MIND, BRAIN, AND EDUCATION

Implementing Full-Body Movements in a Verbal Memory Task: Searching for Benefits but Finding Mainly Costs

Gianluca Amico[1] and Sabine Schaefer[1]

ABSTRACT— Studies on "embodiment" show that moving your body can enhance cognition. We investigated such effects in a verbal memory task across age. In Study 1, children, adolescents, and young adults (N = 148) were tested in group sessions and reproduced number series of increasing length. In the "embodied" condition, subjects walked to numbered gymnastic mats. In the "sitting" condition, the numbers were presented visually. All age groups, except the youngest, showed a deterioration of verbal memory performance in the embodied condition compared to sitting. In Study 2, young adults (n = 33, M_{age} = 24.5 years) and children (n = 28, M_{age} = 7.3 years) were tested individually, with smaller target fields. There were no differences in verbal memory performance between the conditions. This indicates that "embodiment" does not always lead to performance enhancements. Instead, moving through space while thinking represents a dual-task situation, causing performance decrements across age.

In most schools, students sit in class and are instructed to listen but not to move, as almost every body movement is considered to be a disruptive behavior. However, movement can have positive effects on learning in children. This has been shown in intervention studies, in which physical fitness training led to cognitive improvements (Hillman, Kamijo, & Scudder, 2011; Vazou, Pesce, Lakes, & Smiley-Oyen, 2016), and in acute exercise studies (Tomporowski, 2003; Tomporowski, Davis, Miller, & Naglieri, 2008; Tomporowski, McCullick, Pendleton, & Pesce, 2015). In addition, cognition can profit from body movements if the movement is related meaningfully to the cognitive task (Hainselin, Picard, Manolli, Vankerkore-Candas, & Bourdin, 2017; Mavilidi, Okely, Chandler, & Paas, 2016; Skulmowski & Rey, 2018b), in particular, if cognitive processes are acted out. The concept of "embodied cognition" has recently attracted an increased research interest (Barsalou, 2008; Glenberg, 2010; Kiefer & Trumpp, 2012). Wilson (2002) reviews several views on embodied cognition. She argues that sensorimotor experiences and bodily states play an essential role in higher cognitive processes because the human mind is grounded in mechanisms that evolved for interaction with the environment, including sensory processing and motor control. This hypothesis is supported by the coactivation of brain structures involving both motor and cognitive abilities during cognitive tasks (Diamond, 2000). Kiefer and Trumpp (2012) emphasize that embodiment has important implications for education, in particular, the sensory and motor interactions during learning.

From a cognitive developmental perspective, it is an interesting question how embodiment relates to cognitive and motor development over the life span. Pouw, van Gog, and Paas (2014) describe the development of internalized embodied knowledge as a gradual process. Over time, learners slowly disembed their mental activity from the environment. For example, children stop using finger gestures to count. In their review, Loeffler, Raab, and Canal-Bruland (2016) assume that the embodiment effect is stronger in children compared to older adults, especially when it is driven by new associations. Piaget (1975) also assumed that physical experiences are essential in the very early stages of cognitive development and become less important with increasing age. Grounded on these assumptions, we expected children in particular to profit from embodiment.

[1]Department of Sport Sciences, Saarland University

Address correspondence to Gianluca Amico, Institute for Sport Science, Campus Building B 8.1, Saarland University, 66123 Saarbrücken, Germany; e-mail: gianluca.amico@uni-saarland.de

Several studies could show that embodiment helps children to learn new knowledge. A study by Lozada and Carro (2016) found that active manipulation (embodiment) helps 6- to 7-year-old children to answer correctly to typical Piagetian conservation tasks using wide and narrow containers for water. Embodiment also facilitates the learning of scientific and physical knowledge. Lindgren, Tscholl, Wang, and Johnson (2016) put middle school students in the role of an asteroid. They report significantly higher learning gains and higher levels of engagement for children who learned in a whole-body simulation group compared to a desktop version.

Mavilidi, Okely, Chandler, and Paas (2017) taught a total of 90 preschool children the solar system (i.e., name and relative position of planets using toy versions on the floor). Children were either taught while sitting, or while running laps (task-unrelated physical activity), or while running from the sun to the planets on the floor (task-related physical activity). Memory scores in an immediate and a delayed retention test were highest for children in the task-related physical activity group, followed by the task-unrelated group, and the control condition.

Embodiment has also been shown to improve memory performances of young adults and children if the to-be-learned words are acted out as opposed to more passive encoding conditions (Engelkamp & Cohen, 1991; Hainselin et al., 2017; Jahn & Engelkamp, 2003; Manzi & Nigro, 2008). Embodiment also increased vocabulary learning in preschoolers (Toumpaniari, Loyens, Mavilidi, & Paas, 2015), and in several classroom-based intervention studies (Kosmas, Ioannou, & Retalis, 2018; Kosmas, Ioannou, & Zaphiris, 2019; Kosmas & Zaphiris, 2020; Schmidt et al., 2019).

In addition, embodiment can support the learning of numerical concepts (Ruiter, Loyens, & Paas, 2015) and help children understand abstract number magnitude representations (Fischer, Moeller, Bientzle, Cress, & Nuerk, 2011). Link, Moeller, Huber, Fischer, and Nuerk (2013) showed that first graders who walked to the respective position on a number line on the floor (embodied condition) had larger performance improvements compared to a group that indicated the position on a number line on a tablet PC. Kiefer and Trumpp (2012) emphasize the relation between abstract number concepts and motor experience by describing number concepts to be rooted in visuospatial and action-related representations.

