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ARTICLE

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A randomised proof-of-concept trial on the effectiveness of a game-based training of phoneme-grapheme correspondences in pre-readers

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Abstract

Background: Learning which letters correspond to which speech sounds is fundamental for learning to read. Based on previous experimental studies, we developed a serious game aiming to boost letter-speech sound (L-SS) correspondences in a motivational game environment.

Objectives: The goal of this study was to determine the efficacy of this game in training L-SS correspondences in pre-readers. Additionally, an extended version of the game was developed given the importance of handwriting in audio-visual integration. We established whether including a motoric component in the game boosted the letter-speech sound training on top of the effect of the game without the motoric component.

Methods: One-hundred forty-five kindergartners were randomly allocated to play either the standard audio-visual version of the game, the motoric version or a control math game. All children were pre- and post-tested on L-SS knowledge and reading accuracy.

Results and conclusions: We found that playing the game enhanced pre-readers' L-SS knowledge, but not reading accuracy, after a short, intensive intervention period of 3 weeks. However, children who played the motoric version of the game did not differ significantly from either the standard or the control condition.

Implications: This game was efficient in training L-SS correspondences in pre-readers. These results suggest that this game might be useful as a preventive evidence-based intervention for at-risk children in kindergarten who might benefit from a head start before learning how to read. Future studies are needed to examine whether a longer intervention period results in L-SS knowledge being translated into reading skills.

KEYWORDS
game-based intervention, learning to read, letter-speech sound automatisation, serious gaming

1 | INTRODUCTION

The importance of reading is uncontested in today's society. Learning to read involves successfully linking visual to auditory information. Learning which letters correspond to which speech sounds takes up to 1 year of formal reading instruction in Dutch (Vaessen & Blomert, 2010). However, automatising this process, a fundamental building block for fluent reading, takes much longer and requires much exposure. Based on previous experimental studies, we developed a serious game aiming to boost letter-speech sound correspondences in a motivational game environment. The purpose of the present study was to investigate the efficacy of this game and the effect of implementing a motoric component in the game in children who have not learned how to read yet, which is of great importance to examine whether this game can serve as a preventive intervention for developing severe reading difficulties in the future.

Although the vast majority of the population learns how to read relatively effortlessly, 3%–10% of children worldwide experiences severe difficulties with reading acquisition (Snowling, 2013). These difficulties are typically identified after several years of formal reading instruction, that is, after the most effective time for reading intervention has passed, referred to as the dyslexia paradox (Ozernov-Palchik & Gaab, 2016). As a result of this late diagnosis, the gap in reading performance between children with reading difficulties and their typically developing peers tends to widen over time (Vaughn et al., 2009). In addition, children suffer from adverse long-lasting effects, such as feelings of shame, anxiety, loneliness and depressive thoughts (Hendren et al., 2018; Livingston et al., 2018; Mugnaini et al., 2009; Xiao et al., 2022). Therefore, it is of great importance to identify and prevent reading difficulties at the earliest age possible.

The hallmark of learning to read in an alphabetic language, such as Dutch, is the acquisition of the alphabetic principle. That is, one needs to understand how written language (graphemes) relates to spoken language (phonemes; Castles et al., 2018). When learning how to read, explicit instruction is required to direct attention towards visual and auditory information, after which this information is combined into audio-visual objects in multisensory brain regions (Stein & Stanford, 2008). After explicitly teaching these correspondences, children slowly shift towards automatised word reading (Karipidis et al., 2021; Romanovska & Bonte, 2021). Subsequently, children start to decode unknown words autonomously and create orthographic representations for successfully decoded words, known as the 'self-teaching theory' (Share, 1995). Although these correspondences can commonly be learned within 1 year of formal reading instruction in the Netherlands, developing fully automatised associations involves a substantially more protracted developmental pathway that takes up to about 4 years and requires much exposure (Froyen et al., 2009). Behavioural and neuroimaging studies have reported that strong integration of letters and speech sounds is associated with proficient reading whereas poor integration is associated with dysfluent reading (Blau et al., 2009; Froyen et al., 2009, 2011; Žarić et al., 2014). The difficult pathway towards this L-SS automatisation in children with reading difficulties indicates the need for high exposure to and repeated practice of these correspondences.

Providing intensive teacher support to provide high exposure for all at-risk children is economically and practically unfeasible. One way to provide this support in different settings such as schools and at home is with game-based interventions (Lassault et al., 2022; Neumann, 2018; Patel et al., 2021; Richardson & Lyytinen, 2014; Vanden Bempt et al., 2021). Game-based interventions have increasingly gained interest in recent years to train academic skills (Jaramillo-Alcázar et al., 2021; Lassault et al., 2022; Skiada et al., 2014; Yildirim & Surer, 2021). These games commonly comprise multimodal features (e.g., sounds, animations, text) that stimulate young children's attention and enhance motivation (van de Ven et al., 2017). This might be especially necessary for children who are struggling to master basic academic skills, such as reading, and need to remain motivated to practice the compromised skill for a prolonged period (Froyen et al., 2009; Stafford & Vaci, 2022). In this context, games are the ideal combination of massive, targeted exposure while maintaining the child's motivation and engagement (Prensky, 2003). In addition, immediate and continual feedback prompts children to update their knowledge and improve their learning outcomes (Muis et al., 2015), without the need for an external resource such as a teacher or peer. Their adaptive algorithms allow for individualised, targeted practice, as they provide enough cognitive stimulation while minimising failure experiences, making it appropriate for each learner's developmental stage. Altogether, these features make game-based interventions a low-cost and practical tool to support individual learning in an educational context (Jaramillo-Alcázar et al., 2021; Lämsä et al., 2018).

