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Moving arms: the effects of sensorimotor information on the problem-solving process

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ABSTRACT
Embodied cognition postulates a bi-directional link between the human body and its cognitive functions. Whether this holds for higher cognitive functions such as problem solving is unknown. We predicted that arm movement manipulations performed by the participants could affect the problem-solving solutions. We tested this prediction in quantitative reasoning tasks that allowed two solutions to each problem (addition or subtraction). In two studies with healthy adults ($N = 53$ and $N = 50$), we found an effect of problem-congruent movements on problem solutions. Consistent with embodied cognition, sensorimotor information gained via right or left arm movements affects the solution in different types of problem-solving tasks.

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KEYWORDS Embodied cognition; eye movements; problem solving

Introduction

The term *embodied cognition* refers to the bi-directional interplay between cognitive processes and the human body. It denotes the theoretical position that all cognitive activity must refer back to the sensory and motor activation that was present during knowledge acquisition (Barsalou, 2008; Coello & Fischer, 2016; Fischer & Coello, 2016; Raab, Johnson, & Heekeren, 2009). With this position, the embodied cognition approach stands in sharp contrast to the classical view of the body as an executive part for cognitive processes by adding the body as a constraint on computational processes. More precisely embodied cognition positions postulate the human anatomy

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as a constitutive factor for cognitive processes. Furthermore, radical embodied cognition positions even assume the absence of mental representations (e.g., Chemero, 2009; Jacob, 2016). However, the more widely accepted view is that bodily influences have the potential to affect the outcome of a cognitive task (Barsalou, 2016).

Hundreds of studies have now provided empirical evidence for such bodily influences on cognition. For example, regarding early, low-level cognitive processes, attention allocation is affected by movement preparation (Rizzolatti, Riggio, Dascola, & Umiltá, 1987) and slant perception is affected by physical load (Proffit, 2006). Regarding later, high-level processes, memory retrieval is affected by body posture (Dijkstra, Kaschk, & Zwaan, 2007), decision-making is affected by motor experience (Pizzera & Raab, 2012) and numerical cognition is affected by spatial behaviour of the eyes and hands (Domahs, Moeller, Huber, Willmes, & Nuerk, 2010; Knops, Thirion, Hubbard, Michel, & Dehaene, 2009).

The relationship between spatial bodily behaviour and numerical cognition is of special interest here because it operates bi-directionally, such that number magnitude also influences spatial attention allocation and movement execution (for recent review, see Fischer & Shaki, 2014). For example, small numbers direct one's attention to the left visual field and larger numbers direct one's attention to the right visual field (Fischer, Castel, Dodd, & Pratt, 2003; Fischer & Knops, 2014), presumably reflecting habitual spatial-numerical associations (SNAs). Such habitual SNAs are further modulated by cultural conventions from reading habits (Kazandjian, Cavezian, Zivotofsky, & Chokron, 2010; Shaki, Fischer, & Petrusic, 2009); in Western adults there is a strong preference to begin scanning visually presented arrays from left to right and this body-based habit spills over into the numerical domain (e.g., Berch, Foley, Hill, & Ryan, 1999; Göbel, Shaki, & Fischer, 2011; Han & Northoff, 2008; for recent review, see Maass, Suitner, & Deconchy, 2014). SNAs are also present during arithmetic problem solving, such that subtraction operations are congruent with left-side attention shifts and addition operations are congruent with right-side attention shifts (e.g., Liu, Cai, Verguts, & Chen, 2017; Masson & Pesenti, 2014).

A useful framework to structure the evidence for a close relationship between bodily activities and numerical cognition was proposed by Fischer (2012; see also Fischer & Brugger, 2011; Ninaus et al., 2017). According to this view, we distinguish between grounded, embodied, and situated levels of knowledge representation: Grounding refers to physical constraints, such as the influence of gravity, that have shaped all cognitive structures and are universally present. Embodiment refers to the sensori-motor experiences of a given individual and thus allows for idiosyncratic variability and cultural diversity in the relationship between numerical cognition and sensori-motor activity. Finally, situatedness refers to the task-dependency of cognitive processes as an individual aim to solve a given cognitive challenge.

Despite considerable empirical evidence the underlying mechanisms of this bodily influence on cognition are still unclear. This paper aims to specify the sensori-motor effects on a specific high-level cognitive process, namely problem solving.

Human problem solving offers a suitable research environment to study embodied cognition because it includes a variety of different cognitive tasks that are grounded and/or linked to sensori-motor information in a single task (Newell & Simon, 1972; Öllinger, Jones, & Knoblich, 2013): First, the problem solver creates a problem representation (problem space) by perceptually encoding the problem components available in the specific situation; then she attempts to search this problem space for solutions to the problem task by manipulating the problem components.