A recent study by Schaefer (2018) extended the current findings of embodied cognition to the domain of spatial working memory. She tested 7- and 9-year-old children in a spatial 2-back task and young adults in a spatial 3-back task. The stimuli were presented in a row of nine adjacent fields on the floor. Participants monitored the sequence of stimulus fields (target field turning red) and indicated by saying "tap", whenever a stimulus appears in the same position as the one presented 2 or 3 positions earlier. Participants either stepped into the target fields while working on the task (embodied condition) or remained on their position (standing control condition). Seven-year-olds profited from embodiment, while 9-year-olds and young adults did not, indicating that younger children profit the most from embodiment.

Working and short-term memory develop rapidly from childhood to adulthood (Gathercole, 1999; Isaacs & Vargha-Khadem, 1989; Li et al., 2004). Therefore, research should take developmental differences in working memory capacity into account. Previous embodied cognition studies usually only compared two or three age groups. The current studies investigate the effects of embodied cognition on memory performance in a larger age range across childhood and adolescence. We addressed the question whether moving through space while encoding verbal memory content connected with spatial cues is helpful for performance, and whether there are age differences in this respect. The task was to encode number sequences of increasing length either while sitting or while moving to numbered target fields. We hypothesized increased recall performance in the "embodied" condition because the recall process can be seen as a simulation of past experiences, including motor and mental states (Barsalou, 1999; Dijkstra & Zwaan, 2014). Movement information (e.g., the path walked, the distance between numbers, and the position of turning points) should increase the perceptual richness of the memory trace, increasing its likelihood to be reconstructed successfully.

In Study 1, children and young adults were tested in group sessions in a gym hall. In Study 2, the same memory task was used, but participants were tested individually in a laboratory. Movement was reduced by using smaller target fields to disentangle the effects of physical activity and embodiment. Interstimulus intervals assured that participants could reach the target fields without running. Based on previous studies (Hainselin et al., 2017; Link et al., 2013; Schaefer, 2018), we assumed that younger children profit more from embodiment than older children, teenagers, or young adults. Because earlier studies have mainly focused on long-term memory, the current studies extent the research field to verbal working memory. If embodiment helps to memorize verbal information, these findings could be used to improve educational settings and to enhance learning and memory performance.

STUDY 1

Method

Participants

Study 1 recruited 148 subjects from local sports clubs and schools. See Table 1 for gender and age distribution. All participants had normal or corrected-to-normal vision and

Table 1
Study 1 Descriptives and Cognitive Background Information

Age group	*1*	*2*	*3*	*4*	*5*
School grade	1–3	4–6	7–8	10	Young adults
N (males/females)	27 (10/17)	28 (10/18)	30 (12/18)	40 (24/16)	23 (19/4)
Age (years)					
M	7.8	11.4	14	16.6	23.5
Range	6.4–9.9	9.8–12.1	12.4–14.9	15.7–17.5	20.0–30.0
SD	0.81	0.50	0.68	0.50	2.78
Digit–symbol substitution (correct items per second)					
M	0.27	0.44	0.55	0.68	0.68[a]
SD	0.06	0.08	0.11	0.09	0.14

[a] Note that the Digit–Symbol mean for Age Group 5 was calculated from $n = 21$ because of missing data.

hearing. Participants or their parents provided informed consent. As a background variable, perceptual speed was measured with the Digit–Symbol Substitution Task (Wechsler, 1991). Consistent with the literature on cognitive development (Petermann & Petermann, 2010), an analysis of variance (ANOVA) with age group (5) as a between-subjects factor showed a significant main effect for age group, $F(4, 145) = 94.008$, $p < .001$, reflecting performance increases with increasing age. The study was approved by the Ethics Committee of Saarland University.

Experimental Task

Verbal Memory Task. The Verbal Memory Task was based on the Digit-Span Task (Petermann & Petermann, 2010) but was enriched with spatial information. Participants were instructed to memorize number series of increasing length and to reproduce them in the correct order. The dependent variable was the sum of correctly remembered number sequences. Two trials were tested for each sequence length. Numbers were presented via loudspeakers with an Inter-stimulus interval of 6 s. At the end of the trial, participants wrote down their answers on a sheet of paper. The sequence lengths ranged from 3 to 9 digits for school grades 1 to 8, from 3 to 10 digits for grade 10, and from 3 to 11 digits for young adults, to avoid floor or ceiling effects. Each participant worked on two versions of the Verbal Memory Task: sitting and moving, in counterbalanced order. Figure 1 presents an overview of the experimental setup. In the *sitting* condition, participants sat on gymnastic mats and were presented with the numbers via loudspeakers and via a beamer on a screen. For the *moving* condition, nine gymnastic mats with numbers from 1 to 9 were placed next to each other with a 10-cm gap in between. Subjects were asked to move to each number on the respective mat during encoding. The ISI of 6 s provided enough time to reach each gymnastic mat without running. Participants in both conditions wrote down their answers immediately after the last number was presented, which remained visible in both conditions during recall (last mat reached in moving condition, number presented on the screen in sitting condition).

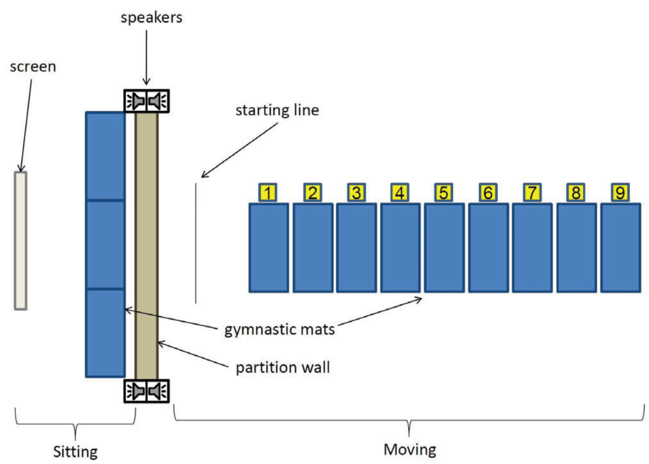

Fig 1. Experimental setup of the sitting and the moving condition in study 1.

