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ORIGINAL RESEARCH

Embodied Counting: Touching Objects Reduces Errors in Counting Under Cognitive Load

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Abstract

The framework of embodied cognition argues that cognitive operations are closely linked to physical states of the body, and that movement acts can support cognition if they are meaningfully related to the task. The current study asked young adults ($N = 54$) to repeatedly count different arrays of colored chocolate lentils and to either report the results immediately for each color ("no load"), or only after all five colors had been counted ("load"). In "embodied" trials, participants were free to point at, touch, and re-arrange the lentils. In the "look only" trials, subjects were not allowed to use their hands. Participants performed all possible task combinations in a repeated-measures design. There were no differences in counting times or error rates between "embodied" and "look only" trials in the no load conditions, when reporting each number immediately. When the cognitive load was added, errors rates were reduced in the "embodied" as compared to the "look only" condition, without increments in counting times. It is assumed that touching and re-arranging the lentils enabled participants to "off-load" cognitive load onto the environment (Wilson, *Psychonomic Bulletin & Review 9*, 625–636, 2002). Although counting objects is a rather easy task for young adults, embodiment can support cognitive performances when task difficulty is increased by introducing a cognitive load.

Keywords Embodied cognition · Counting · Gestures · Touch · Working memory load · Memory span

Introduction

Imagine that you are asked to count different categories of small objects lying in front of you on a table. Would you use your body to support the counting, for example by pointing at the objects one-by-one, or by touching and sorting them? Or would you only look at the array of objects while counting? Would your preferred strategy maybe also depend on how many different categories are part of the array, and on the time-span for which you need to keep the counting results in memory?

For a long time, paradigms used in cognitive psychology have aimed at reducing the influence of bodily movements on the outcome variables of interest (e.g., reaction times or errors). Asking participants to press buttons on a computer keyboard was assumed to represent a "purer" measure of cognitive processes, keeping the variance introduced by body movements as small as possible. In real life, however, we often engage our body when solving cognitive tasks. Over the last years, the concept of "embodiment" has received increasing research attention (for an overview, see Barsalou, 2008, 2010; Glenberg, 2010, 2013; Ionescu & Vasc, 2014; Kiefer & Trumpp, 2012; Loeffler et al., 2016; for critiques, see Caramazza et al., 2014; Goldinger et al., 2016). In this framework, cognition is understood as "enactive," as a skillful activity involving an ongoing interaction with the external world (Engel et al., 2013).

In her influential paper, Wilson (2002) argued that "embodiment" includes situations in which cognitive work is "off-loaded" onto the environment. She states: "Because of limits in our information-processing abilities (e.g., limits on attention and working memory), we exploit the environment to reduce the cognitive workload. We make the environment hold or even manipulate information for us, and we harvest that information only on a need-to-know basis." (page 626). Writing down a list of shopping items could be an example of off-loading to avoid memorizing, but off-loading can also be used to "avoid encoding or holding active in short-term

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memory what is present in the immediate environment" (Wilson, 2002, page 928–929).

The current study aims to investigate whether embodiment—operationalized as the possibility to point at, touch, or physically re-arrange the to-be-counted objects—influences counting speed and accuracy, and whether adding a cognitive load to the counting task exacerbates the effects. The opportunity to physically interact with the to-be-counted objects allows for "off-loading" mental work onto the environment, which is not possible when only looking at the objects.

Counting is a cognitive skill that is acquired relatively early during ontogeny. Studies on cognitive development show that gesturing is helpful when children learn to count in early childhood (Alibali & DiRusso, 1999; Graham, 1999; Gunderson et al., 2015; Saxe & Kaplan, 1981; Wakefield et al., 2019), and that enactive experiences help 3-year-olds to promote their early number understanding (Coccoz et al., 2019). Gestures may be a form of "off-loading" that is effective in some kinds of cognitive tasks (Khatin-Zadeh et al., 2022). Based on the developmental literature, using gestures or other functional acts like touching or re-arranging objects when counting should be particularly helpful for younger children. However, when the counting task is difficult, using the body may "pay off" even in young adulthood. In the current study, counting is performed with the instruction to "only look" at the array of objects, or in an "embodied" condition in which participants are allowed to point at, touch, or re-arrange the to-be-counted objects. Subjects are instructed to count chocolate lentils belonging to five different colors. In some of the experimental trials, task difficulty of the counting task is increased: Instead of writing down the results for each color immediately, participants are instructed to write down the results for the five colors only at the end of the trial. This adds a cognitive load to the task, similar to counting span or reading span tasks (Case et al., 1982; Conway et al., 2005; Daneman & Carpenter, 1980), since participants have to store in memory the total from each subcategory for later recall.

