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A short mindfulness induction might increase women’s mental rotation performance

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ABSTRACT

The study aimed to investigate the effects of an embodied mindfulness treatment on chronometric mental rotation. Forty-four women and 47 men participated and were randomly divided into two groups: a mindfulness induction group and a control group. They completed two sets of 150 mental rotation tasks with cube figures each. Subjective cognitive effort (measured after each block), reaction time, and accuracy were analyzed using linear mixed models with the factors of time, mindfulness, angular disparity, and gender. The significant finding was a three-way interaction between pre-post testing, mindfulness, and gender for reaction times. This interaction suggests that women might benefit more from the mindfulness induction, while men may benefit more from the control condition. The analysis of subjective cognitive effort indicates that women and men perceive the same cognitive effort when solving cube-figure tasks.

1. Introduction

Spatial abilities include skills that involve the mental representation and transformation of visual information, such as objects or shapes, and the relationships between them (Newcombe & Shipley, 2015; Uttal et al., 2013; Xie et al., 2020). One is mental rotation, the cognitive ability to mentally rotate two- or three-dimensional objects or images quickly and accurately (Linn & Petersen, 1985; Shepard & Metzler, 1971).

In their seminal study for chronometric mental rotation experiments, Shepard and Metzler (1971) described that the behavioral variable reaction time increases linearly as a function of angular disparity between two images. Later research has shown similar results with not always as perfect linear relationships (Heil & Rolke, 2002). The relationship between error rates and angular disparity follows a weaker but somewhat similar pattern like reaction times, with a constant and approximately linear increase of error rates with increasing rotation angles (Carpenter et al., 1999; Hyun & Luck, 2007).

1.1. Sex and gender differences in mental rotation test performance

A critical matter in mental rotation research is the potential existence of sex and gender differences. The performance differences in psychometric mental rotation tests favoring males are among the most significant sex differences observed in cognitive psychology (Halpern, 1989, 2013; Voyer et al., 1995). In contrast to the more stable sex differences in psychometric mental rotation tests, there is a continuous discussion about whether and how sex influences performance in chronometric mental rotation tests. Here, differences are

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more minor and mostly non-significant or emerge only in subtests or for specific stimuli (Jansen-Osmann & Heil, 2007; Peters & Battista, 2008; Rahe & Jansen, 2022). Overall, the various existing versions of mental rotation tests correlate in terms of performance, but their differing results regarding sex differences cannot be extensively explained yet (Jost & Jansen, 2024; Voyer et al., 2006). There are several explanations for the possible sex differences, if they exist, like, for example, implicit gender stereotypes (Guizzo et al., 2019) or the use of spatial toys during childhood (Moè et al., 2018). One possible explanation might be that the cognitive effort of chronometric mental rotation tasks is related to sex or gender differences.

1.2. Cognitive effort in mental rotation

Cognitive load theory incorporates making predictions about problem-solving and learning processes via the number of mental resources and effort invested in a task (Ayres et al., 2021). According to this theory, intrinsic cognitive load is elicited by the interacting elements of a task, which have to be processed simultaneously (see Sweller et al., 2019). As complex tasks involve more interacting elements, they generate higher levels of intrinsic cognitive load. In their review of different measurements of intrinsic cognitive load, Ayres et al. (2021) described that pupillometry was the most sensitive and that subjective cognitive load measurements showed the highest levels of validity. In a recent paper, Gieshoff and Heeb (2023) pointed out that the terms cognitive load and cognitive effort are often used interchangeably in scientific literature. In their study investigating the relationships between self-perceived effort and load as well as performance in translation and interpreting, self-reported load and effort correlated strongly. Thus, regarding the participants' experience of the cognitive demands of translation and interpreting, the difference between load and effort showed little relevance. Nevertheless, we support the notion to better differentiate these terms. "[C]ognitive load [is associated] with the complexity of the stimuli and task (i.e., source text, commission, situation, and so on), and cognitive effort with the actual response by the task performer" (Ehrensberger-Dow et al., 2020, p. 221; see also Gieshoff, 2021; Gieshoff & Heeb, 2023).