Only two lines of research have previously determined the mechanism of embodied problem solving. In the first line of research, Grant and Spivey (2003) asked participants to solve Duncker's (1935/1963) radiation problem that requires destroying a tumour with a laser beam without injuring the healthy tissue around it. "The correct solution to this problem entails firing multiple low-intensity lasers from different locations around the tumor so that they converge at the tumor" (Thomas & Lleras, 2007, p. 663). Grant and Spivey (2003) manipulated each participant's gaze behaviour by highlighting either the tumour or the healthy tissue. As a result the solution rate was doubled when highlighting the healthy tissue. On the one hand, the finding can be explained by postulating different problem representations based on the different gaze behaviours during the problem-solving process. Alternatively, an embodied cognition approach would claim that the gaze paths associated with looking at the healthy tissue surrounding the tumour were more situationally appropriate and thus primed the solution "different paths from the outside towards the tumor" (see also Litchfield & Ball, 2011; Thomas & Lleras, 2007, 2009a).

In the second line of studies, Werner and Raab (2013, 2014) recently developed a problem-solving task where two different solutions can be primed by two movements generating different sensori-motor cues. Specifically, they computerised Luchins' (1942) water jar problem that can be solved either by addition or subtraction and presented problem layouts that primed one of those arithmetic concepts. This was accomplished by placing the jar needed for the subtraction solution on the left side and the jar needed for the addition solution on the right side, consistent with the SNAs mentioned above (cf. Fischer & Shaki, 2014). Participants performed a 30 s movement linked to either the addition or subtraction concept; specifically, they put marbles together in a central glass bowl or divided them from this bowl. This activity was predicted to provide sensori-motor information and to subsequently guide participants' gaze behaviour, thereby priming the respective solutions. In contrast with this prediction, no difference was found for the dependent variables gaze behaviour and number of respective solutions. The results instead suggested that a situation-general, habitual reading-related bias might guide participants' gaze behaviour to the left jar and thereby induce more subtraction solutions overall. However, in the absence of experimental manipulation of the jar arrangement and thereby of the resulting problem space, this embodied interpretation of Werner and Raab's (2013, 2014) findings remains speculative. We conducted two studies to clarify the effect of spatial layout and body movements on arithmetic problem solving.

Study 1

Based on our prior work we conducted the first study, which implements two different arrangements for the jars to create two different representational spaces for the problem. This was done to test the influence of situation-specific problem representations on the problem solution, resulting in two main conditions. Moreover, we added directional arm movements to the right or left side immediately before the problem task was presented. As mentioned, such lateral movements are associated with the two arithmetic concepts of addition and subtraction, respectively (Knops et al., 2009; for review see Fischer & Shaki, 2014). We thereby aimed to prime the representation phase of the problem-solving process with an embodiment manipulation.

We predicted (a) an initial shift of participants' gaze to the left jar across arm movement conditions (e.g., Kazandjian et al., 2010); (b) that the left jar would be used more often for the initial problem representation and subsequently for producing problem solutions (Werner & Raab, 2013, 2014); (c) a small effect of the sensori-motor information on solution preferences (Fischer & Shaki, 2014); and (d) a combined effect of jar arrangement and sensori-motor information on solution preferences (cf. Öllinger, Jones, & Knoblich, 2014).

Method

We used a 2 x 2 between-subject design, resulting in four groups of between 12 and 15 participants. The first independent variable was jar arrangement (normal: small jar on the left side; reversed: small jar on the right side). The second independent variable was arm movement direction (right; left). Dependent variables were the distribution of gaze behaviour (for the perception task as well as the problem-solving task) and the type of solution (during problem solving). Independent of the solution time, only the first 10 s of gaze behaviour during the problem-solving tasks were analysed to compare them to the first 10 s of gaze behaviour in the baseline perception task, described next. The duration of 10 s was used to facilitate comparisons with identical problem-solving periods studied in previous research (Werner & Raab, 2013, 2014).

Before they took part in the main experiment all participants performed a baseline perception task: They made a single 3-second lateral arm movement while their eye movements were recorded. This allowed us to control for any effect of arm movements on gaze behaviour during the problem-solving task. In contrast to previous studies using 30 s movements, the lateral arm movement in this study lasts for only 3 s. Repeating this arm movement 10 times could resolve this issue, but we decided against this procedure because movements in both directions will be made during repetitive arm movements. Moreover, using simple lateral arm movements will allow us to implement these movements also while participants are trying to solve problem tasks (see Study 2).

Participants

Fifty-four students (31 men) from various universities in the local area were tested (mean age =24.28 years, SD =2.6; 20–33). Three participants self-reported to be left-handed. All participated voluntarily and were unfamiliar with the presented problems. They were assigned randomly to the four groups. The study was approved by the ethics committee of the local university. All subjects gave written informed consent in accordance with the Declaration of Helsinki.

Apparatus

The experiment was programmed with Inquisit 3 (Millisecond Software, Seattle; WA) and presented on a 55″ monitor at a distance of 1.20 m to the participants. This set-up is identical to perceptual displays of previous studies (Werner & Raab, 2013, 2014). Head movements were reduced with a chin rest (see Figure 1). Participants' gaze behaviour was recorded with the eye tracking system Tobii glasses (Tobii technology, Stockholm) at a rate of 30 Hz and with a spatial range of 56 degrees for the horizontal and 40 degrees for the vertical visual field.