Although many games targeting math and literacy skills have been developed in recent years, studies reporting on their effectiveness and features that moderate this effectiveness are scarce and yield mixed results (Kim et al., 2021). A recent review by McTigue et al. (2020) has synthesised findings from 28 studies that examine the effectiveness of GraphoGame, a game that was initially developed for dyslexia prevention but further developed as an intervention focusing on the connections between written and spoken language representations (Lyytinen et al., 2009). Given that behavioural and neuroimaging studies have shown that strong integration of letters and speech sounds is associated with proficient reading, one would expect that intensive training of these connections would lead to enhanced word reading performance (Blau et al., 2009; Froyen et al., 2009, 2011; Žarić et al., 2014). Multiple studies reported a significant increase in sub-lexical skills, such as letter knowledge or phonological processing (McTigue et al., 2020). In addition, studies that involved high adult interaction (i.e., adults providing technological and motivational support) reported better word reading skills ($g = 0.48$). However, estimation of the overall mean effect size ($g = -0.02$) indicated that a transfer to word reading was not consistently found, especially in studies in which the game was played in solitude. To get more insight into which game features exactly contribute to better learning, Wouters et al. (2013) proposed to compare learning outcomes of learners who played different versions of the same game, referred to as a value-added approach (Mayer, 2011). In the current study, we employed such a value-added approach to examine a feature that is assumed to support pre-readers in shifting from letter-speech sound knowledge to accurate word decoding: a sensori-motoric component.

Successful letter-speech sound learning is accompanied by functional specialisation of the left ventral occipitotemporal cortex, a core region for fast recognition and processing of print (Brem et al., 2010; Karipidis et al., 2017; Pleisch et al., 2019). Studies have shown greater brain activation when letter learning was combined with handwriting practice than with other types of practice including typing and visual recognition training (James & Atwood, 2009; James & Engelhardt, 2012). These results suggest that motor experience may facilitate the integration of auditory and visual word form information, and consequently change visual processing (Guan et al., 2021; James, 2017). Moreover, studies reported that handwriting training did not only shorten the acquisition course (Bosse, 2015; Guan et al., 2011; James, 2017; Wiley & Rapp, 2021), but this knowledge was also extended to untrained tasks such as word reading (Wiley & Rapp, 2021). Although this sensorimotor approach has already been proposed to be implemented in education when teaching children to recognise shapes such as letters (Montessori, 1912), studies examining the effect of this motoric component on top of extensive exposure in the context of a game-based reading intervention remain scarce.

The serious game KlankKr8 was developed as a collaboration between a national clinical centre for children with learning difficulties and technical partners based on previous experimental studies (e.g., Aravena et al., 2013, 2018; Guerra, 2022). As most game-based interventions concerning reading considered an English-speaking or Finnish-speaking sample (e.g., McTigue et al., 2020), the game used in the current study was developed in Dutch. Regarding orthographic consistency, Dutch is a semi-transparent language because it has few rules and a small proportion of irregular words (Schmalz et al., 2015). This makes it less complex than English which has a great number of irregular words that cannot be sounded out phonetically, but more complex than Finnish, which is highly consistent in how speech sounds are mapped onto visual symbols (Schmalz et al., 2015). This game systematically and explicitly introduces Dutch letter-speech sound correspondences in a highly engaging game environment. Children first become familiarised with Dutch letters and speech sounds after which they are massively exposed to the correspondences. Besides the standard audio-visual version of the game, which specifically aims to train letter-speech sound mappings, we developed a version in which children practiced the motoric movement associated with the letters as well. The aim of the current study was to examine the efficacy of these two game versions in improving letter-speech sound knowledge, potentially giving more insights into how we can intervene on the letter-speech sound automatisation deficit associated with reading difficulties. As proposed by Wouters et al. (2013) and Mayer (2011), we followed a value-added approach in which one compares a standard version of a game to an enhanced version. That is, we aimed to examine the effect of adding a motoric component to the game on the learning outcomes, on top of the effect of the standard audio-visual version.

To this end, we used a randomised controlled trial with three conditions: (1) the standard audio-visual version of the game; (2) the motoric version of the game and (3) a control game (mathematical training). In line with the dyslexia paradox (Ozernov-Palchik & Gaab, 2016), we aimed to examine the effect of the game before children received formal reading instruction, and therefore this study was conducted in kindergartners. All children were tested prior to the intervention period during the first half of the second year of kindergarten. Measures included letter-speech sound knowledge, phoneme awareness and reading accuracy. Children were randomly allocated to one of three conditions and played the game for an intensive period of 3 weeks. After the intervention period, letter-speech sound knowledge and reading accuracy were assessed again to quantify the effect of the intervention. We expected that children who played either the standard version or the motoric version of the game would improve more in letter-speech sound knowledge compared to the control condition and that playing the motoric version (i.e., the enhanced version of the game) would even lead to stronger gains given the importance of handwriting in facilitating the integration of auditory and visual word form information. In addition, we aimed to examine whether this game could enhance reading accuracy.

2 | METHOD

2.1 | Participants

Based on an a priori power analysis for a one-way fixed effect analysis of covariance with three levels, 42 cases per cell were required to obtain a power of 0.90. In anticipation of a possible attrition rate of 15%, we aimed to include 50 participants in each condition ($N = 150$). Six primary schools in the Amsterdam metropolitan area participated. The only inclusion criteria were that children were required to be in the second year of kindergarten (i.e., just before receiving formal reading instruction) and had Dutch as their mother tongue (mono or multilingual). Schools sent information letters to all parents of children in the 2nd year of kindergarten ($N = 222$). After receiving active consent from both parents and their children, children were randomly assigned to one of three conditions using a computerised, within-classroom randomisation to control for the influence of teacher and school. In total, 177 parents and children gave consent, of which six children had to be excluded because they were still in the first year of kindergarten ($n = 5$) or already in Grade 1 ($n = 1$). This resulted in 58 children in the standard audio-visual condition (AV), 57 children in the motoric condition (AV+) and 56 children in the control condition (CC). As can be seen in Figure 1, some children had to be excluded from the final sample due to missing data or because they did not have enough playtime. The final sample comprised 145 children in the last year of kindergarten (66 boys) with a mean age of 63.56 months ($SD = 4.47$).

2.2 | Design and procedure

The intervention was a single-blind randomised controlled trial in which children were randomly allocated to one out of three conditions. This study was approved by the ethical committee of the local university and pre-registered at Netherlands Trial Register (Trial NL9604). All children were tested individually prior to the intervention period (i.e., baseline) during the first half of the second year of kindergarten, including measures of letter-speech sound knowledge, phoneme awareness and reading accuracy. The individual sessions lasted approximately 20 min and were conducted by trained research assistants who also guided the intervention to reduce the burden on schools. After the baseline measures, children played one of the serious games for a period of 3 weeks in total (15 min/5 days/week).