Cognitive pupillometry is one way to objectively measure changes in mental load and cognitive effort. However, this method can only be used in some experiments, depending on test design, apparatus availability, and other constrictions. To ascertain the cognitive demands of test problems in these types of experiments, self-rating scales of mental effort can be used (see Paas & van Merriënboer, 1994; Paas et al., 2003). Depending on the test design, these measurements can be done after each task or whole test blocks. Chronometric mental rotation experiments usually include an extensive number of items to ensure test power. Including a subjective rating of perceived exertion after each item would drastically increase the experiment duration, which must be considered. For instance, Ayres (2006) measured cognitive load once after finishing each answer booklet in a study on mathematical learning. Similarly, Jost et al. (2023) measured the subjective cognitive effort after each mental rotation task block and analyzed these block values. As one of the findings in their study regarding mental rotation and aerobic exercise, they reported subjective cognitive effort being significantly lower for females than for males. In another study using pupillometry to measure cognitive load, Campbell et al. (2018) reported that females showed higher cognitive load than males in mental rotation tasks of abstract figures. In contrast, using pupillometric measurements, no significant differences in cognitive load between females and males were found (Bauer et al., 2021, 2022). Therefore, in this online study, we measured subjective cognitive effort to analyze further the connection between mental rotation performance, cognitive effort, and possible gender differences. Furthermore, we enlarged our study by investigating the role of embodiment, especially embodied mindfulness.

1.3. Embodied mindfulness in cognitive tasks

According to Embodied Cognition, the brain incorporates experiences of the whole body and combines sensory and motoric information (Barsalou, 2008; Lakoff & Johnson, 1999). Hence, embodiment effects can influence the performance in cognitive tasks. Some of these effects are observed in embodied mindfulness meditation, which can improve attentional control capacity and redirect attention to a current task (Chiesa et al., 2011). Embodied mindfulness meditation (e.g., body scan) encompasses "the intentional and progressive ability to notice, differentiate, and modulate top-down processes in such a way that does not prevent one from experiencing bottom–up present-moment sensations" (Khoury et al., 2017, p.1167; also see Siegel, 2007, 2010).

> According to Dreeben et al. (2013), the main objective of the *body scan* is to help establish the connection between physical sensations and emotional labels, identify somatic correlations with cognitive activity, and understand what it modifies without paying attention to past and future thoughts but only to the here and now, and noticing and appreciating affective states using non-reactive and descriptive language (review by Cebolla et al., 2015, p.38).

Regarding the effectiveness of brief mindfulness interventions, Zeidan et al. (2010) found that four days of twenty-minute mindfulness meditation training seemed to increase the ability to sustain attention in cognitive tasks that require sustained attention and executive processing efficiency. The brief mindfulness training also reduced fatigue and anxiety ratings compared to the control group. Similarly, Tang et al. (2007) reported that five days of Integrative Body Mind Training had improved cognitive processes and mood. However, as this training includes various techniques (e.g., music therapy, mindfulness, and guided imagery), it needs to be clarified how much of an impact mindfulness had on the improvements. Overall, longer mindfulness meditation practices over several weeks improve attentional control (Lutz et al., 2008). However, a short meditation practice can impact cognitive control tasks differently depending on the kind of short meditation form (Colzato et al., 2016).

Regarding even shorter and one-time inductions, the effects of a ten-minute mindfulness meditation on the P300 event-related potential, which is a neurophysiological marker of attention (Polich, 2012) and known to be highly dependent on expectancy, were analyzed (Bokk & Forster, 2022). The authors employed a classical oddball paradigm, where the somatosensory P300 decreases with higher block numbers (Kida et al., 2012), which indicates the task not being challenging enough, leading to mind-wandering (Picton, 1992; see Bokk & Forster, 2022). In meditation-naïve participants, the mindfulness meditation prevented the decrease of somatosensory P300 commonly observed with task repetition (Datta et al., 2007; Kida et al., 2012; Lammers & Badia, 1989; Nakata et al., 2015; see Bokk & Forster, 2022), which was observed in their control group. This decrease with task repetition suggests a habituation effect of diverting attention from the task (Isreal et al., 1980; Wickens et al., 1983). The mindfulness group not showing such an effect may suggest either changes in attention mechanisms or preservation of these mechanisms against habituation effects (Bokk & Forster, 2022). The authors concluded that "even a short mindfulness meditation prevents the depletion of attentional resources on the task" (Bokk & Forster, 2022, p. 2027).