Task

In the perception task, four identical jars (three at the top and one at the bottom) were presented to the participants on a computer screen without any additional information (see left panel of Figure 2). Participants were instructed to look at the screen while these jars were presented and their

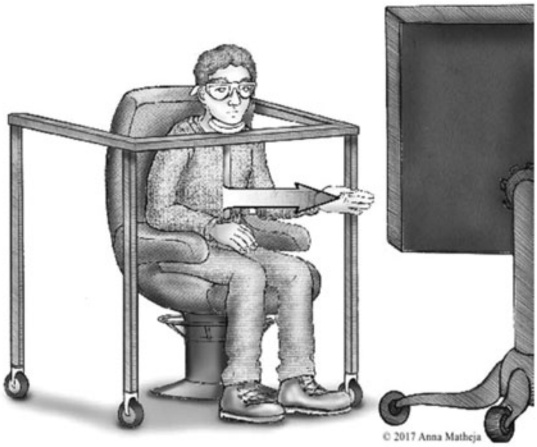

Figure 1. Sketch of the experimental set-up.

eye movements were recorded. The problem-solving task is adapted from Werner and Raab (2013, 2014). In more detail, we kept all values constant in comparison to previous studies, but we changed the design of the jar images. In contrast to the previous experiments the jar images at the top contain no water. This was done based on the observation that the water level might affect the focus of attention to the jar with the highest water level. We adapted Luchins' (1942) water-jar problem such that the volume of water in the different jars allows two possible ways to solve this problem. Participants did not interact with the jars; rather, they were asked to perform mental calculations with the volumes given in the top line of the display to reach the target volume given in the bottom line (see right panel of Figure 2). Once the solution came to their mind participants stopped the task by pressing the space bar and immediately named the solution in form of an equation consisting of the numbers displayed above the jars (e.g., 1-2-2 or $3 + 2 + 2$, see right panel of Figure 2). One possible correct solution was to subtract the amount of water held by the middle jar (2) twice from the one with the largest amount (1). The other possible correct solution was to add the amount of water held by the middle jar (2) twice to the jar with the lowest amount (3, see right panel of Figure 2). In all trials both solutions were possible. Moreover, the arrangement of jars was manipulated to test the influence of problem presentation on solution preferences, resulting in two conditions. In the first condition the jar with the highest amount (jar 1, only needed for the subtraction solution) was presented on the left side (normal arrangement) and the jar that was only needed for the addition solution (jar 3) on the right side – the middle jar was needed for both solutions. This problem presentation fits the cognitive representation of arithmetic concepts, associating left space with subtractions and right space with additions (Knops et al., 2009; Pinhas, Shaki, & Fischer, 2014; Shaki et al., 2009). In the second condition, the left and right jars were switched while the numbering of jars was kept constant (reversed arrangement). Consequently, the two responses for correct solutions changed to "1 + 2 + 2" for addition and "3-2-2" for subtraction.

Procedure

The procedure followed previous work for comparability (Werner & Raab, 2013, 2014): Each participant was individually tested in about 40 min. First the participant was told a cover story: "The aim is to investigate how breaks during problem solving influence your ability to solve this problem." The experiment started with the task instructions and two examples that explained the problem. Participants were instructed to reach the target volume (displayed in millilitres) by thinking about which jars in the top line they would have to pour over, allowing refilling of the top jars at any time. Thereafter, participants had to solve two simple water-jar problems with only two jars in the top line to become familiar with the procedure. We used a computer-based visualisation of Luchins' (1942) task such that participants had to mentally calculate the different numbers representing the volumes. The participants reported the problem solutions verbally without manipulating the displays.

After these examples, the experimenter demonstrated the arm movement. For the movement to prime addition, participants moved their right arm from a central position to a vertical bar at the final position on their right side that was approximately 50 cm away from the central position, and vice versa with the left arm, to prime subtraction (see Figure 1). The respective movement was briefly practiced to last approximately 3 s.

Participants next performed three perception trials. Their instruction was to move their arm to one side, as practiced, before each trial and thereafter look at the screen for 10 s while we recorded their gaze behaviour. When compared against the subsequent experimental trials, these baseline data allow us to determine how the problem-solving presentation, corrected for the influence of arm movement, affects visual exploration.

After these trials participants performed four problem-solving trials and were asked to solve each of them within 120 s. Each trial of the main experiment began by presenting a visual stimulus (red circle) that told participants to adopt their starting position. After 3 s the circle's colour changed into green, which was the start signal for the movement. Participant were instructed to move their arm with a constant speed to the end position and to arrive at the vertical bar at the same moment when the green circle disappeared, namely after 3 s. Immediately after the green circle disappeared the problem task was presented on the screen.

At the end of the experiment, participants completed a questionnaire to determine whether they were aware of the intended effect of our movement manipulation and were then debriefed by the experimenter.