Wilson and Golonka (2013) argue that research on embodied cognition should start with a task analysis, which characterizes from a first-person perspective the specific task that a person is faced with. Researchers should address the following questions: What are the task-relevant resources that can be used to solve the task, and how can the resources (spanning brain, body, and environment) be assembled to solve the task at hand? In the current study, the "counting with load" task in the "embodied" condition allows for an "off-loading" of mental load to the environment. It is hypothesized that when the lentils can be pointed at, touched, and re-arranged into meaningful patterns, remembering the exact number of objects for each subcategory will be easier than when participants are only allowed to look at the lentils. When writing down the numbers at the end of the trial, taking a quick look at the sorted array will support memory for the result, and should reduce the number of recall errors. However, the counting of the objects may take longer if items are touched or re-arranged, as compared to the "look only" condition. I therefore predict that embodiment does not have an influence on counting times and accuracies in the "no load" condition. When cognitive load is added, embodiment is predicted to cause longer trial times, but lower error rates, compared to the "look only" condition.

Method

Participants

Due to the lack of published data in the domains of interest, the effect sizes of previous studies could not be used for a priori power analyses. I assumed the effects to be small or medium sized. Using a within-subjects design increases the power to detect the effects of interest. I reasoned that testing about 50 participants would be a sufficiently large sample for the current study, given that data would be collected with 24 counting trials over the course of eight testing sessions. The study was preregistered (https://researchbox.org/4011), and the study design was approved by the Ethics committee of Saarland University.

Fifty-four sports students from the Saarland University participated in the study ($M_{age} = 23.09$ years; $SD_{age} = 4.14$ years; age range = 19–38 years; 16 women, 38 men) in exchange for course credit. All participants had normal or corrected-to-normal vision and hearing, did not suffer from color blindness, and gave informed consent to the study. The data collection took place in three pre-established seminar groups ($n = 25$ in group 1, $n = 8$ in group 2, and $n = 21$ in group 3). Note that the seminar groups only differed concerning the exact order of experimental conditions (see Table 1 for details), but all participants contributed data to all conditions in a 2 × 2 repeated-measures design.

As a background variable, cognitive speed was measured with the Digit Symbol Substitution task (Wechsler, 1981). This paper-and-pencil test requires participants to quickly and accurately copy specific symbols belonging to the digits

Table 1 Cognitive background information by seminar group: Digit Symbol test score

Group	*n*	*M*	*SD*	*95% CI*
1	25	71.84	10.01	[67.71, 75.97]
2	8	65.38	13.46	[51.12, 76.63]
3	19	71.84	12.18	[65.97, 77.71]

Note. *CI*, confidence interval of the mean from 1 to 9 into the corresponding empty cells on the testing sheet. A testing trial lasted 90 s, and the dependent variable was the number of correctly filled cells. An ANOVA with seminar group as between-subjects factor showed no differences in cognitive speed across the three groups, $F(2,49)=1.093$, $p=0.343$ (see Table 1).[1] In addition, Digit Symbol scores corresponded well to young adults' samples in other representative studies (see, for example, Schmiedek et al., 2010).