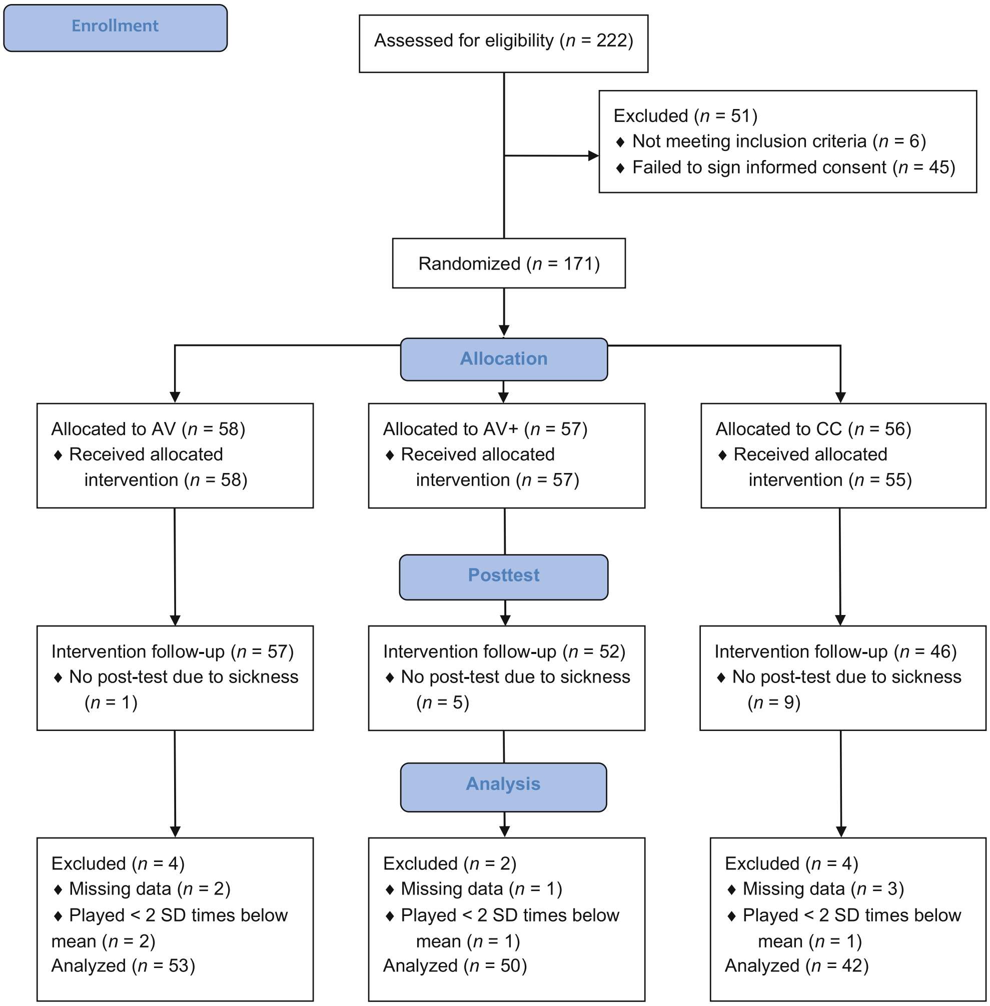

FIGURE 1 Flowchart showing enrolment and allocation of participants (adapted from Moher et al., 2010)

Intervention sessions took place in a spare classroom during regular school hours. Tablets with headphones (IMG stageline MD-5000DR) were positioned in a spare room and children were brought in class-by-class. Each child had a pre-created profile for either the experimental game or the mathematical control game to ensure that children played under the same profile for the entire intervention period. The tablet games closed themselves after 15 min to ensure that all children had the same amount of playtime. Post-tests were done by research assistants who did not guide the intervention for that specific classroom, and these research assistants were therefore blinded to the intervention condition of the child. Parents and children were also blinded to intervention assignment but were debriefed at the end of the trial period. Children allocated to the control condition received the opportunity to play the serious game after the trial period ended.

2.3 | Assessment battery

2.3.1 | Outcome measures

Letter-speech sound knowledge was measured with a letter-speech sound identification task that was programmed in PsychoPy3 (Peirce et al., 2019). Children heard a Dutch speech sound through headphones which was accompanied by two Dutch letters (or letter combinations) on a computer screen; one on the left side and one on the right side of the screen (see Figure 2). They had to indicate which letters corresponded to the sound by pressing the left, yellow ('A' key) or right, blue button ('L' key). Children received no feedback on whether the answer was correct, but a spaceship appeared on the side of the selected answer to indicate that the computer had recorded their answer (see Figure 2). If no response was given after 4000 ms a picture of a snail appeared prompting the child to respond faster. Each Dutch speech sound, 44 in total, was presented four times, resulting in a total of 160 items with a break in between. As the task was self-designed, no norms were available and, therefore, raw scores were used in the analyses. The score was calculated as the number of correct items with a maximum score of 160.

Reading ability was measured with a one-minute reading task. Children were asked to read as many words as possible within 1 min. The task consisted of 20 carefully selected words with increasing difficulty that were all known to Dutch toddlers according to a list of basic vocabulary in kindergarten in the Netherlands (Basiswoordenlijst Amsterdamse Kleuters; Mulder et al., 2009). As the task was self-designed, no norms were available and, therefore, raw scores were

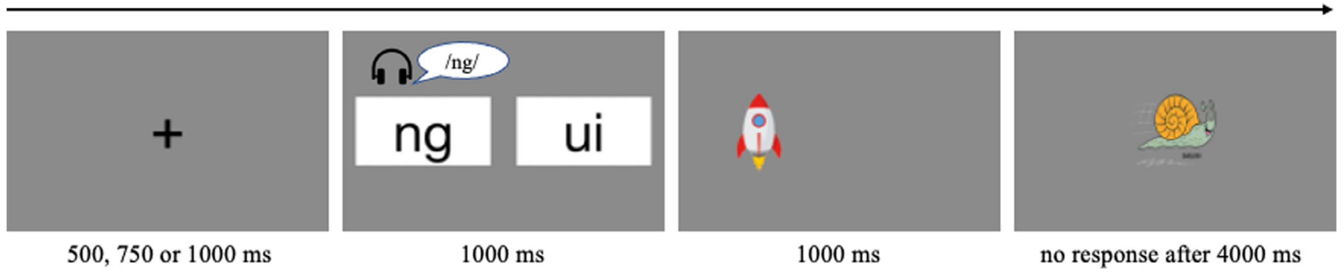

FIGURE 2 Task design of the letter-speech sound knowledge task

used in the analyses. The score was calculated as the number of correctly read words within the time limit of 1 min, with a maximum score of 20.

