in between to control for memory effects. Despite these considerations, these trends nicely highlight individual differences in learning to read and we therefore believe that such an artificial learning design is a promising platform to investigate early reading skills and a potential tool for the prevention of reading difficulties.

Our findings relate to the major debate concerning the role of instructions in skill learning. Constructivists suggested for decades that people learn best in a minimally guided environment, based on the principles of discovery learning (e.g., Bruner, 1961). There are however empirical and theoretical grounds for questioning this. The current study demonstrated that directing children's attention toward the goal of the task shortens the course of acquisition and eventually leads to a better learning outcome. This means that in a rather transparent language, that is, Dutch, children do better when they receive direct instructions rather than when they need to discover underlying regularities on their own. In contrast, technology-based interventions which are recently gaining field often rely on implicit, statistical association mechanisms without a clear goal that is related to the new knowledge. Our results suggest that, even in serious games, implementing instructions that direct the learner toward the goal and stress mastery of knowledge might be a key design factor to obtain the most efficient learning. In learning to read, explicit instruction is required to direct attention toward visual and auditory information, after which visual and auditory information is combined into audiovisual objects in multisensory brain regions (Romanovska & Bonte, 2021; Stein & Stanford, 2008). Repeated practice consequently feeds implicit learning mechanisms and ensures that audiovisual objects are stored in the neocortex for fast and automatic retrieval (Klinzing et al., 2019). This was also found in the work of Aravena et al. (2013), in which the authors argued that at least some explicit preparation is required to strengthen the benefits of implicit, associative training. Likewise, Rastle et al. (2021) showed that very few adults who had to rely on discovery learning performed on the same level as the adults who received explicit instructions in a task where they had to learn how to read novel words printed in two artificial alphabets, even after 18 h of training. From a neural perspective, this learning process is accompanied by an inverted developmental U-curve in cortical responses to text and audiovisual stimuli, with maximal activations in beginning readers when reading is effortful that slowly decrease when reading becomes automatized and fluent (Fraga González et al., 2021). From an educational perspective, Wouters and van Oostendorp (2013), argued that clear instructions help learners to use their cognitive capacity efficiently and therefore improve learning. A recent review by McTigue et al. (2020) corroborated this notion. The authors synthesized 28 empirical studies that examined the effect of playing GraphoGame, an adaptive serious game that promotes sound-symbol connections to prevent reading difficulties, and factors that moderated the outcome measures. Results suggested that adult involvement was a critical parameter when individuals had to learn from a serious game. More specifically, they argued that adult involvement helped learners to efficiently select and organize new information, which seems to have a similar effect as the goal-directed instructions in the current study.

Although this study provides some important insights into how top-down control contributes to L-SS learning and subsequent consolidation, some limitations need to be taken into account. First, this study did not assess common predictor measures such as phonemic awareness and rapid automatized naming. However, previous studies suggested that the outcome of a comparable learning task still uniquely contributed to the variance of reading performance (Gellert & Elbro, 2017; Horbach et al., 2015). The same is true for short-term memory. Although verbal short-term memory is needed to memorize speech sounds and to merge sounds into whole words (Gathercole et al., 2006), studies showed that a sound-symbol paradigm was positively associated with reading performance over and above short-term memory. Second, our results suggest that sleep consolidation increases L-SS knowledge. However, we did not include any measure to quantify sleep quality, which might have influenced the consolidation process. Likewise, results might be influenced by motivation. Previous studies have shown that prompting children to pursue a specific goal can considerably impact intrinsic motivation (Barron & Harackiewicz, 2001), and consequently the quality of learning. In line with this, our goal-directed instructions, that is, learn the symbols to crack a secret code at the end, might have been more motivating for the child compared to the implicit instructions. Including a subjective measure to assess children's motivation during the task in future studies would allow us to get a more detailed insight into the dynamic interplay of attentional and motivational influences and strengthen the conclusions about the benefit of goal-directed instructions. Moreover, although gender distribution was not significantly different between our goal-directed and implicit instruction condition, gender could still influence the results given possible attentional and motivational differences between girls and boys. A future study should use stratified randomization, which might prevent gender imbalance between the two conditions. Third, all our participants received several years of formal reading instruction, meaning that they were already aware that letters correspond to sounds. This may have helped them during the L-SS learning task, although the learning curves showed that learning the new correspondences was nontrivial. Last, due to our design, it was not possible to examine the influence of goal-directed instructions on the application of the new knowledge without accounting for differences in symbol knowledge. Although we were interested in the full range of individual differences in reading levels, we had to select a subgroup of children who obtained full mastery of the new symbols to compare reading fluency within the artificial and Dutch script, as fluent reading requires the knowledge of all symbols. Moreover, for children who could not learn a substantial number of the symbols, it was rather difficult to perform the reading tasks. As our reading tasks comprised short, monosyllabic words, children could guess the word when they for example knew two out of three symbols, whereas some would immediately say that they did not know the answer. It is not known to what extent our reading outcomes were influenced by such personality traits, as for example introversion and performance anxiety. Although this again nicely highlights individual differences between participants, future studies might want to employ either a longer learning task to ensure learning or an adaptive design in which participants need to obtain a predefined level of performance before moving to follow-up tasks (e.g., Karipidis et al., 2017).

In sum, our findings contribute to understanding the mechanisms that are associated with typical and atypical audiovisual integration at the early reading stage as well as to the long-standing debate concerning the role of top-down control in cross-modal learning. We showed that goal-directed instructions significantly influence how children learn new L-SS correspondences after only 20 min of learning. In addition, we showed that children in both conditions profited from offline sleep consolidation, but this effect was most apparent in the goal-directed group. The influence of top-down control on L-SS binding highlights this mechanism as a potential contributor to the atypical audiovisual integration in individuals with dyslexia, and thus, appears pertinent for intervention research. Our results also suggest that learning to read should be considered a multidimensional process influenced by other mechanisms such as top-down control and motivation, although most dyslexia research still focuses on one single underlying deficit and dyslexia diagnoses typically exclude co-occurring cognitive or neurological deficits. Future work should test this paradigm in a clinical sample comprising children with dyslexia and attention deficit hyperactivity disorder to explore the role of goal-directedness in learning to read on a behavioral and neural level and include test moments after a longer period to examine retention. Understanding such mechanisms is particularly relevant to educational and clinical practice, which are recently benefiting from new tools based on implicit associative learning (e.g., serious games). Better identification of individual differences in these mechanisms is of great importance for literacy policy, and for timely, effective therapeutic remediation strategies, as these can be better matched to the needs of the child.

AUTHOR CONTRIBUTIONS

Cara Verwimp and Jurgen Tijms were involved in the conception and design of the study. Cara Verwimp performed the analyses and wrote the first version of the manuscript. All authors gave substantial feedback on the manuscript and approved the final version.

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CONFLICT OF INTEREST STATEMENT

None declared.

DATA AVAILABILITY STATEMENT

The data and code necessary to reproduce the analyses presented here are publicly accessible. The materials are available from the first author upon reasonable request. Most analyses were pre-registered or were identified as exploratory in the manuscript otherwise. The data, code and the preregistration for this research are available at Open Science Framework upon publication of this manuscript (https://osf.io/2cge6).

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SUPPORTING INFORMATION

Additional supporting information can be found online in the Supporting Information section at the end of this article.

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