In one study with a mathematical task, Weger et al. (2012) used a brief mindfulness intervention to alleviate the effects of stereotype threat. The authors reported a significant main effect of a five-minute mindfulness intervention (eating two raisins) versus a control condition. Similarly, in a psychometric mental rotation task, Rahe and Jansen (2023) reported a significant positive effect of a five-minute mindfulness intervention (eating two candies) in their group of 152 adolescents (72 females, 80 males). In contrast, the effects of a five-minute mindfulness induction (eating two raisins) versus a control condition on chronometric mental rotation performance were tested, and no significant main effects were found (Bauer et al., 2022). However, both groups had elevated levels of state mindfulness after the inductions, which influenced the interpretation of the results.

1.4. Goals and hypotheses

With mathematical abilities and mental rotation performance being related (Xie et al., 2020) and mental rotation also being influenced by embodiment effects through mindfulness induction (e.g., Rahe & Jansen, 2023), the reported effects of mindfulness in mathematics (Weger et al., 2012) might also apply to chronometric mental rotation tasks. Thus, our goal was to investigate the effects of an embodied mindfulness treatment on chronometric mental rotation. Participants of both genders performed mental rotation tasks and were assigned to two condition groups, that is, with either a mindfulness induction or a control condition. Additionally, we used a scale for the perceived cognitive effort to investigate if the gender differences in mental rotation are connected to subjective cognitive effort. The following hypotheses were investigated:

In line with former research indicating task performance improvements (e.g., Weger et al., 2012), we predicted an interaction between pre-post testing and mindfulness, with mindfulness improving the mental rotation performance in the posttest compared to the control group (Hypothesis 1). We expected these changes to be more significant for tasks of higher difficulty, that is, a higher angular disparity between both objects being compared (see Jost & Jansen, 2020).

Regarding the benefits of focused attention meditation (see Lutz et al., 2008), mindfulness was expected to lead to lower subjective cognitive effort in the posttest (Hypothesis 2).

Apart from the treatment effects, we expected a general decline in subjective cognitive effort from pre- to posttest due to possible learning and habituation effects (Hypothesis 3).

Based on the findings of Bauer et al. (2021, 2022) regarding the link between reaction time and objective cognitive load, we expected subjective cognitive effort for pre- and posttests to be linked to their overall sum of reaction times. As we measured cognitive effort per item block, the total sum of reaction time describes the time per block (pre- or posttest) for participants to respond to all 150 items. Longer overall response times were expected to lead to higher values in cognitive effort (Hypothesis 4).

In the form of additional hypotheses, we expected a time effect of angular disparity, that is, higher behavioral performance improvements in the posttest for higher angular disparity. According to the mental rotation paradigm, we expected reaction times to increase and accuracy rates to decrease with higher angular disparity. The effect of gender differences will be analyzed, too, exploratively. Additionally, we also analyzed exploratively possible gender differences in overall reaction time sums of the test blocks.

2. Methods

2.1. Participants

In the study, 149 students (84 women, 65 men) participated and received study credits. In the preprocessing of the data, various filters led the data of 58 participants to be excluded from further analysis (for details, see Data Processing). Consequently, 91 students

Table 1

Participants' Experience in Mindfulness, Meditation, Yoga, and Mental Rotation Tests Before This Study.

Experience	Mindfulness	Meditation	Yoga	Mental Rotation
None	22	10	4	19
Tried out once		40	32	
Done a few times per year		28	26	
Done a few times per month		10	22	
Done a few times per week		3	7	
Minor theoretical knowledge	37			
Practical experience	32			
Participated in 1–3 experiments				49
Participated in > 3 experiments				23

(44 women, mean age (SD) = 21.8 (1.2) years; 47 men, mean age (SD) = 22.8 (3.5) years) form the sample for statistical analysis. In the study of Weger et al. (2012), the main effect of mindfulness on mathematical performance for women was detected with a $d = 0.58$. The required sample size for women was estimated using the software G*Power (Faul et al., 2007). With an effect size of $d = 0.58$ ($f = 0.29$), a power of 0.90, and an alpha value of 0.05, a sample size of 66 women was estimated (F-test for GLM with repeated measures and between factors; see Bartlett, 2022; also see Brysbaert & Stevens, 2018). For the explorative analysis of gender differences, the same amount was estimated for men. Due to the filtering, the resulting sample was, therefore, smaller than estimated *a priori*. However, the power should increase using linear mixed models in the analysis (Barr et al., 2013; Hilbert et al., 2019). Regarding our sample size of 44 women, the actual power of this study was 0.76.