Procedure

The testing took place in groups with up to five participants per condition. Both conditions ran simultaneously in a gym, separated by a partition wall (see Figure 1). After the assessment of some demographic variables and the Digit–Symbol Substitution Test, participants were instructed in the Verbal Memory Task and performed the sitting and moving condition (order counterbalanced across participants). Sessions lasted between 60 and 90 min.

Data Analysis

The Verbal Memory Task was analyzed with mixed-design ANOVAs with condition (2: sitting or moving) as a within-subjects factor and age group (5) as a between-subjects factor. F values and partial Eta square values for effect sizes are reported. The alpha level used to interpret statistical significance was $p < .05$. Significant main effects were further investigated by planned t-tests with Bonferroni corrected levels of significance. For paired-samples t-tests, we present Cohen's d_z effect sizes, and for independent-samples t-tests, we present Cohen's d effect sizes.

RESULTS

An ANOVA with condition (2: sitting, moving) as a within-subjects factor and age group (5: grade 1 to 3, grade 4 to 6, grade 7 to 8, grade 10, young adults) as a between-subjects factor was conducted. Figure 2 depicts the pattern of findings. The results show a significant main effect of condition, indicating better cognitive performance in the sitting condition ($M = 10.22$, $SD = 4.02$) compared to the moving condition ($M = 8.54$, $SD = 3.5$), F (1, 143) = 71.09, $p < .001$, $\eta^2_p = .332$. Furthermore, the results show a significant main effect of age group, F (4, 143) = 40.08, $p < .001$, $\eta^2_p = .529$. A post-hoc ANOVA shows a significant linear trend of age group, F (1, 143) = 124,72, $p < .001$, indicating higher cognitive performance with increasing age. The results show a significant interaction of condition and age group, F (4, 143) = 2.87, $p = .025$, $\eta^2_p = .074$. Paired-samples t-tests (with Bonferroni corrected significance levels of $p < .01$) showed that memory performance was significantly better in the sitting than the moving condition for all groups except the youngest (see Table 2).

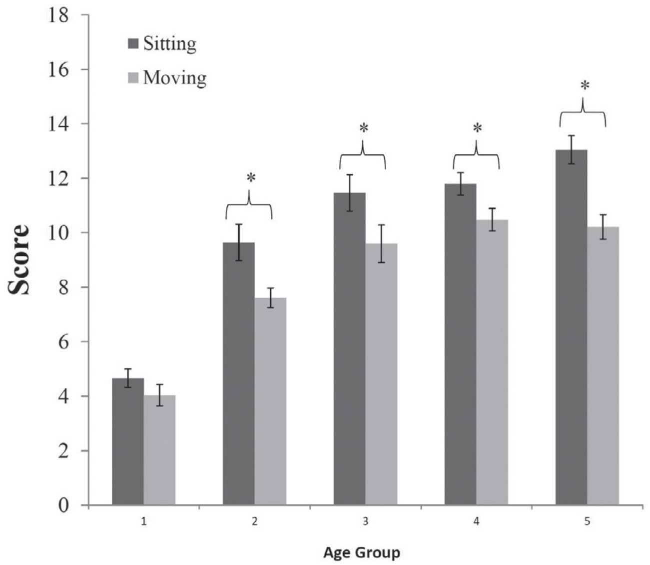

Fig 2. Results of the verbal memory task in the sitting and moving condition for the five age groups. Error bars = SE means.

Table 2
Results of Paired Samples t-Tests comparing the Memory Performance of the Sitting and the Moving Condition for all Age Groups

Age group	*T*	*df*	*p*	d_z
1	1.910	26	.067	.37
2	4.681	27	<.001*	.88
3	4.157	29	<.001*	.76
4	2.940	39	.005*	.46
5	5.069	22	<.001*	1.06

DISCUSSION STUDY 1

The current study is the first to investigate if meaningful full-body movements can improve memorizing sequences of verbal information. However, we found costs instead of performance increases in all age groups except the youngest. In the moving condition, participants walked to the respective location while concurrently working on a cognitive task. Dual-task research predicts that sharing attentional resources between two tasks can lead to performance decrements (Kahneman, 1973; Navon & Gopher, 1979; Schaefer, 2014). Episodic memory tasks often suffer from concurrent walking (Krampe, Schaefer, Lindenberger, & Baltes, 2011; Li, Lindenberger, Freund, & Baltes, 2001; Lindenberger, Marsiske, & Baltes, 2000).

But why did we find no costs in the youngest age group? Maybe younger children rely on physical experiences more than adults, who rather use abstract mental constructs to solve cognitive tasks. This would fit into the concepts of Piaget (1975) and Pouw et al. (2014) who mentioned that physical experiences are especially important for cognition during childhood. Still, we found no performance improvements in the youngest age group. In addition, walking may have disturbed the use of memory strategies (e.g., rehearsal, clustering), which are used more extensively and successfully with increasing age (Ornstein, 1978). A review by Schneider and Sodian (1997) shows that only 40% of 8-year-old children use cognitive memory strategies efficiently.

We also observed that younger children had a tendency to run to the next mat, while older children and adults preferred to walk. These differences in physical activity between the age groups could have influenced cognitive performance (Drollette et al., 2014; Niemann et al., 2013; Tomporowski et al., 2008, 2015). In addition, testing took place in group sessions with up to five participants. It is possible that moving in a group is particularly disturbing.