Data analysis

One participant was aware of the intended effect of the movement manipulation and thus his data was excluded from the analysis. This left 12, 14, 15, and 12 participants in the groups with normal jar arrangement and left arm movements, normal jar arrangement and right arm movements, reversed jar arrangement and left arm movements, and reversed jar arrangement and right arm movements, respectively. For the perception task we analysed the distribution of participants' gaze behaviour as follows: We created two areas of interest (AOI) around the left and the right jar, respectively, ignoring the two jars in the centre (top and bottom; see Figure 1). For statistical analysis, we used the single gaze points in the AOI (which is the *x*/*y* coordinate for each frame) and subtracted the number of data points for the right AOI from the number of data points for the left AOI (left–right). Hence positive values indicate a left bias of attention and negative values a right shift. These left–right difference scores were compared between the two groups with leftward vs. rightward movements ($N = 27$ and 26 participants, respectively), using a *t*-test. The same was done with the eye-tracking data of the first 10 s in the problem-solving tasks. We will use the distribution in per cent (relative frequencies of single gaze points) to report these results (Figure 2). The left–right values used for the statistical analysis cannot illustrate the gaze distribution. In order to demonstrate any possible left shift of gaze behaviour in the problem tasks, we conducted a paired *t*-test for the baseline vs. the problem-solving task. From the 53 data sets obtained we analysed gaze behaviour in the perception task for 42 cases (three participants looked straight to the middle jar, the eye tracking data of eight participants could not be used due to recording error),

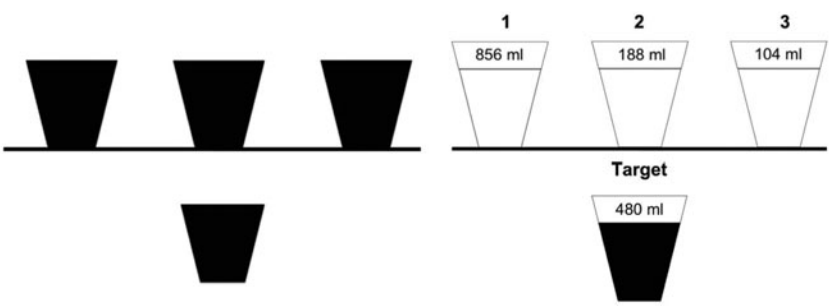

Figure 2. Examples of the perception task with four identical jars (left) and one problem task in the normal arrangement condition (right).

and we analysed the first 10 s of problem solving also for 42 cases (three participants solved the problems in less than 10s but the three participants who looked only straight ahead in the baseline condition were re-included here). This left 10, 10, 14, and 11 participants in the groups with normal jar arrangement and left arm movements, normal jar arrangement and right arm movements, reversed jar arrangement and left arm movements, and reversed jar arrangement and right arm movements, respectively. The differences between types of solutions were analysed with a chi-square test and a *t*-test. Regarding the chi-square analysis for the solution type we compared correct addition and subtraction solutions [$n = 115$ out of a maximum of 212 (4 trials by 53 participants)]. Regarding the *t*-test we calculated the proportion of addition and subtraction solutions for each participant and subtracted the subtraction value from the addition value. As a result, negative values represent more subtraction solutions and positive values more addition solutions. Overall, 10 participants showed no correct solution in all trials, therefore, we analysed 43 data sets.

Results

Gaze behaviour

Perception task

A baseline measure was computed to assess spatial biases to the left or right side of the display as a result of the respective arm movements made. Participants who moved their arm to the left looked more to the left ($M_{\text{left}} = 58.03\%$, $M_{\text{right}} = 41.97\%$, $SD = 27.01$); this pattern differed significantly from the group who moved their arm to the right ($M_{\text{left}} = 40.18\%$, $M_{\text{right}} = 59.82\%$, $SD = 25.06\%$), as indicated by a reliable difference between their difference scores, $t(41) = 1.89$, $p = .033$, $d = .58$ (see left panel of Figure 3).

Problem-solving task

Due to the reading direction bias we hypothesised an overall spatial bias to the left that was independent of arm movement condition. Our results

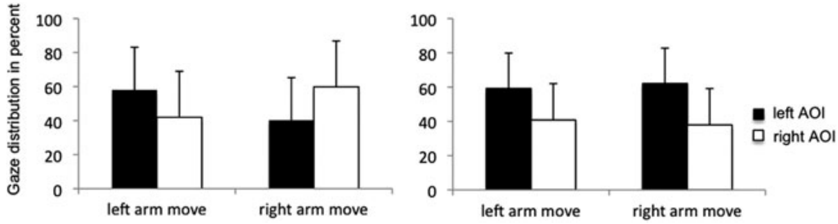

Figure 3. Mean gaze distribution and SD (in per cent) for the perception tasks (left panel) and the first 10 s of problem solving (right panel).

confirmed this hypothesis for the overall gaze behaviour of all participants in the first 10s after presenting the problem task ($M_{\text{left}} = 60.27\%$, $M_{\text{right}} = 39.27\%$, $SD = 20.70\%$). When compared against their data for the baseline measure, a reliable difference between their difference scores emerged, $t(39) = 2.61$, $p = .007$, $d = .41$. However, we found no difference during this time interval between the left arm movement condition ($M_{\text{left}} = 59.22\%$, $M_{\text{right}} = 40.78\%$, $SD = 21.25\%$) and the right arm movement condition ($M_{\text{left}} = 62.09\%$, $M_{\text{right}} = 37.91\%$, $SD = 20.60\%$), $t(41) = 0.01$, $p = .990$, $d < .01$ (Figure 3, right panel), indicating that the habitual reading bias was stronger than any movement-induced bias.