The participants' experience in mindfulness, meditation, yoga, and mental rotation tests before this study is shown in Table 1. To mitigate possible experience effects, participants were required not to have participated in any mental rotation task experiment within the six months preceding this experiment. All participants reported no relevant physical or mental limitations. Informed consent was obtained from all individual participants. The experiment was conducted according to the ethical declaration of Helsinki. We communicated all considerations necessary to assess the question of ethical legitimacy of the study.

2.2. Conditions

Participants were randomly assigned to one of two test groups. The induction after completing the first block of mental rotation tasks depended on this assigned group. In line with Ussher et al., (2014; ten-minute reading) and as in the studies of Aaron et al. (2020) and Schroter et al. (2023), the control group heard a twenty-minute reading about natural history in German ("A Short History of Nearly Everything"; Bryson, 2004). For the mindfulness condition, a twenty-minute audio track consisted of recorded instructions by a professional *Mindfulness-Based Stress Reduction* instructor with more than ten years of experience in doing a mindfulness-based body scan. The focus of the meditation was on body sensations and the perception of the hands. In the final sample with 91 participants, 25 women, and men were assigned to the mindfulness condition. Nineteen women and 22 men were assigned to the control condition.

2.3. Setup

Stimulus presentation and response handling were controlled with OpenSesame software (version 3.3.1 *Lentiform Loewenfeld 2020*; Mathôt et al., 2012) using the OSWeb tool (version 1.3.8.0) together with JATOS software (version 3.5.4; Lange et al., 2015) and Ngrok software (version 2.3.35; Ngrok Software, 2023). With this setup, the study was run as an online experiment, which participants could access through their Internet browser. To mitigate possible confounding variables in the online experiment setup, various instructions were given to the participants beforehand. The participants were asked to prepare a room where they could spend at least 90 min quietly and undisturbed. They were also advised to prepare a comfortable place, for instance, a bed, mattress, or sofa, where they could lie down during the twenty-minute session in the middle part of the experiment. They were also asked to put their phones on silent mode and make sure that their computer had a power supply connected as well as a sufficiently loud volume output and monitor brightness. All participants used keyboard arrow buttons for task response to control input lag.

2.4. Stimuli

Stimuli consisted of a selection from the stimulus library of Peters and Battista (2008). Ten cube figure models with rotations around the x- and z-axis in 45° steps and mirrored/non-mirrored orientation were used with a checkered pattern on a black background (see Fig. 1).

In the main experiment, which was divided into two parts, each part consisted of 150 stimuli, resulting in a total of 300 different stimuli. The first 150 stimuli were figures one to five, and the second 150 were six to ten of the stimulus library (Peters & Battista, 2008). The order of the stimuli in each block was randomized for all participants. On the left side of the screen, every model was presented in orientation *a*, rotated by 30° in the x direction and 15° in the z direction so that the base model for x or z rotation was identical. On the right side of the screen, a rotated and mirrored/non-mirrored stimulus was presented. Stimulus pictures were sized 400px times 400px and presented vertically centered and horizontally positioned 300px to the left or right of the center of the screen