To counteract these limitations in Study 2, we measured heart rates to monitor physical activity and used smaller target fields to reduce the movement space and to shorten ISIs. This reduces physical activity and exertion and gets closer to the traditional verbal short-term memory task Digit-Span Forward (Petermann & Petermann, 2010). Participants were tested individually to eliminate the influence of group testing. Study 2 investigates whether these experimental adjustments increase the chances to find positive embodiment effects.

Table 3
Study 2 Descriptives and Cognitive Background Information

Age group	*Children*	*Young adults*	*Differences*
N (males/females)	28 (17/11)	34 (16/18)	
Age (years)			
M	7.3	24.5	
Range	7.0–7.9	20.0–51.0	
SD	0.27	6.4	
Digit–symbol substitution (correct items per second)			Age group t (60) = 17.842, $p < .001$, $d = 4.57$
M	0.29	0.71	
SD	0.05	0.12	
Digit-span forward (memory span)			Age group t (60) = 6.739, $p < .001$, $d = 1.74$
M	5.11	7.00	
SD	0.875	1.26	

Note. There were two rather old participants in the young adults' sample, one 43-year-old participant and one 51-year-old participant, who were enrolled as sport students. All other young adults were between 20 and 27 years old. Excluding the two oldest participants from the sample did not change any of the reported effects.

STUDY 2

Method

Participants

Study 2 tested 28 7-year-old children and 34 young adults. Children were recruited via the participant pool of Saarland University, by distributing flyers and by word-of-mouth advertisement. The university students participated in the study in exchange for course credit. The children's parents received 15€ to compensate their expenses. All participants had normal or corrected-to-normal vision and hearing. Participants or their parents provided informed consent. As background variable, cognitive speed was measured with the Digit–Symbol Substitution Task (Wechsler, 1991). In addition, the Digit-Span Forward Test (Petermann & Petermann, 2010) was conducted to have a reference value for verbal memory performance (see Table 3). The memory span depicts the longest sequence of digits that could be remembered correctly. The study was approved by the Ethics Committee of Saarland University.

Experimental Task

Verbal Memory Task. The Verbal Memory Task was similar to that of Study 1, with auditory stimulus presentation. Target fields were 50 × 50 cm wide and directly adjacent (see Figure 3 for experimental setup). The ISI was decreased to 4 s. At the end of a trial, participants reported the string of numbers verbally, and the experimenter scored the result.

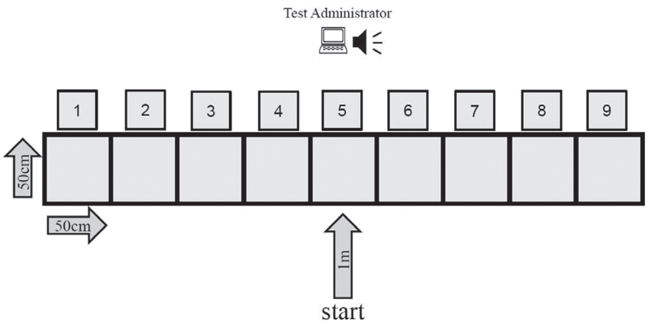

Fig 3. Experimental setup of the verbal memory task in study 2.

All numbers had to be reproduced in correct order. The number sequences ranged from 3 to 7 digits for the children and from 6 to 11 digits for the young adults. The untested sequence scores (lengths 3 to 5) of the young adults were added to their score because testing them would have resulted in ceiling effects. No child except one reached a maximum span length of 7. As in Study 1, the Verbal Memory Task was assessed under two conditions, in counterbalanced order: In the *standing* condition, participants stood in front of the target fields during encoding. In the *moving* condition, participants stepped into each target field during encoding.

Procedure

Participants were tested individually in our laboratory. Their heart rates were continuously monitored (using a Polar heart rate monitor RS44). After assessing the background measures (Digit–Symbol Substitution Task and Digit-Span Forward Task), participants performed the two versions of the Verbal Memory Task, in counterbalanced order. After that, participants worked on a short (20-min) aiming task, which is not part of the currentarticle. Testing sessions lasted between 70 and 90 min.

Data Analysis

The Verbal Memory Task and the heart rate data were analyzed with mixed-design ANOVAs. All other information on data analysis is identical to Study 1.

RESULTS

Verbal Memory Task

The ANOVA with condition (2: standing, moving) as a within-subjects factor and age group (2: children, young adults) as a between-subjects factor was conducted. Figure 4 depicts the pattern of findings. The results show no main effect of condition, F (1, 60) = 1.038, p = .312, η^2_p = .017. There was a main effect of age group, F (1, 60) = 166.336,

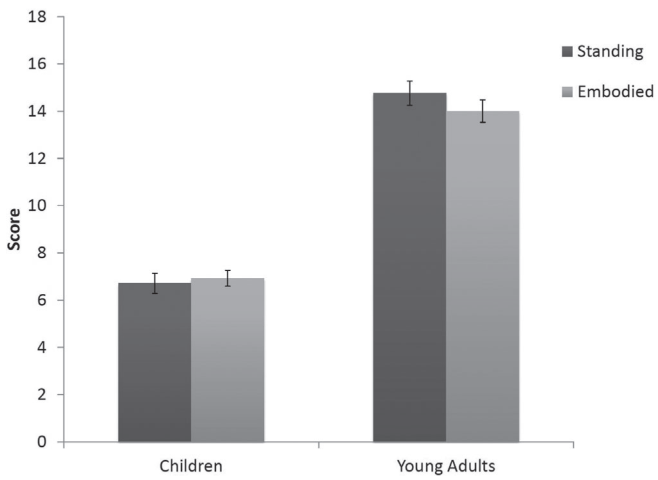

Fig 4. Results of the verbal memory task in the standing and moving condition for children and young adults. Error bars = SE means.

