The Cognitive Benefits of Embodied Learning in the Context of Early School Literacy

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It currently has 8 tables/figures which is the limit, so no more can be added to the main article. The main text (introduction, results and discussion excl table and figure captions is currently 4954 words and the limit is 5000. Abstract is max 150 words and it's 148 currently.

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ABSTRACT

Reading is a complex, yet fundamental academic skill that school children are taught all over the world. Although, literacy learning relies on attentional and perceptual processing of visual and auditory inputs, it has been found to also benefit from embodied learning, e.g., motor activities as an integrated strategy to recognise and remember letters. We explored mechanisms and effects of integrated embodied activity in young school children (5-8-year-olds), in both a lab experiment (n=18) including electroencephalography and ecological settings (8-week school intervention project; n=144). The electroencephalographic experiment revealed that embodied activity stimulates attentional and perceptual processing compared to control (non-active) letter discrimination practice and the school intervention study showed that early literacy educational outcomes were facilitated in children with an initial lower working memory performance. These novel results indicate that reinforcement of cognitive processing could be a candidate mechanism to explain the efficacy of embodied literacy learning.

INTRODUCTION

Recent reviews in cognitive and educational fields have emphasised the importance of embodied learning for improved acquisition of perceptual, conceptual, and semantic knowledge (Clark et al., 2015; Hald et al., 2016; Macedonia, 2019; Skulmowski & Rey, 2018). Broadly, embodied learning requires bodily engagement during learning tasks to stimulate the engagement of sensorimotor processes (Hald et al., 2016; Macedonia, 2019). Embodied learning can be either integrated (meaningful movements relevant to the task) or incidental (movements unrelated to the task; Skulmowski, & Rey, 2018). Both types of embodied learning are beneficial in educational practice (Hald et al., 2016; Skulmowski, & Rey, 2018) which has been shown in the context of literacy, second language and mathematics (Hald et al., 2016; Macedonia, 2019). However, the engagement of sensorimotor processes and their effect on cognition may differ for integrated and incidental movements. For incidental embodied learning, the benefit of using movements during learning tasks may be due to assumed induced improvement in executive and attentional control (Clark et al., 2015). On the other hand, integrated embodied learning has been discussed in the context of the Dual-Coding Theory (Paivio, 1990) as it may facilitate the formation of multimodal (verbal and non-verbal) perceptual codes for the acquired information (Hald et al., 2016). To our knowledge, no studies to date have directly investigated the cognitive benefits and processes underlying incidental or integrated embodied learning.

The application of embodied learning may be especially promising in the context of early literacy education. Previous research showed that the use of general physical activities during the learning of letters and spelling led to better pre-reading skills in 6- to 7-year-olds (Macdonald et al., 2021). Phoneme identification and pre-reading skills were also significantly better in 5-year-old children who learnt the meanings and spellings of words through songs and movements (Walton, 2014). The use of integrated meaningful movements may have especially beneficial effect on early letter-sound knowledge learning. This would involve the use of movements to represent the learnt letter forms and sounds. Such approach has been found to be more beneficial for letter recognition and letter-sounds knowledge compared to the standard school curriculum for 6-7-year olds (Damsgaard et al., 2020, 2022). However, the cognitive mechanisms behind the advantages of embodied learning for pre-reading skills are not yet clear.

Therefore, the aim of the current study was to answer the following research question:
What are the likely cognitive benefits of integrated embodied learning in the context of early literacy education?

One crucial pre-reading skill developed in early literacy education is the ability to associate letter graphemes and phonemes. This skill is known as letter-sound knowledge and is a cornerstone for learning to read in alphabetic orthographies as children use these connections when decoding unfamiliar words (Byrne & Fielding-Barnsley, 1989). Letter-sound knowledge is achieved through multisensory learning and audio-visual integration engaging perceptual, attentional, and working memory processes (Blomert & Froyen, 2010). Specifically, attentional resources are required to encode individual perceptual features of multimodal letter objects – graphemes (visual feature) and phonemes (auditory feature). Cross-modal *binding* occurs where graphemes are associated with corresponding phonemes (Jones et al., 2013). Binding is a key concept in working memory literature where perceptual features from different modalities are processed individually and bound to create object representations in the episodic buffer (Baddeley et al., 2011). The episodic buffer interfaces with long-term memory where the bound object information can be consolidated.

This multisensory process of learning about graphemes and phonemes could be further enriched with embodied learning based on the assumptions of the Dual-Coding Theory (Paivio, 1990). One suggestion is that integrated movements further enrich the audio-visual multisensory letter learning process through an addition of meaningful sensorimotor information. This may occur through selective top-down attention engaged for the processing of multisensory information specific to the task at hand. This has previously been demonstrated in a study on audio-visual number learning. Matusz et al. (2019) showed that presenting number information in visual and auditory modalities at the same time is the most beneficial for selective attention in children at the age of six who may not yet have well developed number knowledge. In terms of letter knowledge, the use of embodied learning could help to efficiently harness attentional resources and give children a chance to process visual, auditory, and motor-sensory features relevant to the learnt letter objects to create richer multisensory bindings. Furthermore, efficient engagement of attentional resources through the integration of multisensory information has been shown to have a beneficial effect on working memory (Quak et al., 2015). Presumably, multisensory processing of task related information alleviates the cognitive load on working memory by filtering out stimulus-irrelevant information (Quak et al., 2015).

In accordance with the above assumptions, embodied learning could be seen as a multisensory learning tool for efficient engagement of attentional and perceptual processes potentially alleviating working memory load. It has been suggested that the ability to sustain attention on relevant information facilitates working memory performance through shared underlying cognitive constructs (Gazzaley & Nobre, 2012). Working memory performance, described as the limited capacity for information that can be manipulated and kept temporarily available for cognitive tasks, tends to differ from person to person (Adams et al., 2018; Baddeley, 2012; Eriksson et al., 2015). This may lead to individual differences observed in children's literacy skills. Children with good working memory performance may find it easier to learn the shapes and sounds of the letters and the connections between them, and when attempting to decode a word, they may be more successful because they can temporarily store more letter-sounds that need to be blended into actual word forms (Preßler et al., 2014). In contrast, children with low working memory performance may experience an overload of the working memory system when acquiring early reading skills. Therefore, the use of embodied learning for letter-sound knowledge acquisition could be an effective tool for enhancing literacy skills in children with limited working memory performance.

Our first study aimed to investigate whether the application of an integrated embodied activity in the context of early literacy facilitates multisensory perceptual code binding and attentional processing. We used electroencephalography to investigate the neurocognitive signals reflecting early perceptual and attentional processes as children performed letter-related movements. Eighteen 6-8-year-old children were randomly assigned to complete a sequential visual search task with target stimuli in the form of letters. The aim of the task was for children to practice identifying letters "b" and "d". The embodied response group responded with letter-related arm movements, whilst children in the control group used no movements and instead, selected their answers by fixating their gaze on the target letter, which was facilitated using an eye tracker. To successfully complete the task, children would require sufficient attentional resources to enable a quick perceptual categorisation of the stimuli and identification of the target letter. We therefore expected differences in midline stimulus-locked event-related potentials (ERPs). It is a challenging task to predict what exact ERPs could be observed as these signals are very variable in child populations in terms of latency and topography (Brooker et al., 2019; Meyer et al., 2021). However, we hypothesised that we would observe an enhanced P300 component in children who used arm movements compared to the control group based on the wealth of evidence suggesting that this signal corresponds to attentional processing (Polich, 2007).

The results from the first study confirmed our expectations and showed that an embodied learning activity facilitated enhanced engagement of multisensory perception and attention processes as evident in the identified early latency ERPs. We therefore wanted to further investigate whether embodied learning could prove especially beneficial for children with lower working memory performance. In a school intervention project, 144 children at the age of 5-6 years old participated in an eight-week randomized control trial focusing on pre-reading skills and word reading performance in combination with movements three times a week for 30 minutes. Children were divided into two groups based on their working memory scores on a 1-back test. We predicted that children using embodied learning would in general reach higher improvement in pre-reading skill gains compared to children who used no movements and that this effect would be especially pronounced in children with lower working memory.