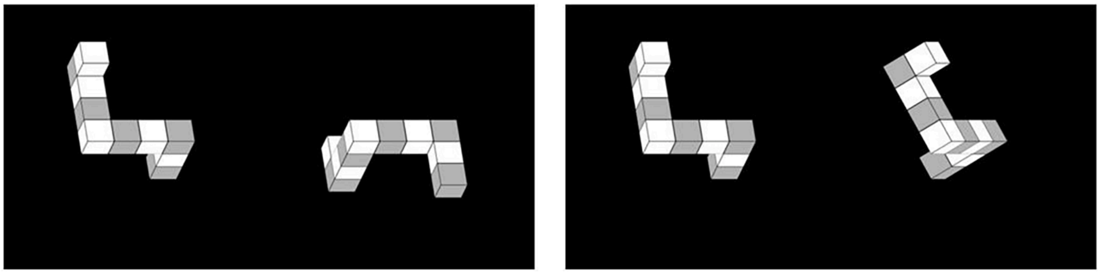

Fig. 1. *Examples of Mental Rotation Stimuli Used in the Experiment*. Selected from the stimulus library of Peters and Battista (2008). Left: 90° rotation in the x-axis. Right: 45° rotation in the z-axis.

until a response was given. Thus, depending on the monitor resolution, the stimuli were possibly slightly bigger or smaller for each participant. However, since the distance or position to the screen could not be controlled either, and as no pupillometric measurements are conducted in this setup, these differences can be regarded as negligible. In the practice block, three different models were presented in overall 24 practice stimuli (figures 11 to 13 of the stimulus library), that is, four rotations in the x-axis and z-axis for each model, combined with using each possible angular disparity once and half of the trials being mirrored. In the practice session, between the stimuli pairs, participants received feedback for 1000 ms (✔- right, ✘- wrong) shown at the center of the screen. In experimental sessions, a fixation cross ("+") was shown there for 500 ms.

2.5. *Subjective cognitive effort*

After the practice, pretest, and posttest block, participants filled out a Likert-type scale for subjective cognitive effort. Here, they rated their response to each block on a ten-point scale. The measure of cognitive effort was similar to Ayres (2006): "In the recent section, how demanding/ strenuous did you perceive solving the mental rotation tasks?" The answers were given as a number and a verbal expression, ranging from "0 – Not at all demanding" to "9 – So demanding that I could not solve them". Measuring the cognitive effort for each block of tasks was chosen over the measurement for every task. This was done to maintain the general mental rotation task design without disrupting the consecutive tasks with other questions and because the complete experiment duration would have been extended by about an hour for each participant. This aligns with Jost et al. (2023), who also used this scale to measure the RPE (rate of perceived exertion) for subjective cognitive exertion after each block in their study regarding mental rotation and aerobic exercise.

2.6. *Toronto Mindfulness Scale*

To check whether the mindfulness manipulation had the desired effect, we used the Toronto Mindfulness Scale (TMS; Lau et al., 2006) to measure state mindfulness. The TMS was translated to German and included 13 items with five answer alternatives (0 = not at all; 4 = very much). For each participant, we computed summed scores for all items (see Lau et al., 2006). To prevent priming the participants to focus on mindfulness behavior before the treatment (either control or mindfulness condition), the TMS was only done after the second mental rotation task block. Thus, these values served as a check whether the treatments showed an overall different effect between the groups. In this study, the internal consistency of the questionnaire is good (Cronbach's alpha = 0.82).

2.7. *Procedure*

The experiment was a single session and lasted between 60 and 90 min, depending on the participants' speed to complete all items (see Fig. 2). At the start of the online experiment, the participants were presented with written information about the study protocol and the study's goals. Then, they gave informed consent and were directed to a follow-up page with instructions for the following experiment. One of those was to set the browser window to a full-screen presentation. After that, the practice session with feedback followed that was introduced by a digitally presented instruction. Participants used the keyboard for response handling and received written instructions to press the left arrow button if the stimuli could be rotated into congruence (non-mirrored, "same") and the right arrow button if the two stimuli were mirrored ("different"), and to answer as quickly and precisely as possible. After completing all practice trials, they answered the scale for cognitive effort. Then, the first part of the main experiment was run, after which they answered the scale for cognitive effort again. Depending on the assigned test groups, an induction followed. This induction was either a twenty-minute mindfulness induction, during which the participants listened to recorded instructions to do a mindfulness-based body scan, or a twenty-minute control condition, during which the participants listened to a section of an audiobook about natural history. Then, the second part of the main experiment (posttest) was done. Following this part, they answered the scale for cognitive effort, filled out the TMS (Lau et al., 2006), a demographic questionnaire, and questioned whether they had been attentive during the twenty-minute listening part (e.g., they had fallen asleep or used their phones). After this, the participants received their participation code, and the experiment concluded. All participations were conducted anonymously, and the presented participation codes, in the end, were distributed randomly from a predefined list of one thousand codes and were not recorded anywhere. As it was an online experiment, all instructions were standardized.