Experimental Task: Counting Chocolate Lentils

Participants were given paper cups containing chocolate lentils (similar to M & M's) in five different colors: yellow, red, blue, green, brown. Each of the 33 sets used in the current study contained between 98 and 101 lentils. On average, there were 20 lentils per color in each set, but the exact number of lentils for a specific color could vary between five and 33 lentils across sets. The task was to count the lentils for each color. Participants were instructed to document the set number for the respective trial on their testing sheet. The counting task was performed while sitting on a chair, and all participants of each seminar group worked on the task concurrently. Each trial started with all participants holding a paper cup with a new set in their hands. After the "go" signal, participants emptied the contents of their cups onto a small piece of carpet (about 35 × 25 cm), allowing them to see each lentil of the overall set. A running timer was projected onto the wall of the testing room. Participants wrote down the numbers for each color in their testing sheets, using a pre-specified table. As soon as they had written down the last number of their set, they recorded their finishing time on the sheet. Participants were instructed to focus on speed and accuracy in the counting task. The dependent variables of the counting task were the times taken to finish counting the entire set and the sum of errors for each trial. If participants deviated by one item from the true number of lentils for a specific color, this was recorded as one error. For example, if there were 17 yellow lentils in the set, but a participant reported 19 lentils, this was coded as 2 errors. Errors were summed over the five colors for each trial. Over the course of the study, counting took place under different instructions (see below). To increase motivation, participants were informed that the most successful candidates of each seminar group would receive monetary rewards (15 Euro, 10 Euro, 5 Euro) for their combined performance score at the end of the data collection. The combined performance score was calculated by adding three extra seconds to the counting time for each error. Note that the score was only used to come up with a combined performance measure for the award ceremony, and it is not the dependent variable of the current study. Due to differences in participant numbers across the three groups, the six most successful participants received money in seminar groups 1 ($n=25$) and 3 ($n=19$), and the three most successful participants received money in seminar group 2 ($n=8$).

Counting While Touching and Moving the Lentils ("Embodied") or While "Looking Only"

In some "embodied" trials, participants were allowed to point at, to touch, or to move the lentils during counting. Each individual was free to choose their preferred way of handling the lentils. In the trials of the "looking only" condition, participants were instructed to leave their hands on their lap while counting the lentils.

Counting With and Without Cognitive Load

For the counting trials of the "no load" condition, participants were instructed to write down the number for each of the five colors immediately after they had finished counting a specific color. For example, a subject counts 22 red lentils, writes down the number in the respective cell of the answer sheet, and moves on to the next color. For the "load" condition, participants had to count all five colors and then write down all the resulting numbers at the end of the counting trial. This adds a cognitive load to the task, since participants have to store in memory the total from each color for later recall. The testing sheets included a visual reminder to only write down the numbers at the end of the trial in the "load" condition.

Procedure

The study consisted of eight sessions. In session 1, participants provided informed consent, filled in a demographic questionnaire, and worked on the Digit Symbol Substitution test (Wechsler, 1981). Four trials of the Counting task were assessed in each session. Before each trial started, participants received a new set which they had not worked on in the respective session. Participants exchanged their sets with other participants before the next trial, and always recorded their set number on the testing sheets. Within each session, trials 1 and 2 were always assessed in the "no load" condition (writing down each number immediately) and trials 3 and 4 in the "load" condition (writing down each number only after all colors had been counted). All groups started and ended the study with the "embodied" counting task in sessions 1 (pretest) and 8 (posttest). For sessions 2 to 7, the "embodied" versus "looking only" conditions varied according to seminar group, with group 1 starting with the

[1] Please note that there were missing data on the Digit Symbol for two participants of group 3 who missed the respective session.

Table 2 Experimental procedure by seminar group and session

Session	Group 1	Group 2	Group 3
1	Pretest Counting (Embodied)	Pretest Counting (Embodied)	Pretest Counting (Embodied)
2	Counting Embodied	Counting Looking	Counting Looking
3	Counting Looking	Counting Embodied	Counting Embodied
4	Counting Embodied, Glasses	Counting Looking, Glasses	Counting Looking, Glasses
5	Counting Looking, Glasses	Counting Embodied, Glasses	Counting Embodied, Glasses
6	Counting Embodied	Counting Looking	Counting Looking
7	Counting Looking	Counting Embodied	Counting Embodied
8	Posttest Counting (Embodied)	Posttest Counting (Embodied)	Posttest Counting (Embodied)