2.3.2 | Baseline measures

Phoneme awareness was measured with a beginning phoneme identification task (Boets et al., 2010). Each item was visually presented, followed by four pictures. Children had to indicate which items had the same beginning phoneme as the target item. All items represented high frequent one-syllable Dutch words and were named for the child before they were prompted to give the answer. To prevent guessing, the distractor alternatives contained a correct, semantically related, phonologically related and non-related answer. The task consisted of 10 items preceded by two practice items to which the researcher gave feedback ensuring that the child understood the task. The score was defined as the number of correctly answered items with a maximum score of 10. Cronbach's alpha was 0.59 at age 5.4 (Boets et al., 2010).

Non-verbal intelligence was measured with Raven's 2 Progressive Matrices (CPM-2; Raven et al., 1998). Children had to indicate the missing element in a pattern out of five answer alternatives. The task comprised three sets of 12 items each with increasing complexity. Small groups of children were seated in a silent room and received 20 min to fill out all 36 items individually after they received feedback from the researcher on the practice items to ensure that they understood the task. The number of correctly answered items out of 36 was norm-referenced afterwards. The reliability coefficient based on a Fisher's *z*-transformation was 0.82.

2.4 | Interventions

2.4.1 | Audio-visual only condition

In the first condition, children played the standard version of the game. The purpose of this game was to learn letter-speech sound correspondences with high exposure in a motivational environment. The game took place in a space environment in which an astronaut systematically introduced all Dutch speech sounds (44) and their corresponding letter-representations to the child with increasing difficulty. The game comprised eight levels, built up as different star constellations. Each constellation consisted of multiple speech sounds children had to learn, with the first star system comprising short vowels, and the more complex speech sounds like /eeuw/ appearing in the later levels. The astronaut first introduced a letter with its corresponding speech sound and explained how it should be pronounced. A variety of intonation patterns was introduced for each speech sound, resembling the different pronunciations in real life. Afterwards, children had to tap the bullets with the corresponding letters (see Figure 3a). Immediate feedback was provided; when the correct bullets were tapped, a green smiley appeared, whereas a red smiley appeared when a wrong bullet was tapped (Figure 3c). By tapping the correct letters children collected stardust which made their start grow. The game was adaptive in nature meaning that speech sounds that elicited errors or slower response rates were repeated and subsequently presented more often. In addition, misidentified letters were temporarily presented more frequently as distracter stimuli (see e.g., Lyytinen et al., 2009). This implies that children were provided with exercises at their own level, that is, neither too easy which could result in less engagement, nor too difficult which may cause feelings of failure. In addition, the multimodal features of the game in combination with external motivational components, such as time bonuses and rewards for obtained levels, contributed to the enjoyableness of the game.

2.4.2 | Audio-visual condition with motoric component

In the second condition, children played an extended version of the game [hereafter referred to as motoric condition (AV+)]. Getting familiar with the Dutch speech sounds and tapping the corresponding bullets was accompanied by instructions on how a certain letter had to be written. This writing motion was first introduced by the astronaut after which children had to write the letters on the tablets themselves. Considering the premature fine motoric skills of kindergartners, children used their index finger to draw the letters on the tablet instead of using a pen or pencil. This writing motion was guided by a spaceship that followed the movement of the child's finger while writing the letter. When children did not follow the correct shape of the letter, the rocket stopped until they continued following the correct shape of the letter (see Figure 3d).