RESULTS

Study 1: Embodied Activity Engages Early Attentional and Perceptual Processing

In Study 1, 18 6- to 8- year-old children completed a visual serial search task requiring overt attention to detect target letters "b" or "d" and perceptual distractors consisting of letters "p" and "q". The aim of the task was for children to practice identifying letters "b" and "d" and distinguishing them from other similar letters ("p" and "q"). The sequence of the task was as follows: children kept the space bar pressed down with both hands, the visual task screen display appeared, once children identified the target letter, they released the spacebar and made their response. In the embodied response group (MOVE), children selected the target by performing arm movements representing the shape of the target letter and touching the letter on the screen (see the methods section for details). In the control group (CON), children made their response by fixating their gaze on the target letter. The responses were selected with the use of an eye tracker. An overt visual-attention task was therefore chosen to ensure that a comparable amount of eye-movements would be required to complete the task in both the MOVE and CON groups. Throughout this procedure, participants' brain activity was recorded with electroencephalography (EEG). Table 1 presents participants' demographic information.

Table 1. Study 1: Children's demographic information by group.

	MOVE	CON
N	9	9
Age Median (years)	7	6
Female %	66	22
Year 0 %	33	67
Year 1 %	67	33
Bilingual %	22	22
Right-Handed %	78	100

Data analysis.

A baseline test with EEG recording during a letter recognition task was completed by all children regardless of their assigned group to ensure that there were no pre-existing literacy-recognition differences between the two groups. The baseline measurement of EEG signals between the two groups revealed no significant differences. In terms of task performance, children in the MOVE group had significantly faster reaction times (p=.049, BF_{10}=3.47) but not accuracy (see the supplementary file).

For the main task, stimulus locked averaged EEG amplitudes (event related potentials; ERPs) were extracted for the MOVE and CON groups across 64 EEG channels. Based on recent guidance for investigating ERPs in children, we expected to observe task related potentials at the Fz, Cz and Pz and their surrounding channels (Brooker et al., 2019). We expected to observe a P300 component but had no specific predictions regarding the channel or the latency of the component due to lack of previous research using this specific visual serial search task. In addition, it is well known that EEG potential latencies vary significantly with age and such predictions are generally difficult in child populations (Brooker et al., 2019; Meyer et al., 2021). We therefore followed advice suggested by Brooker et al. (2019) whereby we visually investigated averaged amplitudes to detect ERPs and their latencies. We found clear indications of three ERPs. N200 (Pz) and P300a (Fz) were present in the MOVE group and P300b (Pz) was present in both groups. To ensure that the observed ERPs represented valid components that differed from noise, we performed one-sample one-tailed signed rank Wilcoxon tests on the three observed ERPs in both groups separately. We then conducted group analyses on the observed ERPs. Lastly, we were interested in a potential relationship between the observed ERPs and task accuracy.

Embodied Activity Facilitates Task Performance

Behavioural analysis of task performance focused on the percentage of accurate responses (task accuracy) and the time it took children to identify the target letter and release the space bar (decision time). The Mann-Whitney U test and Bayes Factor analysis in favour of the alternative hypothesis (BF_{10}) results indicated that participants in the MOVE group achieved significantly better task accuracy compared to the CON group (U=14, p=.042, BF_{10}=3.79, r=.654). The results for decision time were non-significant and inconclusive with regards to whether there may be no difference between the two groups as reflected by the obtained BF_{10} (decision time: U=39, p=.931, BF_{10}=0.42, r=.037). The results are displayed in Table 2. Figure 1 presents the task accuracy and decision time for both groups.

Table 2. Study 1: Main task results. Group medians and inter-quartile ranges for task accuracy are displayed in percentages; decision times are displayed in milliseconds. Further, grand average mean amplitudes for each identified component are presented per group. These results are displayed as mean (standard deviations) and the one-sample signed-rank test *p*-value.

	Movement Group (MOVE) *Mdn (IQR)*	**Control Group (CON)** *Mdn (IQR)*
Task accuracy (%)	99.51 (0.15)	94.48 (9.91)
Decision Time (ms)	1752.40 (408.99)	2061.42 (564.77)
	M (SD)	*M (SD)*

P300a(µV)	3.25(3.12)	0.57(2.51)
(150-300ms Fz)	*p*=.020	*p*=.326
N200(µV)	-2.68(3.42)	1.35(4.61)
(200-250ms Pz)	*p*=.030	*p*=.298
P300b(µV)	9.65(6.71)	6.49(4.33)
(300-400ms Pz)	*p*=.011	*p*=.011

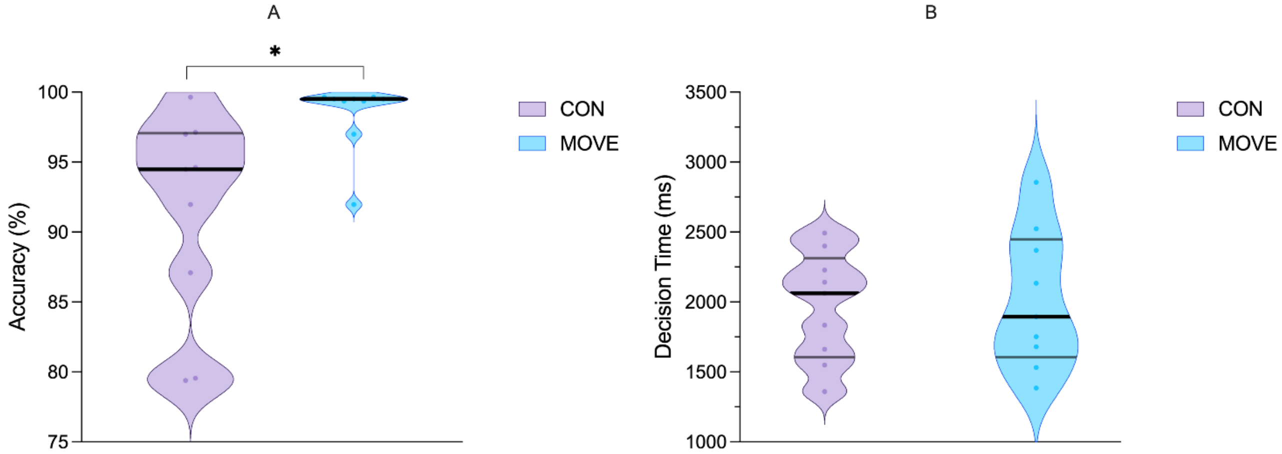

Figure 1. *Study 1. A: Children performing an embodied activity (MOVE) by figuration of the letters 'b' and 'd' with their arms had a significantly higher accuracy in letter recognition compared to a control group recorded with eye tracking (CON). Y-axis represents task accuracy (%). B: Illustrates the decision time in the two groups (CON/MOVE). Y-axis indicates children's decision time (ms). In both violin plots horizontal bold line indicates the median, the thin line indicates quartiles and dots symbolize individual data points.*

Embodied Activity Engages Early Attentional and Perceptual Processing

The first analysis step was the visual ERP identification which focused specifically on channels Fz, Cz and Pz. We identified a P300a component at channel Fz (150ms-300ms, MOVE peak at 220ms, CON peak at 253ms), N200 (200-250ms, MOVE peak at 214ms, CON peak at 231ms) and P300b (300-400ms, MOVE max peak at 343ms, CON peak max at 343ms) at channel Pz. No ERPs were identified at channel Cz. A figure of all extracted ERPs can be found in the supplementary file. The Wilcoxon analysis showed that all identified ERPs were significantly different from 0 in at least one of the groups. The mean amplitude of the P300a identified at channel Fz and N200 identified at channel Pz were significantly different from 0 in the MOVE group (W=42, p=.020 and W=5, p=.030 respectively) but not in the CON group (P300a: W=27, p=.326; N200: W=29, p=.298). The P300b was significantly different from 0 in both groups (MOVE: W=44, p=.011; CON: W=44, p=.011). Table 2 displays the mean amplitudes of these components for each group.

The next step included between-group non-parametric cluster-based t-statistic permutation analyses. The frontal P300a was analysed at the F1, Fz and F2 channels and there was a significant positive cluster between 182ms and 245ms (p=.011, d=0.765) indicating significantly larger amplitudes in the MOVE group. There was also a significant negative cluster for the posterior N200 measured at P1, Pz and P2 between 200ms and 241ms (p=.006, d=1.355), indicating significantly more negative amplitudes in the MOVE group. No clusters were found for the group difference in the posterior P300b at channels P1, Pz and P2. Figure 2 displays the P300a and N200 ERPs per group with marked significant clusters. Figure 3 illustrates topography over time including P300a, N200 and P300b per group.