$p < .001$, $\eta^2_p = .735$, indicating a better performance in the memory task for young adults ($M = 14.38$, $SD = 2.6$) compared to children ($M = 6.82$, $SD = 1.8$). Furthermore, the results show no interaction of condition and age group, F (1, 60) = 3.285, $p = .075$, $\eta^2_p = .052$.

Heart Rate

The ANOVA with condition (2) as a within-subjects factor and age group (2) as a between-subjects factor was conducted. There was a significant main effect of condition, F (1, 60) = 17.525, $p < .001$, $\eta^2_p = .226$, indicating a higher overall heart rate in the moving condition ($M = 98.65$, $SD = 18.34$) compared to the standing condition ($M = 93.23$, $SD = 16.82$). There was a main effect of age group, F (1, 60) = 89.928, $p < .001$, $\eta^2_p = .600$, because of higher heart rates in children ($M = 110.1$, $SD = 9.11$) compared to young adults ($M = 84.26$, $SD = 11.81$). Furthermore, the results show a marginally significant interaction of condition and age group, F (1, 60) = 3.720, $p = .058$, $\eta^2_p = .058$. Paired-samples t-tests (with a Bonferroni corrected $p < .025$) indicate that there is no difference in heart rate between the standing ($M = 82.74$, $SD = 12.79$) and moving ($M = 85.79$, $SD = 13.03$) condition for young adults, t (33) = 1.712, $p = .096$, $d_z = .29$. However, the difference between the standing ($M = 105.96$, $SD = 11.51$) and moving ($M = 114.25$, $SD = 9.61$) condition reached significance in children, t (27) = 4.036, $p < .001$, $d_z = .76$.

GENERAL DISCUSSION

The two studies of the current article were designed to reveal embodiment effects in a memory task connecting verbal with spatial information. The concept of embodied cognition argues that higher cognitive processes are deeply connected with sensorimotor experiences and bodily states (Wilson, 2002). Based on the literature on positive embodiment effects in children's cognition (Hainselin et al., 2017; Link et al., 2013; Mavilidi et al., 2016; Schaefer, 2018), we predicted that younger children should profit more from embodiment than older children and young adults. However, contrary to our predictions, Study 1 found costs in verbal memory performance during walking for all age groups except the youngest, and Study 2 found no differences between walking and standing in 7-years-olds and young adults. Methodological differences between Study 1 and Study 2 may have caused the observed differences in the results.

The smaller size and the shorter distances between the target fields in Study 2 decreased locomotion demands. Instead of walking distances of several meters to reach the next gymnastics mat, participants simply had to step into the next target field. This probably decreased the cognitive load of the secondary motor task (=reaching the target field in time). In addition, individualized testing assured that distractions from other participants were excluded. The rather long ISIs in the memory task provided participants with enough time to step into the target fields. However, they may have allowed for more strategic encoding activities, which are particularly helpful for the young adults (Schneider & Sodian, 1997).

Research on acute effects of physical exercise shows that moving while working on a cognitive task can lead to performance increases (Davranche & McMorris, 2009; Schaefer, Lövdén, Wieckhorst, & Lindenberger, 2010). For Study 2, the heart rate was monitored throughout the whole session. As expected from normal physiological development (Fleming et al., 2011), children's heart rates were higher than adults'. In addition, heart rates did not differ between moving and standing for young adults, but the moving condition physically activated the children. However, the average heart rate while moving only reached 114 beats/min in children, which is likely too low to induce cognitive improvements (around 60% of maximum heart rate = 128 beats/min, see Verburgh, Königs, Scherder, & Oosterlaan, 2014). The physical activity of Study 1 was probably also insufficient to increase memory performance. Future studies should address this issue in more detail.

In embodied cognition paradigms, movements are generally performed during a cognitive process (e.g., encoding words and digits) and are designed to be meaningful for the cognitive task. When designing the study, we assumed that moving one's body to a specific location in space should help participants to create a memory trace, leading to higher recall success when reconstructing the sequence of target locations. We additionally predicted that this should be more helpful for children, who do not have other efficient encoding strategies yet. Because we used numbers from 1 to 9 that corresponded to specific locations in space, participants could also rely on the number information and neglect the spatial information. In addition, numbers were also presented auditorily, allowing for covert verbal rehearsal strategies as well. To frame it in relation to Baddeley's model (Baddeley, 2000), participants could use either the visuospatial sketchpad or the phonological loop to keep the content in short-term memory until it had to be recalled. Despite having two options to memorize the number sequences, it is possible that participants used more than one modality to create the strongest memory trace possible (Dijkstra & Zwaan, 2014).

Skulmowski and Rey (2018b) recently suggested a taxonomy for embodiment in educational settings. They distinguish the dimensions "task integration" and "bodily engagement." The authors argue that if bodily activities are integrated into the learning task and participants perform bodily movements and locomotion (as opposed to a sitting condition), embodiment effects are larger (Skulmowski & Rey, 2018a). Our moving version of the memory tasks definitely required locomotion and bodily movements, but our multimodal stimulus presentation did not maximize the integration of physical activities into the learning strategies. In future research, embodiment effects could be triggered by creating tasks that enforce the physical encoding of specific locations in space (e.g., embodied versions of the Corsi block task, Belmonti, Cioni, & Berthoz, 2015; Piccardi et al., 2008; Piccardi et al., 2014). The aspects of cognitive load and bodily effort should also be considered when planning future studies in this domain (Skulmowski & Rey, 2017a, 2017b). Mavilidi et al. (2018) also have proposed a conceptual framework combining the exercise and cognition research with the embodied cognition research into a blended approach. They emphasize gross movements with high intensity, high task relevance (which resembles the dimension "task integration" from Skulmowski & Rey, 2018a), and high temporal connection of the movement and the cognitive task.