Problem solutions

We expected two effects on the solutions of the problem tasks. First, based on the overall results for gaze behaviour we expected more subtraction solutions when presenting the jar needed for subtraction on the left side (normal order). Accordingly more addition solutions were expected when presenting the jar for addition on the left side (reversed order). Indeed, solutions differed significantly as a function of jar arrangement: for the normal order 22 addition solutions and 38 subtraction solutions and for the reversed order 35 addition solutions and 20 subtraction solutions were obtained, $\chi^2(1, N = 115) = 8.35$, $p = .004$, $w = .27$. The computed differences between addition and subtraction solutions also differed significantly in the predicted direction ($M_{normal} = -.19$, $SD = .63$; $M_{reversed} = .17$, $SD = .51$), $t(41) = 2.05$, $p = .024$, $d = .62$. Second, we expected an effect of the movement manipulation independent of jar order, that is, more subtraction solutions for left arm movements and more addition solutions for right arm movements. We found for left movements, 25 addition solutions and 31 subtraction solutions and for right movements, 32 addition solutions and 27 subtraction solutions. Although this pattern is consistent with our prediction, the difference failed to be statistically significant and revealed only a small effect, $\chi^2(1, N = 115) = 1.06$, $p = .152$, $w = .10$, $t(41) = .70$, $p = .246$, $d = .21$.

In addition to these two main effects of problem presentation and arm movement manipulation, we predicted an additive effect for their congruent combination. To test this prediction, we combined problem presentation and movement manipulation in a congruent and incongruent way. Based on our theoretical arguments (see Introduction), "congruent" is the combination of normal order of jars and left arm movements, which should both prime subtraction solutions. Similarly, the combination of reversed order and right arm movements should both prime addition solutions. The results revealed a significant difference between the two congruent combinations (normal/left: 9 addition and 17 subtraction solutions, reversed/right: 19 addition and 6 subtraction solutions), $\chi^2(1, N = 51) = 8.82$, $p = .002$,

$w = .42$. For the incongruent combinations of problem presentation and movement manipulation (normal/right: 21 addition and 13 subtraction solutions, reversed/left: 14 addition and 16 subtraction solutions), no reliable difference was obtained, $\chi^2(1, N = 64) = 1.47$, $p = .226$, $w = .15$ (see Figure 4).

Additional analyses of solution times with respect to jar arrangement and movement direction revealed no significant differences: jar arrangement $t(51) = 0.17$, $p = .867$, $d = .05$; movement direction $t(51) = 0.26$, $p = .793$, $d = .07$.

Discussion

This study manipulated the layout of the problem space and replicated previous findings of an overall bias towards the left side during problem representation (Werner & Raab, 2014). This bias is probably culturally mediated, as was documented by Shaki and Fischer (2008) who biased their participants' SNA by merely providing either Hebrew- or Russian-language task instructions. The present bias was stronger than the mere tendency to orient to the left or right side due to eye-hand coupling, as evidenced by a reliable contrast with the baseline task. Nevertheless, the expected effect of movement direction on problem representation, and thus on problem solving, was visible when critical jar position and movement direction were congruent. This is indicated by the increased effect size when compared to the main effect for problem representation alone. This outcome suggested that, in order to establish the intended main effect of movement manipulation on arithmetic problem solving more clearly, a modified method was needed.

Study 2

In the second study, the focus of our investigation of the problem-solving process shifted towards the later phase in a problem-solving task, namely the search within the problem space. Therefore, differences based on the

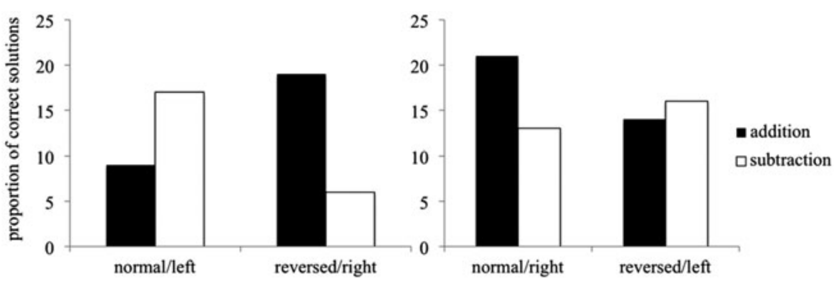

Figure 4. Proportion for the correct solutions in the congruent (left) and incongruent (right) trials.

initial problem representation were minimised. In the new task, participants were simultaneously shown four numbers, the two operators for addition and subtraction and the equal sign on a touch-screen monitor. Their task was to create a correct mathematical equation by touching some of these elements. Note that every addition equation can be expressed as a subtraction equation by re-ordering the same numbers and using a different operator: $a + b = c$ becomes $c\text{-}b = $a. In contrast to our first study, the exact same numbers could thus be used for addition and subtraction. Inserting motor activities into this new task allowed us to attribute any differences regarding the type of solution to the differential concept activation for addition vs. subtraction as a result of embodied search processes, rather than a result of the encoding of different problem components.