Finally, non-parametric cluster-based permutation tests using the independent samples regression coefficient t-statistic were performed. A non-significant positive cluster was detected for the regression between P300a and task accuracy (p=.037). No clusters were found for the regression between N200 and task accuracy.

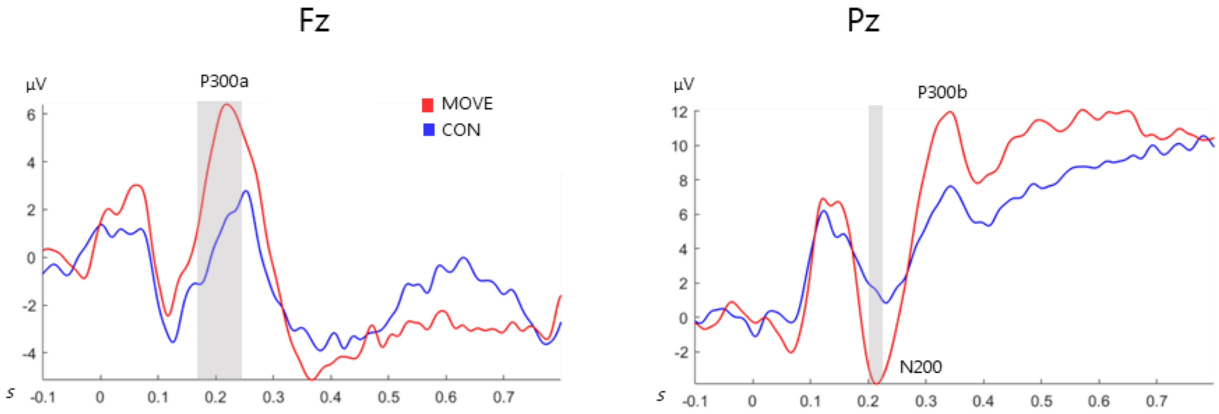

Figure 2. *Study 1. ERP plots for the three measured stimulus-locked components, P300a (at the Fz channel), N200 and P300b (at the Pz channel). The embodied activity group (MOVE) is presented in red and the control group (CON) in blue. The X axis is in seconds and the Y axis is in µV. The grey mask indicates the temporal location of the identified significant clusters for amplitude difference between the two groups.*

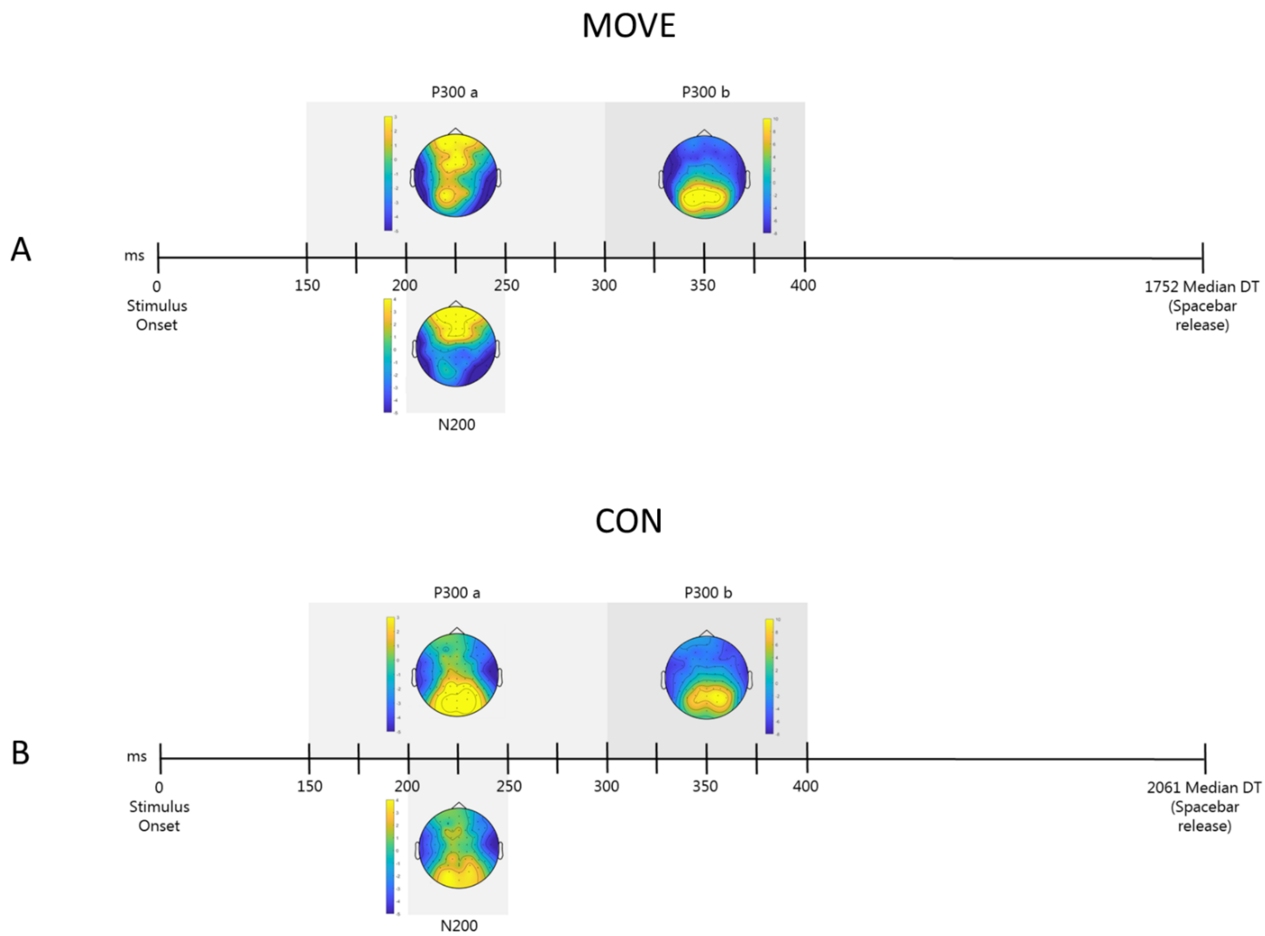

Figure 3 *Study 1. Topographic plots for the three measured components P300a, P300b and N200 presented over time (ms) relative to stimulus onset (time 0). For each group, the median decision time is also displayed to the right on the timeline. The grey areas indicate the latency that the amplitudes were averaged over for each component P300a: 150-300ms; N200: 200-250ms; P300b:300-400ms). Amplitude scales were matched between the groups (P300a: -5 to 3µV; N200: -5 to 4µV; P300b: -8 to 10 µV).* ***A*** *Movement group (MOVE).* ***B*** *Control Group (CON).*

Study 2: Embodied Learning and Improvement of Pre-Reading Skills in Children with Low Working memory.

Based on our findings from study 1, we wanted to investigate the utility of embodied learning for children's (5-6 years old) pre-reading skills and word reading performance in relation to varied working memory performance. Study 2 was a school-based randomized controlled trial including one embodied learning intervention group (MOVE) and one control group (CON). One hundred forty-four participating children were individually randomly assigned before baseline assessment to receive either teaching activities with embodied activities (MOVE) or a control group with no movements (CON) over an eight-week period. The learning activities focused on the acquisition of letterforms, letter-sound correspondence and reading and spelling short words. In the two groups, the learning content of the activities were identical, however, the groups varied with regards to the degree of bodily movement. The participating children were divided into low and high performers in working memory based on their baseline performance in 1-back test. Based on normative data for 1-back (Pelegrina et al., 2015), children who scored seven or fewer correct answers on congruent targets were categorized as low performers (n = 72, average mean at baseline ± SD = 4.87 ± 2.39) and children who scored more than seven correct answers on congruent targets were categorized as high performers (n = 74, average mean at baseline ± SD = 9.59 ± 2.44; see Table 3). Children were tested on their knowledge of letter sounds and word reading before (T1), after (T2) and 17-22 weeks after intervention (T3). In the current report, we focus on conditional letter sounds specifically, because it has been shown that the opaque nature of Danish language is a strong candidate factor for delaying literacy acquisition in Danish school children and requires the adoption of compensatory cognitive strategies by the learners (van Daal & Wass, 2017; Seymour et al., 2003). For more information about the intervention, see the study protocol (Gejl et al., 2021).