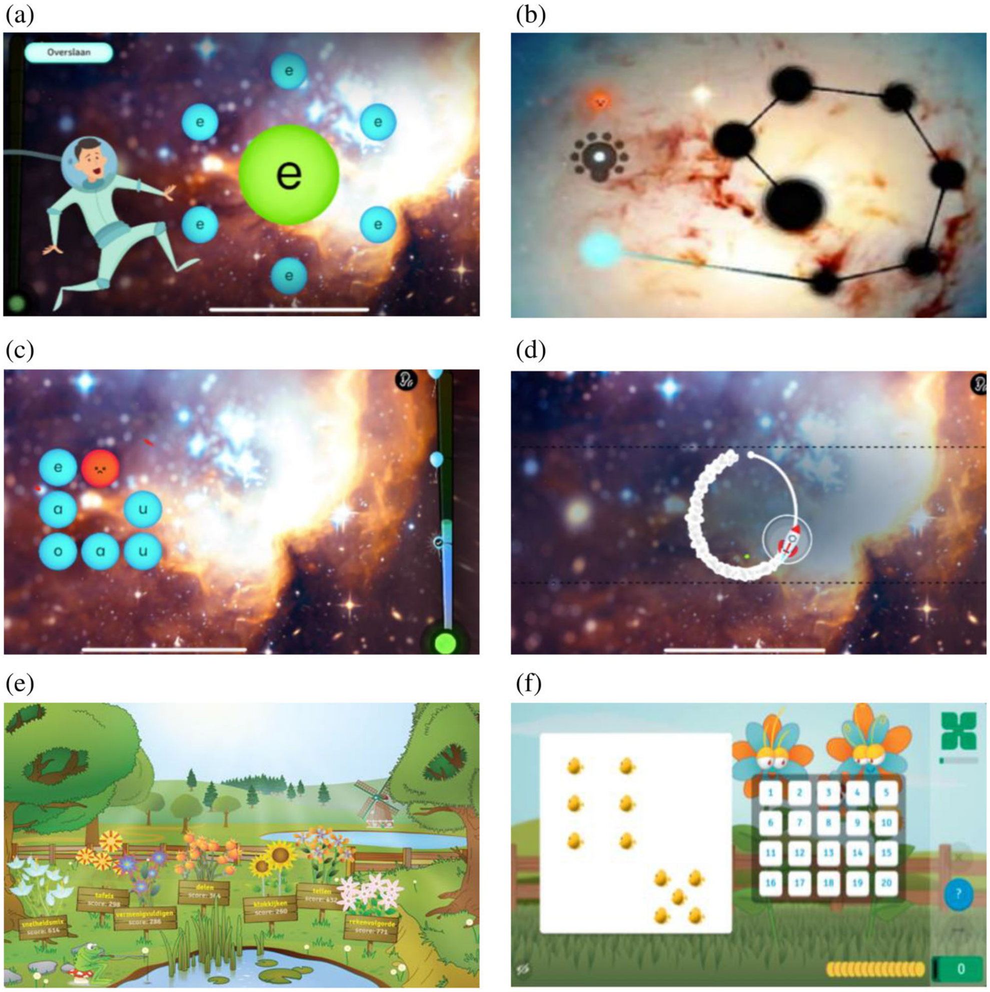

FIGURE 3 Examples of screens in the experimental games (KlankKr8) and the control game. (a) The astronaut introduces the child to the letter 'e'. (b) Example of a star constellation that comprised different speech sounds. (c) Children saw a sad smiley when they tapped the wrong (non-corresponding) bullets. (d) Example of the writing exercise that was included in the motoric version of the game. Children had to follow the pattern to write the letters. (e) Home screen of Math Garden. Different plants represent different games. (f) Example of the counting game in Math Garden. Children had to count the little fish and fill in the correct number

2.4.3 | Mathematical control condition

Math Garden was used as a control condition that did not involve any learning of letters or reading while being exposed to a tablet-based game with an equivalent amount of playtime. In this game, children were learning basic mathematics by watching educational videos and making assignments with numbers and shapes (Straatemeier, 2014). These mathematical skills included counting, comparison skills and basic arithmetic operations. The game took place in a garden in which each plant represented a game (see Figure 3e). This game was also adaptive in nature, and children saw their plants grow when their ability increased.

2.5 | Data analysis

Children were excluded when post-test data was missing due to illness ($n = 14$) or when they played the intervention 2 *SD* sessions below the mean (<9 sessions, $n = 4$). In total, the analysis included 53 children who played the standard audio-visual version of the game, 50 who played the motoric version and 42 children who played the mathematical control game. To examine differences in baseline measures between the three conditions, univariate ANOVAs were conducted. Differences in gender distribution between the three conditions were examined with a Chi-square test. As a primary question, we examined the effect of the game on letter-speech sound knowledge. According to the pre-registered analysis and in terms of power (Van Breukelen, 2006), we conducted a univariate ANCOVA with L-SS outcome at post-test (T1) as the dependent variable and the intervention as factor while controlling for L-SS knowledge at pre-test (T0). As a secondary question, we wanted to examine whether children could read short, easy words after this short intervention period. A similar ANCOVA was therefore repeated with reading accuracy at post-test (T1) as the dependent variable and the reading score at pre-test (T0) as covariate. Assumptions of linearity, homogeneity of regression slopes, homogeneity of variances and normality were checked before conducting the statistical analyses. All assumptions were met except the assumption of normality for the reading scores. However, as each condition contained more than 30 participants and deviations from normal in reading score distribution were minor, normality can be assumed according to the Central Limit Theorem (Kwak & Kim, 2017). Significant results were followed up with Tukey post hoc comparisons. Having a minimal number of intervention sessions was not pre-registered and therefore we examined whether including the four children who played the game less than nine times in the analysis yielded similar results.

As an exploratory analysis, we explored associations between in-game measures and children's pre- and post-test measures. We first computed correlations between the cognitive tasks (i.e., L-SS knowledge and reading accuracy at pre- and post-test), accuracy in tapping the correct bullets (%) and the highest obtained level in the game (max = 50). In addition, we wanted to examine whether the in-game accuracy score and highest obtained level mediated the relation between L-SS score at pre- and post-test, and between the reading accuracy score at pre- and post-test. To this end, two separate mediation analyses were performed using the *lavaan* package (Rosseel, 2012) in R Studio (RStudio Team, 2019) with the two pre-test scores (L-SS knowledge and reading accuracy) as predictors, post-test scores as outcomes and game accuracy and highest obtained level as mediators. A bootstrap analysis with 1000 replications was applied to estimate the total, direct, and indirect (i.e., mediated) effects and their 95% CIs. For these analyses, only children who played either the standard audio-visual version of the game or the motoric version were included ($n = 103$). The two conditions were analysed in one mediation model considering inadequate statistical power to detect mediation effects due to low sample sizes when these two conditions would be analysed separately (Fritz & MacKinnon, 2007). For all analyses, an alpha of 0.05 was used to examine statistical significance.

3 | RESULTS

3.1 | Baseline measures

Univariate ANOVAs did not reveal differences in age or non-verbal intelligence between the three conditions (*ps* >0.63). There were no significant differences in gender distribution across the three groups ($X^2(2) = 4.29$, $p = 0.12$). Comparing the pre-test scores did not reveal any differences in L-SS knowledge, phoneme awareness and reading ability between the conditions (*ps* >0.38). Participants' characteristics are shown in Table 1 and descriptive statistics of the outcome measures at baseline and post-test in Table 2.

3.2 | Intervention effects

Intervention effects for L-SS knowledge and reading accuracy are depicted in Figure 4. The L-SS score at pre-test was significantly related to the L-SS score at post-test ($F(1,141) = 242.80$, $p < 0.001$, $\eta_p^2 = 0.63$). In addition, we found a significant effect of condition on the L-SS score at T1 after controlling for the L-SS score at T0 ($F(2,141) = 4.82$, $p = 0.009$, $\eta_p^2 = 0.06$). Tukey post hoc tests showed that the covariate-adjusted mean of the AV condition ($M = 99.88$) was significantly higher than the mean of the CC condition ($M = 90.59$; mean difference $= 9.29$, $t = 3.03$, $p = 0.008$, $d = 0.63$). However, the covariate-adjusted mean of the AV+ condition ($M = 94.06$) did not differ significantly from the CC (mean difference $= 3.47$, $t = 1.12$, $p = 0.51$, $d = 0.23$) or the AV condition (mean difference $= -5.82$, $t = -1.99$, $p = 0.12$, $d = -0.39$). Corresponding confidence intervals are reported in Table S1. Including children who played the game less than nine times in the analysis yielded similar effects ($F(1,145) = 251.23$, $p < 0.001$, $\eta_p^2 = 0.63$ and $F(2,145) = 4.47$, $p = 0.013$, $\eta_p^2 = 0.06$ for covariate and condition, respectively). Although we controlled for the effect of teacher and school by using within-classroom randomisation, children in the same school might be more similar than children in other schools. To examine whether it was needed to account for this school clustering with a multilevel model, we checked whether there was significant variation across schools. A baseline model with only the intercept included was fitted and compared to a model that allowed intercepts to vary across schools. The model with varying intercepts was not significantly better than the model with the fixed intercept ($X^2(1) = 3.671$, $p = 0.06$), justifying the use of a general linear model (Field et al., 2012).