There were slight indications in the current studies that the youngest children (~8 years old) do react more favorably to embodiment because they did not show costs compared to older participants in Study 1. Given that studies demonstrate embodiment effects in preschool children (Fischer et al., 2011; Mavilidi et al., 2016, 2017), even younger children maybe would have shown positive embodiment effects. This effect could be enhanced if the to-be-learned information was driven by new associations instead of known experiences (Loeffler et al., 2016).

CONCLUSION

While embodiment has been shown to be effective when teaching new knowledge like number magnitude (Link et al., 2013) or gravity (Lindgren et al., 2016), it is still unclear if embodiment can also help to maintain information for shorter periods of time. The results of the current studies showed that linking verbal information with full-body movements and spatial information did not enhance memory performance. This may have been because of a suboptimal study design, leaving too much room for additional strategic options (like verbal rehearsal) to encode and reconstruct the number sequences. Embodiment may be more effective in enhancing cognitive tasks involving understanding and long-term memory. As Kosmas and Zaphiris (2018) put it, further experimental research is needed to clarify the relation between embodiment and abstract representations.

Acknowledgments—The authors would like to thank Nora Matheis, Linda Betzler, Heiko Lesch, and Ann-Kathrin Rohe for their help with collecting and entering the data and Claudia Roebers, Andreas Korbach, and Roland Brünken for helpful discussions. This work was supported by Saarland University. Open Access funding enabled and organized by Projekt DEAL.

SUPPORTING INFORMATION

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

Appendix S1: Supplementary material

REFERENCES

Baddeley, A. D. (2000). Working memory. In A. E. Kazdin (Ed.), *Encyclopedia of psychology*. (Vol. *8*, pp. 276–279). London: Oxford University Press.

Barsalou, L. W. (1999). Perceptual symbol systems. *Behavioral and Brain Sciences*, *22*(4), 577–660. https://doi.org/10.1017/s0140525x99002149

Barsalou, L. W. (2008). Grounded cognition. *Annual Review of Psychology*, *59*, 617–645. https://doi.org/10.1146/annurev.psych.59.103006.093639

Belmonti, V., Cioni, G., & Berthoz, A. (2015). Switching from reaching to navigation: Differential cognitive strategies for spatial memory in children and adults. *Developmental Science*, *18*, 569–586. https://doi.org/10.1111/desc.12240

Davranche, K., & McMorris, T. (2009). Specific effects of acute moderate exercise on cognitive control. *Brain and Cognition*, *69*, 565–570. https://doi.org/10.1016/j.bandc.2008.12.001

Diamond, A. (2000). Close interrelation of motor development and cognitive development and of the cerebellum and prefrontal cortex. *Child Development*, *71*, 44–56. https://doi.org/10.1111/1467-8624.00117

Dijkstra, K., & Zwaan, R. A. (2014). Memory and action. In L. Shapiro (Ed.), *The Routledge handbook of embodied cognition*. (pp. 296–305). New York: Routledge.

Drollette, E. S., Scudder, M. R., Raine, L. B., Moore, R. D., Saliba, B. J., Pontifex, M. B., & Hillman, C. (2014). Acute exercise facilitates brain function and cognition in children who need it most: An ERP study of individual differences in inhibitory control capacity. *Developmental Cognitive Neuroscience*, *7*, 53–64. https://doi.org/10.1016/j.dcn.2013.11.001

Engelkamp, J., & Cohen, R. L. (1991). Current issues in memory of action events. *Psychological Research*, *53*, 175–182. https://doi.org/10.1007/BF00941384

Fischer, U., Moeller, K., Bientzle, M., Cress, U., & Nuerk, H.-C. (2011). Sensori-motor spatial training of number magnitude representation. *Psychonomic Bulletin & Review*, *18*, 177–183. https://doi.org/10.3758/s13423-010-0031-3

Fleming, S., Thompson, M., Stevens, R., Heneghan, C., Pluddemann, A., Maconochie, I., … Mant, D. (2011). Normal ranges of heart rate and respiratory rate in children from birth to 18 years of age: A systematic review of observational studies. *Lancet*, *377*, 1011–1018. https://doi.org/10.1016/s0140-6736(10)62226-x

Gathercole, S. (1999). Cognitive approaches to the development of short-term memory. *Trends in Cognitive Sciences*, *3*, 410–419.

Glenberg, A. M. (2010). Embodiment as a unifying perspective for psychology. *Wiley Interdisciplinary Reviews: Cognitive Science*, *1*, 586–596. https://doi.org/10.1002/wcs.55

Hainselin, M., Picard, L., Manolli, P., Vankerkore-Candas, S., & Bourdin, B. (2017). Hey teacher, don't leave them kids alone: Action is better for memory than reading. *Frontiers in Psychology*, *8*, 325. https://doi.org/10.3389/fpsyg.2017.00325

Hillman, C., Kamijo, K., & Scudder, M. R. (2011). A review of chronic and acute physical activity participation on neuroelectric measures of brain health and cognition during childhood. *Preventive Medicine*, *52S*, S21–S28. https://doi.org/10.1016/j.ypmed.2011.01.024

Isaacs, E. B., & Vargha-Khadem, F. (1989). Differential course of development of spatial and verbal memory span: A normative study. *British Journal of Developmental Psychology*, *7*(4), 377–380. https://doi.org/10.1111/j.2044-835X.1989.tb00814.x

Jahn, P., & Engelkamp, J. (2003). Design effects in prospective and retrospective memory for actions. *Experimental Psychology*, *50*, 4–15. https://doi.org/10.1027//1618-3169.50.1.4

Kahneman, D. (1973) *Attention and effort*. Englewood Cliffs, NJ: Prentice-Hall.