Data from tests of letter knowledge and word reading were analysed using linear mixed models with R package lme4 (Bates et al., 2015). Data were square root-transformed to obtain a normal distribution of residuals.

The effects of the categorization as low and high performers were investigated with group x time x subgroup as interaction with groups as CON and MOVE, time as T1, T2 and T3 and subgroups as low and high based on children's working memory ability at T1. 'Subjects' were added to the model as random-effects and 'age' as fixed effect since children's letter knowledge is age-dependent. Post-hoc analyses were made based on improvement between the contrast from post-intervention (T2) to pre-intervention (T1) and from retention (T3) to pre-intervention (T2) for low performers and high performers within CON and MOVE, respectively. Effect sizes were calculated using Cohen's d (*d*; Cohen, 2013)

Embodied Learning Improves Conditional Letter-Sound Knowledge

Low performers (LP) in MOVE had a higher improvement in conditional letter-sounds compared to low performers in CON from T1 to T2 ($p = 0.008$, mean = 0.49, 95% CI [0.12, 0.86], $d = 1.0$). The same improvement was seen for high performers (HP) in MOVE compared to high performers in CON ($p = 0.008$, mean = 0.5, 95% CI [0.14, 0.88], $d = 1.1$) from T1 to T2. Further, from T1 to T3 a significant improvement for conditional sounds was seen for low performers in MOVE compared to low performers in CON (p = 0.003, mean = 0.58. 95% CI [0.19, 0.97], d = 1.3; Table 3).

Embodied Learning Increases Word Reading Performance in Children with Low Working Memory

Transfer effect of the embodied learning intervention was measured by the significant improvement of word reading. Low performers in MOVE had a significantly higher score (p = *0.02*, mean = 0.70, 95% CI [0.12, 1.28], d = 1.0) in reading words compared to low performers in CON from T1 to T3 (figure 4).

Table 3. Study 2: Improvement from pre (T1) to post (T2) and retention test (T3)

	T1 to T2				**T1 to T3**				**T1 to T2**		**T1 to T3**	
	LP		**HP**		**LP**		**HP**		**CON_{LP}-$MOVE_{LP}$**	**CON_{HP}-$MOVE_{HP}$**	**CON_{LP}-$MOVE_{LP}$**	**CON_{HP}-$MOVE_{HP}$**
	CON	**MOVE**	**CON**	**MOVE**	**CON**	**MOVE**	**CON**	**MOVE**	p-value/MD/ 95% CI	p-value/ MD/95% CI	p-value/ MD/95% CI	p-value/ MD/95% CI
Naming of Condi- tional Sounds	0.6 ±0.3	1.6 ±0.3	1.4 ±0.3	2.6 ±0.3	0.8 ±0.3	2.1 ±0.3	1.6 ±0.3	2.1 ±0.3	0.008**/0.49/ [0.12, 0.86]	0.008**/0.50/ [0.14, 0.88]	0.003**/0.58/ [0.19, 0.97]	0.37/0.19/ [-0.23, 0.60]
Standard- ized Word Reading	3.9 ±1.5	6.3 ±1.5	6.7 ±1.5	6.3 ±1.4	11.4 ±1.5	17.4 ±1.6	14.8 ±1.6	15.1 ±1.6	0.16/0.40/ [-0.15, 0.96]	0.92/-0.03/ [-0.58, 0.52]	0.02*/0.70/ [0.12, 1.29]	0.55/0.18/ [-0.42, 0.79]

Data reported as estimated mean ± SE for the two groups CON/MOVE before intervention (T1), after intervention (T2) and 17-22 weeks after intervention (T3) for naming conditional sounds and for the standardized word reading. Further, improvement from T1 to T2 and from T1 to T3 for low performers (LP) were compared between the two groups (CON/MOVE). Similar comparison was done for high performers.

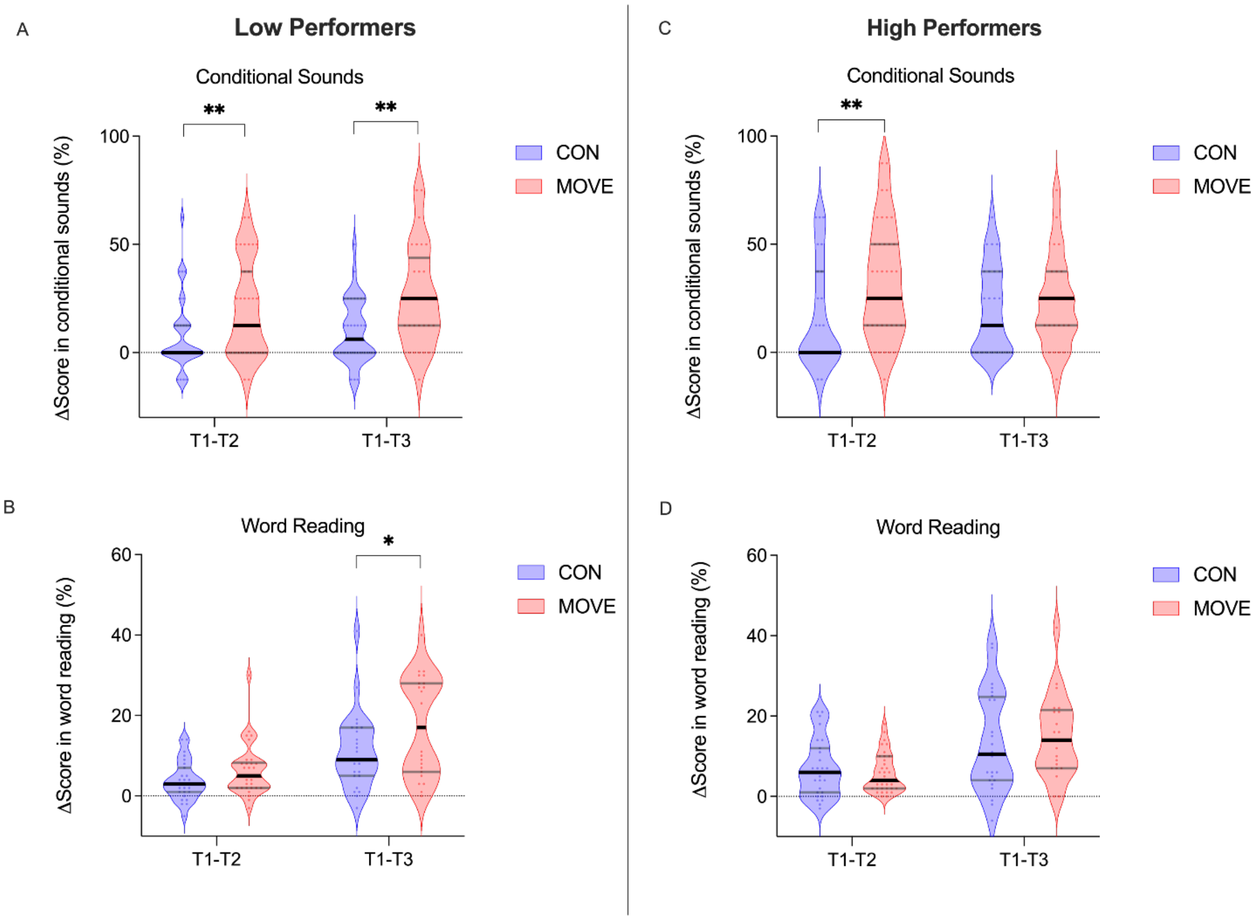

Figure 4. *Study 2: Children's performance in conditional sounds (A and C) and word reading ability (B and D) from baseline (T1) to post-intervention (T2) and 17-22 weeks after an 8-week intervention (T3) with either embodied learning (MOVE) or no-embodiment (CON). Children with low working memory are presented as "Low Performers" (A and B). Children with average-to-high working memory are presented as "High Performers" (C and D). Children with low working memory in MOVE had a significantly higher improvement compared to low performers in the control group in their ability to name conditional letter sounds (A) from T1-T2 (**) and from T1-T3 (**). Children categorized as low performers in MOVE had a significant higher improvement in word reading (B) compared to low performers in CON from T1-T3. Y-axes represent percent correctly answers and dotted line indicates 0% percentage correct. Vertical bold line indicates the median, vertical thin line indicates quartiles and dots symbolize individual data points. Graph is based on completed cases. *, p < 0.05, **, p < 0.01, *** p <0.001*

DISCUSSION

In the current report, we aimed to investigate the cognitive benefits of using embodied learning in the context of early literacy skills. The results of Study 1 show that embodied activities stimulate perceptual and attentional processing during target letter detection in early school years. We interpret this result as supportive of our assumption that embodied learning contributes to the multisensory code binding in the process of forming letter-sound correspondences. In addition, in Study 2, using an embodied learning intervention, we showed that this is especially beneficial for the development of early literacy skills in children with relatively lower working memory performance.