Note. The order of "embodied" and "looking only" trials was counterbalanced across groups. There were two "no load" trials and two "load" trials in each session. Sessions 4 and 5 were conducted with participants wearing glasses which made their vision blurry. This manipulation did not influence counting performances

"embodied" condition and groups 2 and 3 with the "looking only" condition (see Table 2). In sessions 4 and 5, participants were asked to wear glasses which made their vision blurry, as a module of an age simulation suit (Vieweg & Schaefer, 2020). However, this manipulation did not influence counting performances, and there were no interactions of the glasses factor with any of the other factors of interest. Therefore, it is not included as a separate factor in the analyses of the current study.

Analyses

As depicted in Table 2, counting performances were collected over the course of eight sessions, with two trials in the "no load" and two trials in the "load" condition in each session. Finishing times were recorded on the testing sheets and transformed into seconds for the analyses (e.g., 1 min, 27 s = 87 s). To score the errors, deviations from the correct number of lentils for each color were summed over all colors of a specific set.[2]

Times and error rates were averaged across all trials for the following conditions of sessions 2 to 7: (a) no load, embodied; (b) with load, embodied; (c) no load, looking only; and (d) with load, looking only. Note that data from the pre- and posttest sessions, which always took place under "embodied" instructions, were not included when calculating these averages. Some participants missed individual sessions, such that 33 out of 54 participants provided a complete data set. Due to the large number of trials collected over the course of experimental sessions, mean values for each dependent variable could be calculated for each participant. Cronbach's alpha is reported for the reliability of the times and errors. Times were analyzed with repeated-measures analyses of variance (ANOVA) with the factors embodiment (2: "embodied" versus "looking only") and load (2: "no load" versus "load"). F values and partial Eta square values for effect sizes are reported. Due to problems with normality assumptions for the error data, Wilcoxon tests for paired samples were used to detect differences in errors between the two load conditions and the two embodiment conditions. The alpha level used to interpret statistical significance in the analyses was 0.05. Significant main effects were further investigated by paired-samples t-tests with Bonferroni corrected levels of significance to $p < 0.016$.

Results

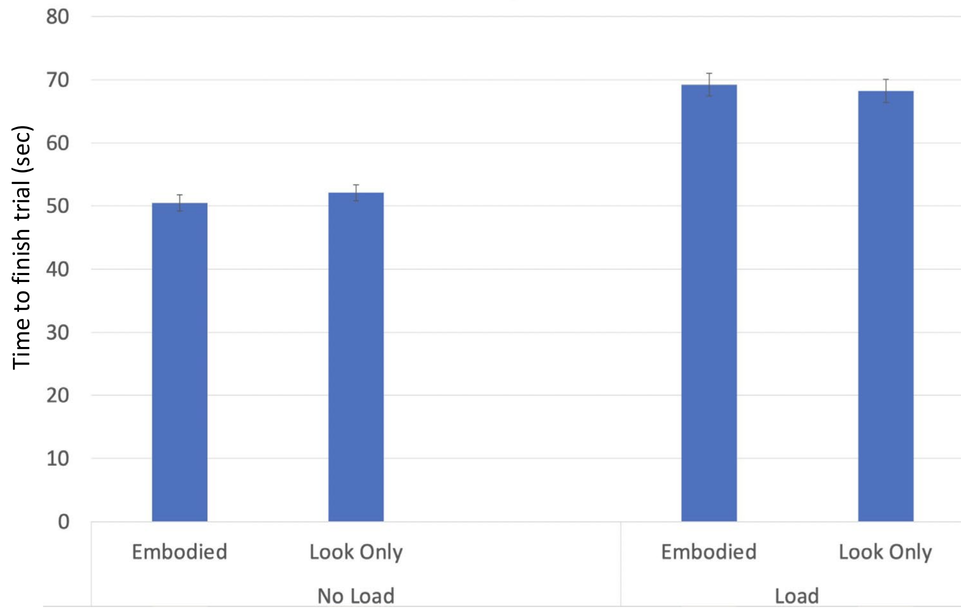
Finishing Times

The reliability coefficient based on the 32 trials measuring times for the counting task was excellent ($\alpha = 0.935$), indicating that interindividual differences in finishing times remained stable over consecutive trials. The Kolmogorov–Smirnov tests for the four averaged dependent time variables showed that data were normally distributed (all $ps > 0.05$.).