Method

We manipulated arm movement direction (right; left) in a between-subject design. Our dependent variable was the distribution of solution types.

Participants

Fifty-eight students (11 men) from the University of Potsdam were tested (Mean age =23.32 years, SD =2.69). They participated for course credit or money (10 €) and were unfamiliar with the presented problems. They were assigned randomly to the two movement direction groups. All subjects gave written informed consent in accordance with the Declaration of Helsinki.

Apparatus

The experiment was programmed with Expyriment (Krause & Lindemann, 2014) and presented on a 55″ touch-screen monitor (iiyama™ ProLite TH5563MIS, iiyama Corporation) standing in front of participants (Figure 5).

Task

In this mathematical problem-solving task participants were asked to create a correct equation composed of the result and at least two operands (e.g., $a + b = c$ or $c\text{-}b = a$; see Figure 5). Along the left side of the screen, the operators were presented, always starting with the equal sign in the top left corner. The vertical placement of plus and minus signs was random. In each trial, a set of four numbers, each consisting of two or three digits, was presented in random order in a 2 x 2 grid layout (see Figure 5). We created

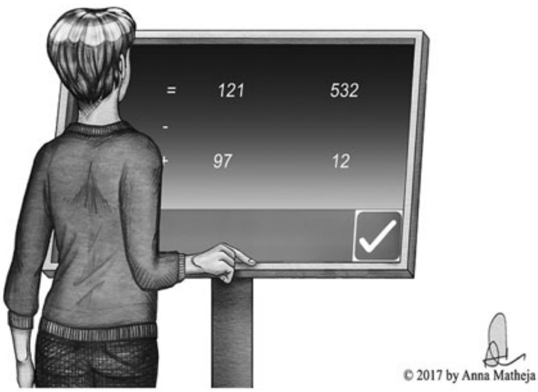

Figure 5. Experimental setup for the second study with the two possible solutions (addition solution 12 + 12 + 97 = 121, subtraction solution 121-12-12 = 97).

four different problem categories to avoid mental set effects: (1) "addition", with only the plus sign available as operator; (2) "subtraction", with only the minus sign as operator; (3) "both", with plus and minus signs present; in this category both operators had to be used for correct solutions (e.g., $a + b\text{-}c = d$); and (4) "either", where both plus and minus signs were displayed but using either of them alone was sufficient to solve the problem; this was our target category for analysis because the "either" problems can be used either for an addition or a subtraction solution and we wanted to see whether arm movement direction affected participants' choices.

Procedure

Each participant was individually tested within about 60 min. After receiving instructions, each participant trained one lateral arm movement five times: They pressed a start button that was located centrally at the lower side of the touch-screen monitor with their index finger to trigger a red mark. Then they followed the red mark which slowly moved at a speed of 10 cm/s to one side of the screen that was approximately 60 cm away from the central start button. Thus, the movement lasted for about 6 s. Participants in the "right" group moved their right arm to the right side of the screen in order to prime additions. Participants in the "left" group moved their left arm to the left side of the screen in order to prime subtractions. Following this motor practice, six example problems were presented with single digit numbers only, three from the addition and three from the subtraction category.

Next, each trial of the main experiment began by presenting the central start button. Participants again began to move their right arm; when reaching the left or right side of the screen, participants were instructed to keep their finger in this final position until they were ready to solve the problem by entering their equation. For entering an equation, each element was selected by simply touching it so that it appeared in a green bar at the bottom of the screen. In the same way, each element could also be removed. Touching the tick mark at the bottom right edge of the display (see Figure 5) terminated the trial. Participants had two minutes to solve each problem. Overall, 25 trials were presented in five blocks with five trials, two from the "either" category, and one each from the remaining three categories. At the end participants filled out a questionnaire to determine whether they were aware of the intended effect of our movement manipulation and were then debriefed by the experimenter.

Data analysis

First we checked our data with regard to possible mental sets. We defined a mental set as solving "either" problems with the same operation (always addition or always subtraction) in six consecutive trials throughout the experiment (cf. Luchins, 1942). As a consequence, we excluded eight participants (four from each group) from further statistical analyses. The differences between types of solutions were analysed with a *t*-test. We calculated the proportion of addition and subtraction solutions across all "either" trials, where a solution was entered for each participant and then subtracted the resulting subtraction value from the resulting addition value. Thus, negative proportions represent more subtraction solutions and positive values more addition solutions. Furthermore, we analysed the occurrences of each participant's first correct "either" solution with a chi-square test.