In Study 1, EEG was recorded as children completed a visual serial search task, practising the identification of letters "b" and "d" and responding either using movements (MOVE group) or gaze fixation (CON group). Brain activity was analysed as averaged stimulus-locked event-related potentials. The visual serial search task elicited early frontal P300a in the MOVE group and posterior P300b in both groups. We also identified a significant N200 component in the MOVE group.

The identification of an early P300a component in the MOVE group supports our hypothesis. The early P300a has previously been observed in children, with the mean peak estimated around 200-250ms, which may vary across different tasks (also called early P3a - eP3a; Čeponiene et al., 2004; van Mourik et al., 2007). Čeponiene et al. (2004) suggested that this component may reflect sensory-attentional processing whereby sensory information guides where attention should be shifted to. It has previously been reported that fronto-parietal attention processes are enhanced by motor engagement and planning of eye movements in line with the premotor theory of attention (De Haan et al., 2008). Our results suggest that these attention orientation processes could be further enhanced by instructing participants to respond with larger and more meaningful movements. Alternatively, the observed signal may be interpreted as an extended frontal P2 component which has been reported to peak at around 200ms. The reported interpretation of the P2 component closely resembles that of the P300a/eP3a. P2, in both children and adults, has been shown to reflect task-oriented perceptual stimulus processing in the transition towards response selection but is not directly related to the selection or initiation of motor responses (Rojas-Benjumea et al., 2015). Consequently, our interpretation of the enhanced early P300a (eP3a) in the MOVE group is that it reflects a beneficial effect of motor-sensory input for stimulus-oriented attentional processing.

On the other hand, a later P300b was identified at posterior channels in both groups at the exact same mean peak latency and with no significant amplitude differences. This finding is consistent with previous research showing the presence of the P300b component in 8-year-old children during a range of executive functioning tasks and it has been interpreted as reflective of the engagement of general executive functions required for task completion (Brydges et al., 2014). We therefore interpret this finding as indicative of children's engagement on the task and reflective of post-perceptual cognitive processing, with no evidence to suggest that this could differ between the two groups.
The enhanced N200 effect observed in the MOVE group was not expected. The posterior N200, also known as the N2c, is a well-known ERP component reflecting visual attention and categorisation of stimuli (Folstein & Van Petten, 2008; Pritchard et al., 1991). It may be especially applicable in the study of letter learning. For instance, a centrally located N200 has been found to be associated with perceptual letter and sound processing in both child (from the age of 7) and adult participants (Čeponiene et al., 2005). The N200/N2c component reflects similar processes as a contralateral signal corresponding to the location of the target stimulus. The component is better known as the N2pc and has been shown to reflect automatic multisensory integration of perceptual information (Talsma, 2015) as well as visual attention processes employed for target selection in visual search tasks in both adults and children (Couperus & Quirk, 2015). Based on these studies, our observed difference in the N200 is likely to reflect enhanced multisensory perceptual and attentional processing in the MOVE group.

Taken together, our findings suggest that in young children, integrated embodiment applied in the practice of letter knowledge may stimulate early brain activity associated with multisensory perceptual processing and attention (P300a and N200). In contrast, we found no evidence of potential differences in ERPs reflecting post-perceptual processing (P300b).

Following the results from Study 1, we considered two main cognitive benefits of integrated embodied learning. First, the attentional benefit. The selection and execution of the correct movement requires additional attentional resources (e.g., selecting and executing the right movement for the target letter). The movement is highly relevant to the learnt information and therefore more attentional resources are dedicated to the learning task itself. Second, integrated movements provide another perceptual code (sensory-motor), which contributes to a perceptual representation of the letter object (visual letter form, letter sound and letter movements). The binding of these perceptual elements to form comprehensive letter object representations occurs in the episodic buffer of the working memory

(Baddeley et al., 2011), which occurs efficiently due to already increased attentional resources that underlie working memory performance (Gazzaley & Nobre, 2012). Consequently, we assumed that working memory performance during the learning of letter objects can be facilitated using embodied learning. This assumption was tested in Study 2 where embodied learning was applied in an eight-week school intervention and was found to be especially beneficial for children with low working memory.

In Study 2, we observe that children with low working memory who did not use embodied learning made the least progress with regards to their knowledge of letters and corresponding conditional sounds when compared to children in the other participating groups (children with low working memory who used movements and all children with higher working memory). The same observation applied to early word reading skills. This pattern was consistent across both T2 (immediately after the intervention) and T3 (at follow-up). In line with our hypothesis, statistical analyses showed that within the group of children with lower working memory, those who used embodied learning showed significantly higher improvement in both letter knowledge and word reading skills. At T3 specifically, this result was unique for children with lower working memory and a similar pattern was not found in children with average-high working memory. Overall, our results demonstrate a direct training effect of the embodied learning intervention by significant improvement in letter-sound knowledge, as well as a transfer effect to word reading which was specific for children with lower working memory. We found that children with lower working memory who performed movements gained more compared to children with lower working memory in the control group on conditional letter-sounds. Letter-sound knowledge is known to have a particular importance for children's reading performance (Caravolas et al., 2005; Furnes & Samuelsson, 2009; Hulme et al., 2012; Kirby et al., 2008; Melby-Lervåg et al., 2012; Schatschneider et al., 2004), and it is known that children need to master standard sounds before mastering conditional sounds (Elbro, 2013). Since the intervention took place at the beginning of grade 0, most children had no prior knowledge of conditional letter-sounds, and so, they needed to learn and recognize these sounds as alternative pronunciations of the letters alongside their names and standard pronunciations. Further, before children can understand the alphabetic code, that sounds and letters can combine, which, in turn, will allow for the development of basic word reading skills, they need both phoneme awareness and letter knowledge (e.g., Bowey, 2005). So, to observe a transfer effect from T1 to T2 on word reading, the children participating in the 8-week intervention would have had to acquire letter-sound knowledge proficiency and translate their newly gained knowledge into a basic word reading strategy. However, only 4% of all children acquired basic word reading skills during the intervention period and at T3, 7–8 months after school starts, the proportion had risen to 29% (Damsgaard et al., 2022). This pattern could explain why a transfer effect to word reading were only seen at T3. Overall, the findings indicate that using embodied learning in the context of letter-knowledge and word reading skills is specifically beneficial for children with lower working memory performance and can be used to facilitate their academic progress. The findings also provide further support to our assumption that integrated embodied learning drives beneficial multisensory processing. Speculatively, the observed training effect may be interpreted as children's ability to accurately create letter-sound correspondences and efficiently recall them to enable word reading. This action may have been challenging for those with lower working memory performance, but embodied learning helped to alleviate those difficulties likely through multisensory integration and improved attentional control.

The findings from Studies 1 and 2 contribute to the wealth of research focused on supporting literacy education. Despite many pedagogical developments for the support of literacy education, up to 14% of children fail to achieve adequate reading skills (Manu et al., 2021; Serry & Oberklaid, 2015). Embodied learning is a highly accessible and free tool that can be adopted for use in any classroom or home. When learning letter forms and sounds using embodied learning, children use their own body to explore, learn and focus their attention on the given learning task. An interesting avenue to explore in further research would be to study the benefit of embodied learning for early literacy learning in children with attentional difficulties and those who display early signs of dyslexia.