Figure 1 presents the results for the finishing times by condition. The repeated-measures ANOVA with embodiment (2: "embodied" versus "looking only") and load (2: "no load" versus "load") showed that embodiment did not influence finishing times, $F(1, 53) = 0.050$; $p = 0.823$;

[2] There were some instances in which a specific set did not include the correct number of lentils any more at the end of the testing session. This was due to errors occurring when participants put the lentils back into the corresponding paper cup. In rare instances, a lentil may end up in the paper cup of somebody else's set. Since it was not possible to reconstruct when this error had happened in a specific session, both possible solutions were coded as correct for all participants who had worked on the set in this session. For example, instead of containing 19 red lentils, set number ten contained 20 red lentils at the end of the session. Both solutions (i.e., 19 and 20) were coded as correct when analyzing the errors of this trial. Out of the 432 instances in which sets had been used in a testing session, 20 sets (4.6%) included an error in one of their colors at the end of the session

Fig. 1 Finishing times were longer in the load compared to the no load condition, but embodiment did not influence finishing times systematically. Error bars = SE means

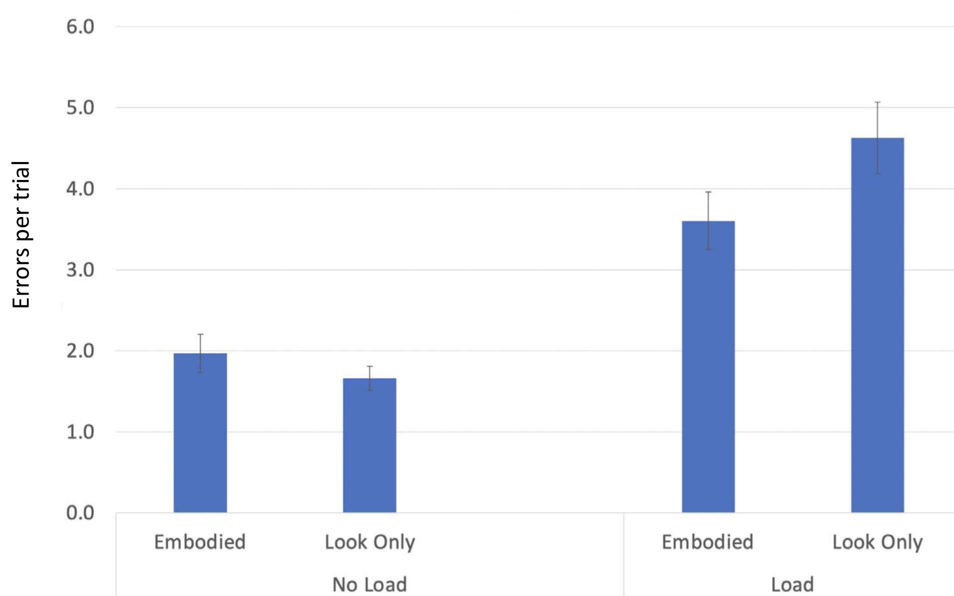


η_p^2 = 0.001. The main effect of load reached significance, $F(1, 53) = 240.430$; $p < 0.001$; η_p^2 = 0.819, due to longer finishing times in the load as compared to the no load condition. The interaction of embodiment and load also reached significance, $F(1, 53) = 4.207$; $p = 0.045$; η_p^2 = 0.074. To follow up this significant interaction, paired-samples t-tests were calculated, comparing the "embodied" to the "looking only" condition for trials without load, t (53) = − 1.56, $p = 0.124$, and for the trials with cognitive load, t (53) = 0.866, $p = 0.390$. This indicates that embodiment did not influence finishing times in the two different load conditions.