Kiefer, M., & Trumpp, N. (2012). Embodiment theory and education: The foundations of cognition in perception and action. *Trends in Neuroscience and Education*, *1*, 15–20. https://doi.org/10.1016/j.tine.2012.07.002

Kosmas, P., Ioannou, A., & Retalis, S. (2018). Moving bodies to moving minds: A study of the use of motion-based games in special education. *TechTrends*, *62*(6), 594–601. https://doi.org/10.1007/s11528-018-0294-5

Kosmas, P., Ioannou, A., & Zaphiris, P. (2019). Implementing embodied learning in the classroom: Effects on children's memory and language skills. *Educational Media International*, *56*(1), 59–74. https://doi.org/10.1080/09523987.2018.1547948

Kosmas, P., & Zaphiris, P. (2018). Embodied cognition and its implications in education: An overview of recent literature. *World Academy of Science, Engineering and Technology*, *12*, 930–936. https://doi.org/10.1999/1307-6892/10009334

Kosmas, P., & Zaphiris, P. (2020). Words in action: Investigating students' language acquisition and emotional performance through embodied learning. *Innovation in Language Learning and Teaching*, *14*(4), 317–332. https://doi.org/10.1080/17501229.2019.1607355

Krampe, R. T., Schaefer, S., Lindenberger, U., & Baltes, P. B. (2011). Lifespan changes in multi-tasking: Concurrent walking and memory search in children, young, and older adults. *Gait and Posture*, *33*, 401–405. https://doi.org/10.1016/j.gaitpost.2010.12.012

Li, K. Z. H., Lindenberger, U., Freund, A. M., & Baltes, P. B. (2001). Walking while memorizing: Age-related differences in compensatory behavior. *Psychological Science*, *12*, 230–237. https://doi.org/10.1111/1467-9280.00341

Li, S.-C., Lindenberger, U., Hommel, B., Aschersleben, G., Prinz, W., & Baltes, P. B. (2004). Transformations in the couplings among intellectual abilities and constituent cognitive processes across the life span. *Psychological Science*, *15*, 155–163. https://doi.org/10.1111/j.0956-7976.2004.01503003.x

Lindenberger, U., Marsiske, M., & Baltes, P. B. (2000). Memorizing while walking: Increase in dual-task costs from young adulthood to old age. *Psychology and Aging*, *15*, 417–436. https://doi.org/10.1037/0882-7974.15.3.417

Lindgren, R., Tscholl, M., Wang, S., & Johnson, E. (2016). Enhancing learning and engagement through embodied interaction within a mixed reality simulation. *Computers & Education*, *95*, 174–187. https://doi.org/10.1016/j.compedu.2016.01.001

Link, T., Moeller, K., Huber, S., Fischer, U., & Nuerk, H.-C. (2013). Walk the number line - An embodied training of numerical concepts. *Trends in Neurosciences and Education*, *2*, 74–84. https://doi.org/10.1016/j.tine.2013.06.005

Loeffler, J., Raab, M., & Canal-Bruland, R. (2016). A lifespan perspective on embodied cognition. *Frontiers in Psychology*, *7*, 1–6. https://doi.org/10.3389/fpsyg.2016.00845

Lozada, M., & Carro, N. (2016). Embodied action improves cognition in children: Evidence from a study based on piagetian conservation tasks. *Frontiers in Psychology*, *7*(393). https://doi.org/10.3389/fpsyg.2016.00393

Manzi, A., & Nigro, G. (2008). Long-term memory for performed and observed actions: Retrieval awareness and source monitoring. *Memory*, *16*, 595–603. https://doi.org/10.1080/09658210802070749

Mavilidi, M.-F., Okely, A. D., Chandler, P., & Paas, F. (2016). Infusing physical activities into the classroom: Effects on preschool children's geography learning. *Mind, Brain, and Education*, *10*, 256–263. https://doi.org/10.1111/mbe.12131

Mavilidi, M.-F., Okely, A. D., Chandler, P., & Paas, F. (2017). Effects of integrating physical activities into a science lesson on preschool children's learning and enjoyment. *Applied Cognitive Psychology*, *31*, 281–290. https://doi.org/10.1002/acp.3325

Mavilidi, M. F., Ruiter, M., Schmidt, M., Okely, A. D., Loyens, S., Chandler, P., & Paas, F. (2018). A narrative review of school-based physical activity for enhancing cognition and learning: The role of relevancy and integration. *Frontiers in Psychology*, *9*, 2079. https://doi.org/10.3389/fpsyg.2018.02079

Navon, D., & Gopher, D. (1979). On the economy of the human-processing system. *Psychological Review*, *86*, 214–255. https://doi.org/10.1037/0033-295X.86.3.214

Niemann, C., Wegner, M., Voelcker-Rehage, C., Holzweg, M., Arafat, A. M., & Budde, H. (2013). Influence of acute and chronic physical activity on cognitive performance and saliva testosterone in preadolescent school children. *Mental Health and Physical Activity*, *6*, 197–204. https://doi.org/10.1016/j.mhpa.2013.08.002

Ornstein, P. A. (1978) *Memory development in children*. Hillsdale, NJ: Lawrence Erlbaum associates.

Petermann, F., & Petermann, U. (Eds.) (2010) *HAWIK IV*. (3rd ed.). Bern: Huber.