When applying embodied learning solutions in early literacy education, it must be considered that children should themselves perform integrated embodied movements. Study 1 showed that embodied learning stimulates early sensory, perceptual and attentional processing suggesting that movements play an important role for the integration of perceptual elements to form letter objects. We assume that embodied learning contributes an additional embodied motor/tactile element to letter representation which would not be achieved if the movements were not performed by the child. For example, if the children watched someone perform movements representing letters instead.

One limitation of the current report is a weak distinction between incidental and integrated movements. In both studies, participants in the embodiment groups performed meaningful integrated movements whilst participants in the control groups performed no other movements (Study 1) or only minor movements (Study 2 – handwriting). It is therefore unclear whether the obtained results are specific to meaningful integrated movements or whether they could also be observed during the use of bigger and more incidental movement (e.g., arm movements that are not associated with the learned letters). This can be investigated in future research.

Another limitation is that in Study 1, during baseline testing, children in the MOVE group were significantly faster at discriminating target letters "b" and "d" compared to the CON group. It is also important to note that no significant differences were found in accuracy or brain activity between the two groups during the baseline testing.

In Study 2, trained instructors carried out the MOVE intervention, but control group sessions were delivered by the class own teacher. The familiarity of the class teachers could have a positive influence on the learning outcomes of the CON group. However, it is unlikely that this caused a significant impact on the study outcomes as the study was sufficiently powered and the MOVE group achieved significantly better improvement than the CON group in letter knowledge and word reading performance.

CONCLUSION

This present report contributes to our understanding of the importance of cognitive benefits of integrated embodied learning in early education. We combined neurophysiological, behavioural and educational approaches to explore the relevant cognitive mechanisms which may explain the utility of applying movements in learning. We conclude that embodied learning facilitates the acquisition of early literacy skills through its facilitation of attentional and perceptual processing and alleviating working memory load.

2.0 MATERIALS AND METHODS

Materials and methods for study 1: Embodied Activity Engages Early Attentional and Perceptual Processing

Study Design and Participants

The study was approved by the local Ethical Committee at the University of Copenhagen, Denmark (protocol: H-17019671 & 70061). Thirty children in the first two grades of school education (grade 0 and 1, age between 6 and 8 years) were recruited using opportunity sampling (poster advertisements, advertisements at school and word of mouth). Children were randomly assigned to one of two groups. One group completed a visual search task using embodied movements (MOVE) and the control group by fixating their gaze (CON). Nine participants were not included in any analyses – one did not meet the inclusion criteria (attended grade 2), three failed to perform the embodied/control task above chance level (less than 50% accuracy), two did not finish the procedure, two were observed to make responses randomly and did not pay attention to the tasks and one with a poor cap fit and loss of data due to noise. Therefore, the dataset for this study consisted of twenty-one participants. Further two participants were excluded following the analysis of baseline EEG data due to outlying ERP amplitudes. One more participant was excluded following the pre-processing of the main task data with extreme drift identified in ERPs. This resulted in a total of eighteen children included in the analyses (nine in the movement and nine in the control group). Demographic details are displayed in Table 1.

The Visual Search Task

A simple visual search task delivered using E-prime version 3.0 (Psychology Software Tools, Inc., 2016). The screen was divided into four rectangles and one lower case letter was presented in the middle of each rectangle. The selected target letters were “d” and “b” because they are visually similar. In addition, they share further visual similarity with letters “p” and “q” which were selected as distractors to make the search task more challenging and engaging. Only one of the target letters was presented on the screen at any one time. Two other letters were the distractors “p” and “q”, and the last letter was randomly selected as either “p” or “q”. The presentation of the letters in different rectangles on consecutive trials was randomised. Each trial consisted of a fixation “#” in the middle of the screen. Children were instructed to press and hold the space bar when they saw the fixation sign. The visual search task screen appeared after 1000ms following the space bar press. Subsequently, children were asked to identify the position of the target letter ("d" or "b"). Once detected, they were instructed to release the space bar. The duration from stimulus onset to space bar release was the task decision time and it was extracted for correct responses only. In the movement group, children were asked to select the target letter by positioning their arms in the shape of the identified letter and pressing on the touch screen with their index finger. See the supplementary file for an illustration of the task and response movements. In the control group, participants were instead asked to fixate their eyes on the target letter. An eye tracking device (Tobii 4C; Tobii Technology, n.d.) was used to track children's gaze and identify their response based on gaze fixation. The experimenter pressed a key-board button to register the selected letter as a response. Once the response was registered, the fixation screen reappeared.

All children completed 60 practice trials in three separate blocks including 20 trials for the identification of the letter "d", 20 for letter "b" and 20 for both "d" and "b" displayed in randomised order. During the practice trials, the experimenter monitored the accuracy of responses and repeated the task instructions in the breaks between the blocks. Subsequently, children completed two more blocks of 20 trials each with target letters presented as "d" or "b" at random. Therefore, each child completed 60 practice trials and 40 main task trials. Decision time on correct responses and task accuracy were extracted from the main task blocks only as measures of task performance. The decision time was displayed on the screen following task completion and the researchers copied it on paper and entered it into an electronic spreadsheet. Correct responses for the CON group were calculated within E-prime (version 3.0; Psychology Software Tools, Inc., 2016) and accuracy was displayed on the screen following the completion of the task which was copied alongside the decision time. For the MOVE condition, experimenters observed children's arm movements and shapes and marked responses for each trial as either correct or incorrect on a paper sheet. Correspondingly, brain activity was also analysed from the main task blocks only.

Electroencephalography (EEG)

EEG data were acquired using a 64 channel Biosemi EEG setup with active Ag/AgCl electrodes (Biosemi, n.d. a) fitted in a 50-54cm small head cap (Biosemi, n.d. b) following the 10/20 system. No external electrodes were added to the setup. The electrodes were attached to a DC coupled Active Two AD box amplifier (Biosemi, n.d. c). An online first order anti-aliasing filter was applied. The data were sampled at 2048Hz. Electrode offset was kept at ± 25 mV. The EEG data were recorded in a .bdf format. Digital markers were recorded for the onset of the visual search task stimuli to allow for stimulus-locked event related EEG analyses.

Procedure

Parents were presented with the study information sheet and signed the consent form prior to the commencement of the study procedure. The EEG procedure was explained to parents and children. Demographic information consisting of the participating child's gender, age, date of birth, school grade, bilingualism and handedness were recorded based on parent report. Children sat at a table, 50cm distance from a 23" screen and used a standard computer keyboard. They watched cartoons whilst the EEG setup was being prepared by the experimenters. A two-alternative forced choice discrimination task was completed by the children prior to the main task as a baseline measure of brain activity and target letter ("b" and "d") discrimination (see the supplementary file). Subsequently, they completed the visual serial search task followed by another discrimination task, which was identical to the baseline task. The final discrimination task was not analysed for the purpose of this report and will not be referred to any further.

Data Analyses

Behavioural Data

Behavioural data were analysed using R Studio (version 2021.09.1; R Core Team, 2021). Variables extracted for the main task included task accuracy (the proportion of correct responses) and decision time on correct trials (the time between stimulus onset and spacebar release). All variables were corrected for the effect of age using the formula:

$$Y_{corr} = Y - X(\frac{X}{Y})$$

Here Y_{corr} is the corrected main variable vector (e.g., corrected task accuracy), Y is the uncorrected main variable vector (e.g., uncorrected task accuracy), X is the confounding variable vector (age). Accuracy and decision time differences between the movement and the control groups were statistically compared using a two-tailed Mann-Whitney U test and the Bayes Factor analysis in favour of the alternative hypothesis (BF_{10}) using the jmv R package and its default priors (Selker et al., 2021).

For the Mann-Whitney U tests, p-values were adjusted using the Benjamin & Hochberg (1995) correction method and significance was based on alpha of < 0.05. For BF_{10}, significance in favour of the alternative hypothesis was based on $BF_{10} > 3$ and in favour of the null hypothesis on $BF_{10} < 0.33$.