Errors

Figure 2 depicts the error rates of the current study. The reliability coefficient based on the 32 trials measuring errors for the counting task was acceptable ($\alpha = 0.710$). Error data for the four dependent error variables was not normally distributed, with significant results for the Kolmogorov–Smirnov tests in three out of four cases: (a) no load, embodied, $D(54) = 0.129$, $p = 0.025$; (b) with load, embodied, $D(54) = 0.107$, $p = 0.186$; (c) no load, looking only, $D(54) = 0.170$, $p < 0.001$; and (d) with load, looking only, $D(54) = 0.147$, $p = 0.005$. Instead of running a repeated-measures ANOVA with embodiment and load as

Fig. 2 Embodiment reduced the error rates when the counting task included a cognitive load, but not in the no load condition. Error bars = SE means



independent factors, I therefore ran Wilcoxon signed rank tests for each load condition separately. Error rates did not differ in the no load condition between "embodied" and "look only" trials, $z = -0.680$, $p = 0.496$; but there were significant differences between "embodied" and "look only" trials under cognitive load, $z = 1.998$, $p = 0.046$. Figure 2 shows that participants committed fewer errors when they were allowed to point at, touch, or re-arrange the lentils during counting with cognitive load.

Supplement 1 shows performance changes from pre-to posttest for finishing times and errors. Supplement 2 presents practice effects for each dependent variable over the course of sessions 2 to 7.

Discussion

The current study asked participants to quickly and accurately count colored chocolate lentils. In the "no load" condition, participants immediately wrote down the number for each subcategory, but in the "load" condition, they had to write down the number for all five subcategories at the end of the trial. When there was no cognitive load, counting times and error rates did not differ between "embodied" and "look only" trials. This indicates that young adults were able to perform the counting task in a "disembodied" manner, without being allowed to use their hands for counting. The pattern of results changed when task difficulty was increased by adding the cognitive load: Counting accuracies profited from "embodiment" (i.e., when participants were allowed to point at, touch, or re-arrange the to-be-counted objects) compared to the "look only" condition. Contrary to predictions, however, there was no significant increase in counting times in the "with load, embodied" condition compared to the "with load, look only" condition. This shows that young adults profit from embodiment.

Note that each experimental session always assessed the two "no load" trials first, followed by two trials in the "load" condition. It is therefore possible that the performance decrement in the "load" as compared to the "no load" condition, or the fact that embodiment exerted positive effects on error rates only under cognitive load, is also influenced by fatigue or boredom. Future research should counterbalance the order of "load" and "no load" trials across sessions.

In the current study, different "embodied" strategies could be observed: While counting, some participants were pointing at the lentils one-by-one, or touching them one-by-one. This strategy may help to keep track of what has already been counted, for example by introducing an additional body-based memory trace, or by directing attention to specific parts of the array (Khatin-Zadeh et al., 2022).

Many participants also re-arranged the lentils, usually by sorting them by color. In several cases, participants even elaborately sorted each color into a specific pattern, for example by lining the lentils up in lines of five items each. Such sorting strategies allow participants to "off-load" cognitive load to the environment, and they suggest that body movements may function as thought-regulating tools during counting. When reconstructing the exact number of blue lentils at the end of the trial, one quick look at the sorted array will immediately show how many blue lentils were included in the set. This strategy eliminates the need to store the number in working memory, but it is likely to increase the time needed to count the lentils. It fits to the assumption of Wilson (2002) that "off-loading" reduces the cognitive workload, by allowing participants to "harvest the information (…) on a need-to-know basis" (page 626).

The current study assessed the counting task in a group setting. Participants were given the choice to do what they wanted in the "embodied" trials. It is therefore not possible to reconstruct which strategy was used by a specific individual in a specific trial. Future research should measure individual performance strategies, or even explicitly instruct participants to use specific "embodied" strategies, to systematically assess their influence on counting times and errors.