Piaget, J. (1975) *L'équilibration des structures cognitives- problème central du développement*. Paris: Presses Universitaires de France.

Piccardi, L., Iaria, G., Ricci, M., Bianchini, F., Zompanti, L., & Guariglia, C. (2008). Walking in the Corsi test: Which type of memory do you need? *Neuroscience Letters*, *432*, 127–131. https://doi.org/10.1016/j.neulet.2007.12.044

Piccardi, L., Palermo, L., Leonzi, M., Risetti, M., Zompanti, L., D'Amico, S., & Guariglia, C. (2014). The walking Corsi test (WalCT): A normative study of topographical working memory in a sample of 4- to 11-year-olds. *The Clinical Neuropsychologist*, *28*, 84–96. https://doi.org/10.1080/13854046.2013.863976

Pouw, W. T. J. L., van Gog, T., & Paas, F. (2014). An embedded and embodied cognition review of instructional manipulatives. *Educational Psychology Review*, *26*, 51–72. https://doi.org/10.1007/s10648-014-9255-5

Ruiter, M., Loyens, S., & Paas, F. (2015). Watch your step children! Learning two-digit numbers through mirror-based observation of self-initiated body movements. *Educational Psychology Review*, *27*, 457–474. https://doi.org/10.1007/s10648-015-9324-4

Schaefer, S. (2014). The ecological approach to cognitive-motor dual-tasking: Findings on the effects of expertise and age. *Frontiers in Psychology*, *5*, 1–9. https://doi.org/10.3389/fpsyg.2014.01167

Schaefer, S. (2018). Embodiment helps children solve a spatial working memory task: Interactions with age and gender. *Journal of Cognitive Enhancement.*, *3*, 233–244. https://doi.org/10.1007/s41465-018-0081-4

Schaefer, S., Lövdén, M., Wieckhorst, B., & Lindenberger, U. (2010). Cognitive performance is improved while walking: Differences in cognitive-sensorimotor couplings between children and young adults. *European Journal of Developmental Psychology*, *7*, 371–389. https://doi.org/10.1037/0012-1649.44.3.747

Schmidt, M., Benzing, V., Wallman-Jones, A., Mavilidi, M.-F., Lubans, D. R., & Paas, F. (2019). Embodied learning in the classroom: Effects on primary school children's attention and foreign language vocabulary learning. *Psychology of Sport and Exercise*, *43*, 45–54. https://doi.org/10.1016/j.psychsport.2018.12.017

Schneider, W., & Sodian, B. (1997). Memory strategy development: Lessons from longitudinal research. *Developmental Review*, *17*, 442–461. https://doi.org/10.1006/drev.1997.0441

Skulmowski, A., & Rey, G. D. (2017a). Bodily effort enhances learning and metacognition: Investigating the relation between physical effort and cognition using dual-process models of embodiment. *Advances in Cognitive Psychology*, *13*, 3–10. https://doi.org/10.5709/acp-0202-9

Skulmowski, A., & Rey, G. D. (2017b). Measuring cognitive load in embodied learning settings. *Frontiers in Psychology*, *8*, 1191. https://doi.org/10.3389/fpsyg.2017.01191

Skulmowski, A., & Rey, G. D. (2018a). Adjusting sample sizes for different categories of embodied cognition research. *Frontiers in Psychology*, *9*, 2384. https://doi.org/10.3389/fpsyg.2018.02384

Skulmowski, A., & Rey, G. D. (2018b). Embodied learning: Introducing a taxonomy based on bodily engagement and task integration. *Cognitive Research: Principles and Implications*, *3*, 6. https://doi.org/10.1186/s41235-018-0092-9

Tomporowski, P. D. (2003). Effects of acute bouts of exercise on cognition. *Acta Psychologica*, *112*, 297–324. https://doi.org/10.1016/S0001-6918(02)00134-8

Tomporowski, P. D., Davis, C. L., Miller, P. H., & Naglieri, J. A. (2008). Exercise and children's intelligence, cognition, and academic achievement. *Educational Psychology Review*, *20*, 111–131. https://doi.org/10.1007/s10648-007-9057-0

Tomporowski, P. D., McCullick, B., Pendleton, D. M., & Pesce, C. (2015). Exercise and children's cognition: The role of exercise characteristics and a place for metacognition. *Journal of Sport and Health Science*, *4*, 47–55. https://doi.org/10.1016/j.jshs.2014.09.003

Toumpaniari, K., Loyens, S., Mavilidi, M.-F., & Paas, F. (2015). Preschool children's foreign language vocabulary learning by embodying words through physical activity and gesturing. *Educational Psychological Review*, *27*, 445–456. https://doi.org/10.1007/s10648-015-9316-4

Vazou, S., Pesce, C., Lakes, K., & Smiley-Oyen, A. (2016). More than one road leads to Rome: A narrative review and meta-analysis of physical activity intervention effects on cognition in youth. *International Journal of Sport and Exercise Psychology*, *17*, 1–26. https://doi.org/10.1080/1612197X.2016.1223423

Verburgh, L., Königs, M., Scherder, E. J. A., & Oosterlaan, J. (2014). Physical exercise and executive functions in preadolescent children, adolescents and young adults: A meta-analysis. *British Journal of Sports Medicine*, *48*, 973–979. https://doi.org/10.1136/bjsports-2012-091441

Wechsler, D. (1991) *Manual for the Wechsler intelligence scale for children*. (3rd ed.). San Antonio, TX: The Psychological Corporation.

Wilson, M. (2002). Six views of embodied cognition. *Psychonomic Bulletin & Review*, *9*, 625–636. https://doi.org/10.3758/BF03196322