For reading accuracy, we conducted an ANCOVA with the reading score at post-test (T1) as the dependent variable and the intervention as factor while controlling for reading accuracy at pre-test (T0). The reading score at pre-test was significantly related to the reading score at post-test ($F(1,141) = 695.83$, $p < 0.001$, $\eta_p^2 = 0.83$), but we did not find any significant effect of condition on the reading score at T1 after controlling for reading accuracy at T0 ($F(2,141) = 0.54$, $p = 0.59$, $\eta_p^2 < 0.01$). Including children who played the game less than nine times in the analysis yielded similar effects ($F(1,145) = 721.76$, $p < 0.001$, $\eta_p^2 = 0.83$ and $F(2,145) = 0.61$, $p = 0.54$, $\eta_p^2 < 0.01$ for covariate and condition respectively). The model with varying intercepts was not significantly better than the model with the fixed intercept ($X^2(1) = 0.141$, $p = 0.71$), justifying the use of a general linear model (Field et al., 2012).

TABLE 1 Participant characteristics for the standard audio-visual condition (AV), the motoric condition (AV+) and the control condition (CC) separately

	Mean (*SD*)			
Characteristic	AV	Av+	CC	Group comparison
n	53	50	42	$X_{(2)} = 1.34$, $p = 0.51$
Gender (M:F)	19:34	23:27	24:18	$X_{(2)} = 4.29$, $p = 0.12$
Age (months)	63.37 (4.86)	63.40 (3.71)	64.00 (4.87)	$F(2,134) = 0.469$, $p = 0.63$
Intelligence	97.34 (13.30)	96.79 (12.86)	96.28 (12.21)	$F(2,132) = 0.096$, $p = 0.91$
N play[a]	12.72 (1.41)	12.72 (1.42)	12.45 (1.55)	$F(2,141) = 0.355$, $p = 0.70$
PA[b]	4.98 (3.01)	4.58 (2.98)	4.12 (2.94)	$F(2,141) = 0.978$, $p = 0.38$

[a]Number of intervention sessions.
[b]Phoneme awareness.

TABLE 2 Descriptive statistics at baseline and post-test for the standard audio-visual condition (AV), the motoric condition (AV+) and the control condition (CC) separately: Mean (Standard Deviation, Range)

Task		Condition		
		AV	AV+	CC
L-SS[a]	Pre	87.77 (18.33; 62–136)	90.44 (21.96; 52–138)	88.98 (18.03; 69–135)
	Post	98.62 (24.55; 49–150)	95.44 (25.83; 55–149)	90.52 (22.25; 56–136)
Reading[b]	Pre	2.42 (4.57; 0–20)	2.48 (4.16; 0–17)	2.07 (3.20; 0–13)
	Post	3.11 (4.75; 0–19)	3.46 (5.22; 0–20)	2.62 (4.02; 0–13)

Note: L-SS = letter-speech sound knowledge. Maximum test score: [a] = 160; [b] = 20.

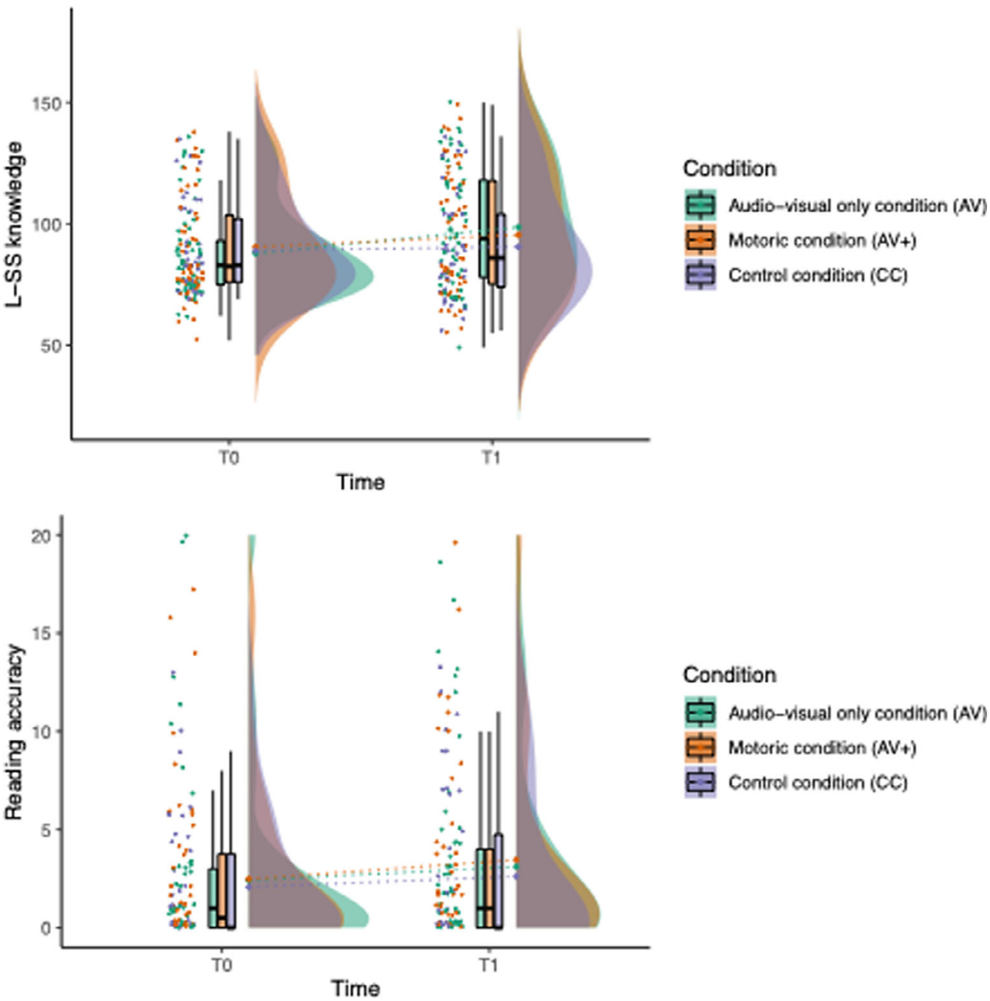

FIGURE 4 Raincloud plots depicting intervention progress in L-SS knowledge (up) and reading accuracy (down) across the three conditions. In the boxplots, lines indicate medians and the areas above and below the medians indicate first and third quartiles. L-SS, letter-speech sound knowledge