EEG Data

Pipeline

EEG data analysis followed best practice recommendations by the MEEG Committee on Best Practice in Data Analysis and Sharing (COBIDAS, Organisation for Human Brain Mapping; Pernet et al., 2018, August 9) as well as recent guidance for reproducible EEG research with children (Brooker et al., 2019; Meyer et al., 2021). Data processing and analyses were conducted using the FieldTrip toolbox (version dated 25/05/2021; Oostenveld at al., 2011) in MATLAB (version 2019b, The Mathworks Inc., 2019). The data were divided into three-second epochs with 1000ms prior and 2000ms post stimulus onset, which marked time 0. The data were baseline corrected to the average activity of each epoch and a notch filter at 48-52Hz was used. Bad channels were interpolated using the spline method. On average, 3 channels were interpolated per participant (MOVE: M=3, CON: M=3.11). Subsequently, the data were re-referenced to the average of all channels. Artefacts were removed semi-automatically using trial and channel visualisation in Fieldtrip. The data were then detrended using a first order polyremoval function. High-pass filter was applied at 0.1Hz and low-pass at 40Hz. Subsequently, the data were down-sampled to 512Hz. A temporary high-pass filter at 1Hz was applied before conducting fastICA independent component analysis (Hyvarinen, 1999) for the detection of eye movement and muscle artefacts. The components were manually inspected and marked for removal. Lastly, each participant's data were inspected for quality, and this included checking continuous and averaged data and manual rejection of any remaining artefacts. The mean remaining number of trials was M=25.56 in the MOVE group and M=27.89 in the CON group.

For each participant, the pre-processed data were averaged over smaller epochs of -100 to 1000ms relative to stimulus onset. Baseline correction was applied between -100ms and 0s. The averaged epochs were corrected for the age effect using the same formula as that used for behavioural data which is implemented in the ft_regressconfound FieldTrip function. Subsequently, grand averages for the movement and the control group were calculated. In accordance with the exploratory nature of the analyses, the grand averaged group ERPs were plotted against each other for visual comparison. They were visually inspected for the presence of N200, P300a/b and N400 at electrodes Fz, Cz and

Pz. We visually identified emerging components with possible group differences on channels Fz (P300a) and Pz (N200 and P300b) and these were selected for statistical analyses (see Figure 1 in the Supplementary File).

First, a statistical check was performed for the mean amplitude of identified P300a (Fz), N200 and P300b (Pz) components to assess whether they significantly differ from noise and reflect a reliable event-related neural response. For P300a (Fz), mean amplitude values were extracted for each participant at 150-300ms, for N200 (Pz) at 200-250ms and for P300b at 300-400ms. The ERPs were assessed for representing activity that differed from noise with the use of a one-sample one-tailed signed rank Wilcoxon test in MATLAB. The p-values were corrected for multiple comparisons with the Benjamin & Hochberg (1995) correction method. All identified components were significantly different from zero in at least one of the groups and therefore, further group analyses were performed.

Group analyses were performed using between-subject, non-parametric cluster-based t-statistic permutation analyses in Fieldtrip (Maris & Oostenveld, 2007). The data matrices used for the permutations were two-dimensional and included amplitude by time data. To ensure sufficient power and reliability of the observed effect, the permutation tests were conducted on sets of three adjacent electrodes. The P300a was compared at 150-300ms at channels F1, Fz and F2. The N200 was compared at 200-250ms, and the P300b at 300-400ms at channels P1, Pz and P2. Significant between-group differences were identified for the P300a and N200 components and these were further tested for a relationship with task accuracy with non-parametric cluster-based permutation tests using the independent samples regression coefficient t-statistics on the earlier specified channels and latencies for P300a and N200 amplitude over time matrices and task accuracy.

The cluster-level statistical distributions were estimated using the Monte Carlo method with 1000 number randomisations. Significance was based on the sum clusters of significant differences that exceeded 95% (critical alpha = 0.025, two-tailed) of the cluster-distributions. We used the Cohen's *d* calculation to extract effect sizes which were calculated by averaging amplitudes over whole significant clusters for each group as recommended by Meyer et al. (2021).

Justification

Contrary to best practice recommendation for ERP preprocessing steps (Tanner et al., 2015), we chose to apply a high-pass filter to epoched data, which could result in distortion of the obtained

ERPs. This decision was made based on the fact that we used the BioSemi system where raw recordings have a large DC offset, which must be fixed right at the beginning of data processing. In some situations, this large offset can be fixed with at low high-pass filter (0.1Hz). However, this also carries the risk of introducing artefacts throughout the whole EEG recording. Another option commonly chosen to correct the DC offset is baseline correction through mean extraction on the channel level, which we decided to apply in the analysis. This carries another limitation. Baseline correction on continuous data can introduce artefacts throughout the recording if there is a high level of noise. The data were collected from young children who moved not only because of the demands of the task, but also because they generally tend to fidget, change position in the chair or get interested by things they see in the environment. Therefore many of the recordings included prolonged periods of noise. To compromise, we divided the recordings into three second epochs to exclude as much movement related noise as possible and we then applied the baseline correction.

Taking into consideration the risk of distorted ERPs due to the application of a high-pass filter on epoched data, we decided to select a filtering frequency (0.1Hz) that was the least likely to lead to marked differences based on a previous report studying language and cognition ERPs (Tanner et al., 2015). Furthermore, we want to emphasise that the risk of misinterpreting the study results is reduced by two additional factors of the study design. Firstly, conclusions are based on group-level differences and preprocessing was conducted in the exact same way in both groups. We therefore expect that any distortion would occur systematically in the two groups and not influence the group-level difference. Secondly, statistical significance of the group-level difference is evaluated using non-parametric permutation analysis, which is less sensitive to differences in the shape and exact latency of the observed ERPs and only indicates whether there is or is not a significant group difference in the selected time-window and on selected channels (Sassenhagen & Draschkow, 2019). The test is also a conservative solution that helps to decrease the likelihood of false positives in multi-dimensional analyses (Meyer et al., 2021).

Transparency

Besides our expectation of observing a P300 ERP component, we did not specify any other ERPs that we expected to observe in the data or that would differ between the two groups and therefore, there was an exploratory element in our analyses. We also did not pre-register our analyses. Our statistical approach could make use of different pipelines and pursue many different lines of investigation. We aimed to maximise transparency regarding our aims and analyses through the sharing of data and analysis code. See the “data availability” section below. In addition to the reported analyses, we explored event-related synchronisation of alpha and theta power in the data, however, this line of analysis was futile and yielded uninterpretable results due to the low number of trials, which is generally recommended to be around 30 (Graimann et al., 2002) and around 40 specifically for children for this type of time-frequency analysis (Morales & Bowers, 2022). Therefore, we do not report on this analysis and will attempt to apply such analyses in future projects with more available trials.

Material and methods for study 2: Embodied Learning and Improvement of Pre-Reading Skills in Children with Low Working memory

Study Design and Participants

The present study, PLAYMORE, is described in detail elsewhere (Damsgaard et al., 2022; Gejl et al., 2021) and only methods pertinent to this report are included here. This study was conducted with 5-6 years old children who just started school (grade 0) and were recruited from 10 different classes from four elementary schools in the Copenhagen area. One hundred eighty-three children were included in the study after obtaining written consent from parents. Due to less than 90% presence of total lessons from the intervention 14 children were excluded. Eight children with neurodevelopmental conditions were excluded, sixteen children did not participate in baseline measurement of 1-back, and one child withdrew from the study, which in the end resulted in 144 participating children (76 girls, 73 boys, mean age ± SD = 6.2 ± 0.4), see table 4 for demographic characteristics by intervention group.

The study was approved by the local Ethical Committee at University of Copenhagen, Denmark (protocol: 504-0032/18-5000), registered in ClinicalTrials.gov (NCT04618822) and was carried out in accordance with the Helsinki Declaration II.

The study is a randomized controlled trial including one intervention group and one control group. 144 participating children were individually randomly assigned before baseline assessment to receive either teaching activities with movements (MOVE) or a control group with no movements (CON) over an eight-week period. Within each class, 12 participants were allocated to MOVE, and the remaining participants were constituted to CON. The control group learning activities were incorporated into the school curriculum for the period of the intervention.

Table 4. Study 2: Demographics of low and high performers on the baseline working memory measure split by intervention condition. CON = control group; MOVE = embodied learning group.