Results

We predicted a difference between the right moving group and the left moving group with respect to the proportions of addition and subtraction solutions. The results confirmed this prediction, showing a significant difference between the right and left moving group for the proportion of addition and subtraction solutions ($M_{right} = .24$, $SD = .29$, $M_{left} = .03$, $SD = .39$), $t(48) = 2.16$, $p = .018$, $d = .61$ (see Figure 6).

Based on the results from prior work, we also checked whether this movement-induced bias could be already seen in the occurrence of the first correct solution. Indeed, first correct solutions to "either" problems differed significantly as a function of movement direction: the 25 right-moving group members produced 16 addition and 9 subtraction solutions and the 25 left-moving group members produced 9 addition and 16 subtraction solutions, $\chi^2(1, N = 50) = 3.92$, $p = .048$, $w = .28$ (see Figure 7). Additional

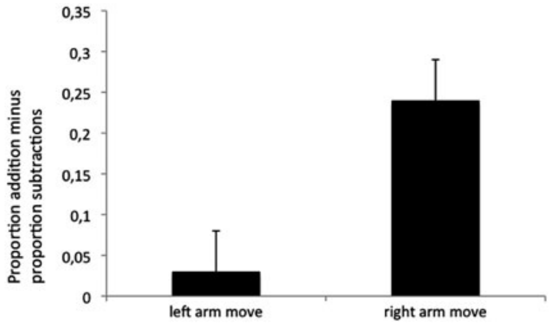

Figure 6. Proportion of addition minus subtraction solutions across all 10 "either" trials for left and right arm movement. Error bars indicate standard error (SE).

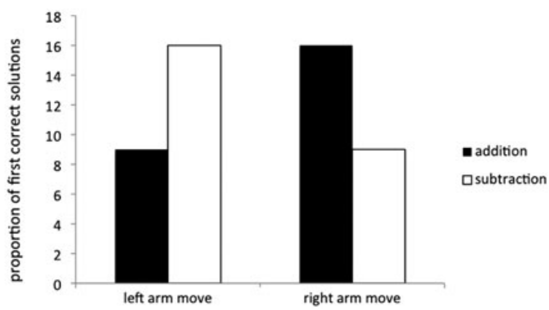

Figure 7. Distribution of first correct solutions in the either category for left and right arm movement groups.

analyses with regard to solution times and the number of correct solutions showed no significant differences between the groups.

Discussion

The second study manipulated movement direction during the search for correct arithmetic equations. We found an effect of arm movement direction on the probability of choosing arithmetic operators, such that reliably more addition equations were produced following rightward movements with the right arm than leftward movements with the left arm. This outcome adds to the evidence for an embodiment of mental arithmetic operations where additions and subtractions are associated with right and left space, respectively (e.g., Liu et al., 2017; Masson & Pesenti, 2014). Whether this association is driven by the effector or the movement direction is unclear from the present experiment because we chose to control biomechanical complexity across movement directions and allowed all participants to make ipsilateral movements. However, previous work on SNAs with crossed hands (Dehaene, Bossini, & Giraux, 1993, Experiment 6) indicates that the priming effect likely reflects a spatial-directional code and not the effector itself (or the brain hemisphere controlling it).

A further limitation of our studies is that we did not control the amount and direction of force produced by the participants in the end position of the movement. Thus, we have no information about the sensori-motor cues provided while participants continued to solve the problem. How much the solutions are influenced by this additional sensori-motor information remains to be studied.

A final limitation of our method, which also applies to the first study, is the lack of an "embodied" baseline condition. Specifically, the present results would be even more diagnostic if participants had also performed in a condition without overt arm movements. This would have clarified if a spatial bias also exists in the absence of movements and whether both movement direction manipulations were equally effective (cf. Thomas & Lleras, 2009b). Nevertheless, both of the present studies converge on a clear and positive answer to the question we had posed at the outset, namely whether we can influence high-level problem solving with sensori-motor manipulations. We now turn to a discussion of these important findings and their implications for theories of embodied cognition.

General discussion

The aim of the present studies was to specify the influence of movement priming on problem solving. An embodied cognition framework was used to derive predictions for both gaze behaviour and problem-solving biases. We used a variation of Luchins' (1942) water jar problem (study 1) and an arithmetic problem-solving task (study 2), both of which allowed two possible solutions (additions or subtractions), in combination with two different arm movements (left or right), to test these predictions. Several novel and informative results were obtained. We describe and discuss these in turn.