3.3 | In-game measures

To better understand how intervention progress was related to game performance, we examined the correlations between L-SS and reading accuracy at pre- and post-test on the one hand, and in-game accuracy (%) and the highest obtained level out of 50 on the other hand. For these analyses, only children who played either the standard audio-visual version of the game or the motoric version were included ($n = 103$). All correlations are reported in Table S2. Pre- and post-test scores of L-SS knowledge and reading accuracy were significantly correlated to in-game accuracy. That is, not only children who had higher post-test scores, but also higher pre-test scores were more accurate in the game. Likewise, the highest obtained level in the game was positively associated with L-SS and reading scores, indicating that children who completed more levels on average had higher L-SS and reading scores and vice versa, children who had higher baseline scores completed more levels in the game.

A mediation analysis showed that the L-SS score at pre-test positively predicted the L-SS score at post-test ($b = 0.97$, $z = 13.83$, $p < 0.001$). The association between L-SS knowledge at pre- and post-test became less pronounced, but still highly significant, when including the two mediators (see Figure 5). Analysing the indirect effects indicated that the highest obtained level mediated the relationship between L-SS at pre-test and post-test ($b = 0.10$, $z = 2.44$,

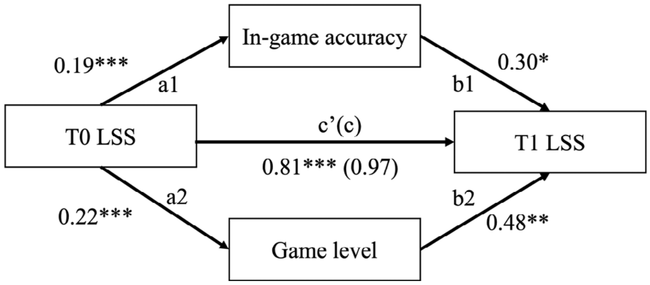

FIGURE 5 Associations between letter-speech sound knowledge knowledge at pre- and post-test with in-game accuracy and highest obtained game level in the game. Coefficients are unstandardised. The direct effect without the mediators is presented in parentheses. ***$p \leq 0.001$; **$p \leq 0.01$; *$p \leq 0.05$

$p = 0.02$), with the 95% bias-corrected confidence interval based on 1000 bootstrap samples entirely above zero (0.03 to 0.20). Although, the 95% bias-corrected confidence interval of the indirect effect through in-game accuracy was also entirely above zero (0.01 to 0.12), this effect was not significant ($b = 0.06$, $z = 1.83$, $p = 0.07$). For the reading scores, the reading score at pre-test positively predicted the reading score at post-test ($b = 1.04$, $z = 15.44$, $p < 0.001$). However, none of the mediators significantly mediated the relationship between reading accuracy at pre- and post-test (game level: $b = -0.02$, $z = -1.42$, $p = 0.16$; in-game accuracy: $b = 0.02$, $z = 1.08$, $p = 0.28$).

4 | DISCUSSION

The goal of this study was twofold. First, we established the efficacy of the game KlankKr8 in training letter-speech sound correspondences in pre-readers. Second, we examined whether including a motoric component in the game boosted the letter-speech sound training on top of the effect of the game without the motoric component. Regarding the first research question, we found evidence for the hypothesised effect of the game in pre-readers; playing the game enhanced pre-readers' letter-speech sound knowledge after a short intervention period of 3 weeks. However, children who played the motoric version of the game did not differ significantly from either the standard or the control condition.

We tested the effect of playing the game on two main outcomes, namely, letter-speech sound knowledge (near transfer) and reading accuracy (far transfer). We found a significant increase in L-SS knowledge in children who played the standard audio-visual version of the game compared to children who played the control game. This is in line with our hypothesis as the game was developed in order to train L-SS correspondences. This finding suggests that KlankKr8 is able to boost L-SS correspondences in younger children who did not receive formal reading instruction yet, and might therefore be useful as a preventive evidence-based intervention for at-risk children in kindergarten who might benefit from a head start before learning how to read.

Second, although the game boosted L-SS knowledge, this knowledge did not transfer to reading short, easy words, as none of the conditions had higher scores for reading accuracy after the intervention period. Although this is in contrast with earlier studies that found a positive effect on word reading skills after training letter-speech sounds correspondences (Fraga González et al., 2015), this is corroborating the findings of a recent review of McTigue et al. (2020). McTigue et al. (2020) found that GraphoGame leads to an improvement in a variety of reading subskills depending on the study, but rarely led to an increase in word reading. It should be noted that fully integrating letters and speech sounds takes up to 1 year of formal reading instruction and takes even longer to become fully automatised (Froyen et al., 2009). As the participants in our study were in the last year of kindergarten, they did not receive any reading instruction yet. In accordance with the self-teaching hypothesis (Share, 1995), a minimal number of mappings is needed before children are able to autonomously decipher words (Perry et al., 2019), which might not be obtained after 3 weeks of intervention. In addition, in Dutch schools, children are commonly getting familiar with how letters relate to words from the second half of the last year of kindergarten onwards or even later. However, our intervention took place in the first half of the last year of kindergarten, implying that most children had no understanding of how L-SS knowledge should be used to decode words. Although the intervention led to an increase in L-SS knowledge, it is therefore not completely unexpected that 3 weeks of intervention is not sufficient for transferring this knowledge to word reading. Future studies might want to consider implementing a longer intervention period, in a period in which letters are getting introduced at school, to examine the transfer to word reading. Implementing the game at the time when informal letter and reading instruction starts, that is, at the second half of the 2nd year of kindergarten in Dutch schools, children might be more goal-directed towards applying the L-SS knowledge in decoding words (see also Verwimp et al., 2023), possibly leading to better word reading skills. In addition, it is worth considering using an alternative task such as the word-specific orthographic knowledge task as used in Lassault et al. (2022). In such task, children have to choose the correct word amongst incorrect answer alternatives after the word was presented auditorily, which more closely resembles the skills practiced in the game used in the current study.