	Low Performers		**High Performers**	
	CON	**MOVE**	**CON**	**MOVE**
Participants (n)	37	35	33	39
Age (Years)	6.2 ± 0.4	6.3 ± 0.4	6.2 ± 0.3	6.3 ± 0.3
Height (cm)	122.5 ± 4.5	121.6 ± 5.8	123.3 ± 5.0	122.5 ± 4.6
Weight (kg)	23.2 ± 3.2	23.0 ± 4.1	23.2 ± 3.2	22.7 ± 2.8
Sex (% Girls)	49	54	67	38
Bilingualism (% Bilingual)	24	20	27	21
Dominant hand (% Right)	97	91	93	90
1-Back (Correct Congruent Target)	4.8 ± 2.0	4.91±1.6	9.27±1.3	9.87± 1.4

Intervention Condition

The intervention focused on reading and spelling short words over an eight-week period. The children participated in three sessions every week of 30 minutes duration, counting 24 sessions in total. For a more detailed description of the intervention, see our protocol paper (Gejl et al., 2021). In the original protocol, there is a distinction between two intervention groups – one using fine and one using gross movements. To enable easier interpretation of the results with the focus on working memory in the current report, we collapsed both embodied learning groups into one. The Danish teaching material, Fandango Mini, which is recognized and used by several preschool teachers in Denmark (Jacobsen & Veber Nielsen, 2011) was used to develop the intervention.

In the intervention group, MOVE, children used arms, hands and their whole-body to make movements. The participating children were taught to make specific movements to letter sounds (phoneme movements), and these movement-sound couplings were used throughout the intervention. The children had to perform the phoneme-movements from left to right, following the reading direction. Often the phonemes were associated with objects or living creatures (e.g., the movement coupled to the letter sound "S" was associated with a snake). Children in the movement group performed the movements using their arms and hands standing or seated on a chair around a table with one trained instructor. The activities were performed individually or in randomly allocated pairs.

Control Condition

Children in the control condition (CON) performed the same activities as MOVE without using movements beside handwriting, and performed all the activities seated in a chair, individually or in random allocated pairs, using paper and pencil. The activities were performed by their own teacher. CON performed a protocol that is typically delivered in schools, though closely matched to the intervention group.

Test Procedures

Age, sex, handedness, bilingualism, height and weight were collected at baseline measures (T1). Measures of reading-related skills were obtained before (T1), after the eight-week intervention period (T2) and after a retention period of 17-22 weeks (T3) to evaluate the effects of the intervention.
In the original protocol the retention test was planned to be eight weeks after end intervention, but it was delayed due to COVID-19.
The tests assessing pre-reading skills and working memory (1-back test) were collected individually (IT) with a trained instructor in a one-to-one session. One test was conducted in groups (GT) of 12 participants separated from one another to avoid copying and were delivered by two trained instructors. The individual tests and the group tests were performed on two separate days.

MEASURES

A test battery was used to test children's working memory and children's pre-reading and word reading ability. For more information about testing see (Gejl et al., 2021).

Working Memory

A test was performed to evaluate the children's working memory.

1. **1-back task (IT)**

To assess working memory a 1-back test was completed. The test was constructed with representations of symbols (cloud, car, headphones, glove, note, airplane, plate, key, eye and bicycle). The symbol was represented one at a time for each trial and was presented in white colour on a black background. In each trial, the children had to compare the presented symbol with the symbol shown in the previous trial. Children were instructed to press "yes" (a green key on the keyboard if these two symbols were identical and "no" (a red key) if they were dissimilar, as fast and as accurate as possible. The test consisted of 20 practice trials (30% yes trials) followed by two blocks of 20 trials each (30 % yes trials). The symbols were presented for 500 ms followed by a 3000 ms blank screen. The response window and inter-stimuli interval were 3500 ms each. The participating children were divided into low and high performers in working memory based on their baseline performance in 1-

back test. Based on normative data for 1-back (Pelegrina et al., 2015), children who scored seven or less correct answers on congruent targets were categorized as low performers (n = 72) and children who scored more than seven correct answers on congruent targets were categorized as high performers (n = 74; see table 4).

Letter Sounds Knowledge Test

A test was performed to evaluate children's letter sounds knowledge.

1. **Naming of Letter-Sounds (incl. the use of movement) (IT)**

To evaluate children's knowledge of letter sounds, they were asked to pronounce the sounds of letters "a", "d", "e", "o", "r", "u" and "v" which have several possible pronunciations in Danish known as standard and conditional pronunciations. In total, the test assessed the knowledge of seven standard letter sounds and eight conditional letter sounds. The trained instructor read aloud the letter names once at the time. The child was asked to stand up while answering with a letter sound and thereby also had the opportunity to make movements to the sound. For every letter sound, the child's answer was registered as correct/incorrect/missing and it was recorded whether any movement was used. The test was previous used to assess children's pre-reading skills (Damsgaard et al., 2022) and the internal consistency of the test evaluated by the Kuder-Richardson formula 20 was reported at 0.73 (95% CI 0.72–0.75; Malling et al., 2021). The result of the test was the number of correct letter sounds pronounced 1) in total, 2) as standard letter sounds and 3) as conditional letter sounds. Only conditional sounds for this study were relevant and are presented in the results. The test was used as a measure of the direct training effect.

Standardized Word Reading Test

A test was performed to evaluate the children's word reading.

1. **Standardized Word Reading Task (GT)**

The test assessed the accuracy and efficiency of reading (Juul & Møller, 2010). It consisted of 78 items and the child had to solve as many as possible within a time limit for 4 minutes. For each item children had to select one of four images that matched a printed word. For a more detailed description of test procedure, see (Gejl et al., 2021). Test reliability is 0.80 (α, Cronbach's alpha; Juul & Møller, 2010). The test outcomes were the percentage of correctly solved items (accuracy) used as a measure of the transfer effect.

Statistical Analysis

The statistical analyses were performed in R studio (R Core Team, 2021).
Each baseline measure was compared between the intervention and control groups using a one-way analysis of variance (ANOVA) and chi-square tests were used for the categorical measures (bilingual, dominant hand and sex). Children with test results of more than +/- 2SD from the mean in two or more tests were considered outliers and were excluded from all analyses (n=11).
Data from letter knowledge and word reading were analysed using linear mixed models with group-time-subgroup interactions as fixed effects, using R package lme4 (Bates et al., 2015). The choice of using linear mixed models was especially beneficial as they allow to account for missing data (e.g., absent at test day). The data were analysed using group x time x subgroup interaction effect with CON and MOVE as groups and time as measures taken at T1, T2 and T3 and high/low as subgroups based on their working memory ability at baseline. 'Subjects' were added to the model as random-effect and 'age' as fixed effect since children's letter knowledge are age-dependent. Pairwise comparisons between the improvements from post-pre and retention-pre were analysed. P-value adjustment was based upon the Tukey Method for comparing a family of three estimates. The level of statistical significance was set to $p < 0.05$.

DATA AVAILABILITY

All data used in the analyses presented in this report are organised in open-access repositories with no restricted access. All raw EEG data have been structured according to BIDs (Gorgolewski et al., 2016) and deposited on OpenNeuro as a dataset (Damsgaard et al., 2023). The scripts used for analyses as well as results from the EEG analyses are stored on GitHub (https://github.com/MovementAndNeuroscience/B-D_EEG_Child). Intermediate EEG analysis derivatives, as well as behavioural data from Studies 1 and 2 are deposited on the Open Science Framework (OSF; https://osf.io/6hrkj/). The project has a landing page on the OSF with a directory to all files and materials relevant to the current report (https://osf.io/6hrkj/wiki/home/).

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AUTHOR CONTRIBUTIONS

The following author contributions are specified following the CRediT guidelines (Brand et al., 2015).

Conceptualisation: LD, MT, JW, AMVN, ASBM, AKG. Methodology: LD, JW, AMVN, ASBM, AKG. Software: MT, LD, ASBM, AKG. Validation: LD, MT, ASBM, AKG, MSC. Formal Analysis: LD, MT. Investigation: LD, MT, ASBM, RAH, SK. Data Curation: MT. Writing - Original Draft: MT, LD. Writing – Review & Editing: MT, LD, JW, AMVN, MSC.

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Conflict of Interest Statement:

The authors declare that the research was conducted in the absence of any commercial or financial relationship that could be construed as a potential conflict of interest.

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