In the first study, we had predicted main effects of jar arrangement and movement direction on the solution pattern, as well as their interaction. The results partially support these predictions. First, we indeed found a significant difference in solution preferences for the jar arrangement manipulation, consistent with spatially directional reading habits: Based on the left-to-right reading direction in Western societies, the jar on the left side had a higher probability to be part of the initial problem space. This is confirmed by our findings from the first 10s of participants' gaze behaviour during problem encoding. Even though the participants' cultural background was not formally assessed in the post-experimental questionnaire we can be confident of the presence of the left-to-right reading bias because we presented written instructions in German prior to data collection (cf. Shaki & Fischer, 2008). Together with our previous work (Werner & Raab, 2013, 2014) Experiment 1 thus provides converging support for embodied cognition during the encoding phase of high-level problem solving.

The second study also manipulated movement direction of participants but held the problem representations constant across conditions This time we observed a clear main effect of movement direction such that more additions were generated after right-side movements and more subtractions were generated after left-side movements. Together, these results provide converging evidence for effects of sensori-motor manipulations in the domain of quantitative problem solving. These findings extend studies from different tasks such as insight-based problem solving (e.g., Litchfield & Ball, 2011).

With regard to the problem-solving process, our results suggest that both the initial problem encoding and the later search phase are affected by sensori-motor information. A more detailed look at this time course, ideally with a time-sensitive measure such as continuous force recordings, is needed. Force recordings have the potential to reflect cognitive processes on a motoric level with a high temporal resolution. With this, different cognitive processes might be distinguishable by having a look at the corresponding forces.

Our results are in contrast with an earlier report showing no effect of an initial hint on the solution (Öllinger et al., 2014). Öllinger and colleagues cued participants by highlighting either the matchstick that has to be moved to decompose the chunk of the central square in Katona's (1940) five-square problem or highlighting the position where this matchstick has to be placed for a successful solution. These seemingly conflicting results can be explained by differences regarding the extent of the problem space. Consider Katona's (1940) five-square problem that was used by Öllinger et al. (2014): in this task, 5 squares built from 16 sticks had to be rearranged into 4 squares by moving exactly 3 sticks. In comparison to our study (which merely required combining three water jars by addition or subtraction to reach a defined target volume), the problem space in that earlier study was broader and this might be the reason why an initial hint had a much weaker effect on the solution (Öllinger et al., 2014).

More generally, we suggest that different problem-solving tasks can be seen as arranged on a continuum from broader problem representations (e.g., Dunckers' radiation problem) to narrower problem representations (e.g., Luchins' water jar tasks or the Tower of Hanoi task). We also assume that sensori-motor information will affect the problems in different ways: As long as the duration of bodily manipulations is kept constant, the effects of sensori-motor information for so-called creative problem tasks with a broader representation should be weaker compared to the so-called analytic tasks with a narrower representation. The assumption for these different effects is based on the interpretation of previous findings implicating that sensorimotor information can narrow the problem representation towards the correct solution but cannot reveal insight in a problem task. Thus a problem with a narrower representation would benefit more from a reduced problem space than a problem with a broader representation.

Secondly, our results in the first study, pertaining to the effect of movement manipulation on problem solving patterns, contrast partly with previous findings (Werner & Raab, 2013, 2014). In Werner and Raab (2013, Experiment 2) an effect of different arm movements on the type of solution that was chosen by the participants in a variation Luchins' (1940) water jar problems was present, whereas in the current Study 1 the main effect for the movement manipulation was only on a descriptive level. We suggest that this contrast might be due to a difference in how sensori-motor information was provided in different paradigms. The effect of movement manipulation and subsequently the effect of sensori-motor information found in our previous studies occurred after acting for 30 s in a marble sorting task, in order to induce the underlying concept of adding or subtracting (Werner & Raab, 2013, 2014). In contrast to this earlier work, current participants acted for only 3 s in Study 1 in order to induce a corresponding bias. These shorter movements clearly provided less sensori-motor information that could prime the problem-solving process. Nevertheless in Study 2 we were able to demonstrate the effect of movement manipulation on problem-solving patterns using a similar movement as in Study 1 lasting for 6 s. Although this is twice the time from the first study it is still less time than in previous work by different researchers (e.g., Grant & Spivey, 2003; Thomas & Lleras, 2009b). We would argue that the doubled amount of time is not causal for the results in the second study, but rather the point in time when the manipulation was inserted. Whereas in the first study participants moved their arm before the problem was presented, in the second study the movement only started with the problem presentation. Thus, movement manipulations during the problem task (online) seem to reveal greater effects on the solution than movements performed before the problem task (offline). This important new hypothesis can easily be tested: Running a study with the same problem tasks, the same type of movement manipulation and duration as in the second study, but performed before the problem task could demonstrate quantitative differences between online and offline effects on problem-solving solutions.

Regardless of the minor limitations mentioned, the findings of the present study provide important novel information about possible mechanisms of embodied cognition and problem solving. Specifically, we have documented a direct effect of sensori-motor activity on the outcome of higher-level cognitive operations such as arithmetic problem solving. We demonstrated additive effects of problem presentation and movement manipulation guiding participants to one of two solutions in a quantitative problem-solving task. Consistent with embodied cognition, sensori-motor information affects our problem representations as well as our insight into possible solutions.

Disclosure statement

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