The second aim of this study was to examine the added value of including a motoric component in the game compared to the standard version. We hypothesised that children who played the motoric version would have better L-SS knowledge compared to children who played the standard version, as handwriting helps young children to understand and recognise letters (James, 2017). Handwriting movements have been found to facilitate the integration of auditory and visual word form information (Guan et al., 2011, 2021), and therefore can act as a scaffold for coupling auditory and visual word forms. Our results showed that children who played the motoric version of the game did not perform significantly better than children in the control condition. However, it is important to note that they also did not perform significantly worse than children in the standard condition. This finding can be explained as follows. First, we wanted to have the same amount of screen time across the three conditions, therefore all games automatically closed after playing for 15 min. For children who played the standard version, this time was mainly occupied with tapping the corresponding bullets. For children who played the motoric version of the game, this time was divided into tapping bullets and writing the letters themselves. As the process of writing the letters is significantly slower than tapping the corresponding bullets, children who played the motoric version of the game in the end thus had less L-SS tapping which might explain why they did not improve as much in L-SS knowledge compared to the standard condition. Second, writing requires fine motor skills that might not have been fully developed in children at this age. The development of handwriting starts around the age of 5 but continues to develop between the age of 6 and 9 (Feder & Majnemer, 2007). Although we aimed to control for the possibly immature fine motoric skills in kindergartners by using their fingers to write instead of a pencil or pen, directing cognitive capacity towards controlling the motoric movement might have hindered the development of specific memory traces contributing to the integration of letters and speech sounds.

In an exploratory analysis, we examined whether in-game measures, that is, accuracy during the game and highest obtained level, were related to letter-speech sound knowledge and reading accuracy at pre- and post-test. We found that children with higher post-test scores, but also higher pre-test scores, were the ones who were more accurate in the game. Likewise, children who completed more levels on average had higher L-SS and reading scores and vice versa, children with higher baseline scores completed more levels in the game. A mediation analysis revealed that only the highest obtained level mediated the relation between the L-SS score at pre- and post-test. It is however important to note that children could independently decide whether to continue with the next level or replay the previous level, leading to huge variability in game progress. This could explain why in-game accuracy does not mediate the relationship between the L-SS score at pre-test and the L-SS score at post-test, as children who kept playing the early, easier levels in the game probably obtained higher accuracy scores but were not exposed to the more complex speech sounds and therefore did not improve in L-SS knowledge. Another explanation can be that children who obtained higher levels, and thus progressed further in the game, were the ones who were more motivated and engaged more, leading to greater benefits of the intervention.

The present results add to the growing evidence of game-based interventions as promising tools to support reading development, and the potential to prevent reading difficulties in more transparent languages such as Dutch. However, some limitations to this study need to be addressed. First, as this study served as a proof-of-concept study, we have chosen to implement a short, intensive intervention period. A longer intervention might, however, be needed to examine the transfer of L-SS integration to word reading and to see the effect of the motoric component. Moreover, previous research has suggested that the intervention, especially in children who are at risk of reading difficulties, is the most effective when it happens in short sessions, multiple times a day, to accumulate the memory trace of the newly learned knowledge (e.g., Lyytinen et al., 2009). In addition, as this study was carried out during the COVID-19 pandemic, some children were absent multiple times during the intervention or were in quarantine when post-tests took place. This resulted in more missing data than anticipated. Providing a longer intervention with multiple sessions a day might lead to better consolidated L-SS correspondences and missing a day of intervention might therefore have less effect on the results. Second, the post-test only took place immediately after the intervention. A future study might want to include a longitudinal follow-up moment to examine whether this intervention still has an effect after a particular amount of time or ultimately, whether playing this game in kindergarten can prevent reading difficulties in elementary school. It is however important to note that the current game design is specifically intended for building automatised letter-speech sound mappings, which is the hallmark of fluent reading (Castles et al., 2018). Only when your ability to decode words is effortless and automatic, you can direct your cognitive capacity to comprehend what is written. Reading comprehension requires the integration of meaning across sentences, making use of contextual cues and inferences based on an individual's general knowledge (Muijselaar et al., 2017). Training reading comprehension thus requires support on a different level, implemented in other game designs (e.g., ComprehensionGame, https://comprehensiongame.com/info/). Third, as we wanted to keep the amount of screen time constant between the conditions, children in the condition with the motoric component had less time for tapping the corresponding bullets compared to the standard condition, possibly explaining why they did not improve on L-SS knowledge. To control for this, it is recommended to implement a second part of the game in the standard audio-visual condition as well, in which children are passively exposed to letters without writing the letters, ensuring that the two conditions have a similar amount of L-SS tapping. Last, the reliability of the phoneme awareness task in the current study was somewhat lower than the reliability of other measures. Phoneme awareness tasks have been found to be very difficult for kindergarten children, often exhibiting floor effects (Catts et al., 2009). Nevertheless, the phoneme awareness task in the current study has been found to load highly on the construct phoneme awareness (Boets et al., 2010), and was only used as a baseline measure in the current study and not as the outcome of interest.

To summarise, the present study showed that KlankKr8 is efficient in training letter-speech sound correspondences in pre-readers. These results suggest that this game might be a useful evidence-based intervention for at-risk children in kindergarten. It may prevent reading problems later in life and may especially be beneficial for at-risk children who need a head start before learning how to read. Future studies can shed light on the optimal duration of the intervention, to determine whether a longer intervention period results in L-SS knowledge being translated into reading skills, and whether using this game in kindergarten can prevent the development of severe reading difficulties.

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

The authors declare no conflict of interest.

PEER REVIEW

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DATA AVAILABILITY STATEMENT

The data, analysis code and study protocol supporting the findings of this study are publicly available on OSF (https://osf.io/kdqf6/?view_only=a93d45510a8248c5a819c204eef46a0d).

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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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