It is possible that interindividual differences in the use of "embodied" strategies are related to performance levels in the counting task, or to cognitive covariates (e.g., reading span tasks, or cognitive speed tests). Maybe participants with shorter counting spans engage in embodied strategies more often, because they help them to compensate for their difficulty in memorizing the numbers in the "load" condition. Future studies should investigate such relationships between performance levels and embodiment, or may even consider individually calibrating task difficulties of the counting task to a person's span length.

In the current study, the counting task was assessed over the course of several sessions. It is possible that the active use of "embodied" strategies decreased over time. If participants become faster and more accurate in the counting task with increasing practice, they may have stopped using embodiment to support their performances. Chu and Kita (2011) have shown that gesture frequency for solving spatial problems like mental rotation and paper-folding tasks decreases over time. The authors argue that gesturing helps initially more than later, and becomes internalized with increasing practice (see also Chu & Kita, 2008). For the current study, practice effects from pre- to posttest are presented in Supplement 1. Note that pre- and posttests always took place under "embodied" instructions, with participants being allowed to touch and move the objects. Finishing times show a clear decrease from pre- to posttest, while error rates increased. This indicates that participants may have in fact stopped using their body when counting in the posttest, which made them faster, but also increased their error rates. In addition, Supplement 2 shows data from the six trials of each condition that were assessed in sessions 2 to 7. While there was a clear decrease in finishing times for all experimental conditions over the course of the study, error rates show a less consistent pattern over time.

Some previous studies on pointing gestures and memory have failed to find positive effects of embodiment. Dodd and Shumborski (2009) showed that pointing to objects only helps to memorize them when the objects are presented alongside objects that are only looked at (see also Chum et al., 2007). When using blocked instruction (i.e., pointing to all objects in an array, or passively viewing all items in an array), pointing to objects decreased memory performance relative to only viewing objects. The authors argue that pointing in mixed arrays led to an enhancement of processing of the pointed-to objects, but to an inhibition of the passively viewed array. In the current study, participants worked on the counting task in a blocked fashion. The embodiment was either allowed throughout the entire session, or a "look only" strategy was instructed.

Other studies on embodiment were searching for positive effects of moving one's body through space, either in a memory span task (Amico & Schaefer, 2021a), or in a visuospatial working memory task (Amico & Schaefer, 2021b), and found negative effects of embodiment in different age groups. Instead of becoming more accurate in reconstructing the sequence of numbers (Amico & Schaefer, 2021a) or spatial locations (Amico & Schaefer, 2021b), recall performances became worse when encoding had taken place in an embodied fashion. This indicates that the specific ways in which the body is used to solve a cognitive task exert an influence on embodiment effects and merit further investigation. Future research should also investigate how eye movements, gestures, and body movements interact when solving a cognitive task (Korbach et al., 2018, 2020; Park et al., 2023).

Conclusion

In the current study, young adults profited from embodiment when task difficulties were increased by adding a cognitive load to a counting task. For counting tasks, the advantages of using gestures and action as forms of "off-loading" cognitive load onto the environment have previously been investigated primarily in the development of early counting skills during childhood, with the typical subjects being preschool age or even younger (Alibali & DiRusso, 1999; Graham, 1999; Gunderson et al., 2015; Saxe & Kaplan, 1981). From a developmental perspective, it would be very interesting to investigate the age ranges in which different "embodied" strategies are most helpful for counting tasks. Adding older adult samples would also enrich the embodiment research field, since it is debated whether embodiment effects become less or more pronounced with increasing age (see Costello & Bloesch, 2017; Loeffler et al., 2016).

To conclude, being allowed to point at, touch, or move the to-be-counted objects reduced error rates in young adults' counting performance when counting with a cognitive load. This indicates that "off-loading" mental load to the environment, for example by re-arranging the array of objects, seems to be a helpful strategy when counting.

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Author Contribution Sabine Schaefer is the sole contributor to this paper.

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Data Availability The data that support the findings of this study are available from the corresponding author, upon reasonable request.

Declarations

Ethics Approval and Consent to Participate The study design was approved by the Ethics committee of Saarland University, and participants provided informed consent to participate in the study.

Consent for Publication Participants provided informed consent that the data can be published in a scientific journal.

Competing Interests The author declares no competing interests.

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