2.8. *Study design*

To analyze cognitive performance, the dependent variables are reaction time (RT) and accuracy (ACC). The cognitive effort was

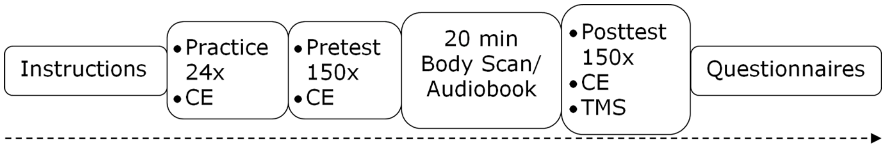

Fig. 2. *Timeline of the Experiment's Phases.* The numbers indicate the mental rotation task items per phase. CE = Cognitive Effort, Body Scan = Mindfulness Induction, Audiobook = Control Condition, TMS = Toronto Mindfulness Scale.

self-reported on a Likert-type scale after the practice trials (but not analyzed) and the pre- and posttest. Independent variables for the analysis of the cognitive performance are pre-post experiment setup (PP), mindfulness induction (MF), gender (GEN), angular disparity (DEG), and their respective interactions. DEG describes the angular disparity between the two figures shown on the screen. DEG was included as a fixed effect as it is the main moderator of difficulty in mental rotation tasks (Jost & Jansen, 2020). Since the left image was always presented with 0° rotation, the angular disparity depicts the rotation in degrees of the right image. The cognitive effort analysis includes PP, MF, GEN, and their respective interactions. Furthermore, the total sum of reaction time (for all items; RT-Sum) for each block (pre- and posttest) is analyzed as an additional fixed effect to analyze the influence of reaction time on subjective cognitive effort. Regarding MF and GEN, the overall TMS score is analyzed to measure state mindfulness.

2.9. *Data processing*

For the behavioral data, outliers were determined by deviance of more than three standard deviations from the mean reaction time of all stimulus pairs with the same rotation angle and were excluded from all analyses. Because angular disparity is not defined for mirrored responses in cube figures (Jolicœur et al., 1985; Shepard & Metzler, 1971), only non-mirrored stimulus pairs were analyzed, and reaction time was additionally only analyzed for correct responses. The data was further processed in R (version 3.5.1; R Core Team, 2018) to obtain valid data. As an online experiment with a twenty-minute induction, the data had to be scrutinized, processed, and filtered regarding participants' compliance and other factors to accomplish valid data. As such, the data were examined and filtered according to predefined guidelines regarding timestamps and noticeable behavioral data anomalies.

As the last questionnaire question, the participants were asked to declare honestly whether they had been attentive and participated committedly throughout the experiment. Accompanying this question, the information was given that the credits for participation would be attained in any scenario. As a result, 36 participants declared that they had occupied themselves with other things, such as using their mobile phones or cooking, or that they had fallen asleep during the experiment. To examine the remaining sample, all actions throughout the experiment were time-stamped. Using this information, an additional filter was a time window of 30 min between the end of the pretest and the beginning of the posttest. Within this time frame, the 20-minute induction was conducted, and thus, whoever took longer to continue the experiment by commencing with the posttest was filtered. As a result, six participants were filtered. Additional filters and respective data inspection led to two more participants being filtered. One took over 80 min from the beginning of the pretest until the end of the posttest and showed response times in the mental rotation tasks constantly over 30 s. The other participant clicked through the tests as fast as possible with reaction times of 10 – 300 ms, resulting in 28 min.

Further filters regarding the behavioral data led to 14 more participants being excluded from statistical analysis. For instance, one exclusion criterion was having mean accuracy values of less than 80 % for non-rotated and non-mirrored figures. Moreover, nine participants had accuracy means of around 50 % and overall short reaction times. Another example is one person who had less than 300 ms and bad accuracy for all figures rotated at 180°, which might indicate frustration and the tendency to just skip through the experiment.

2.10. *Statistical analysis*

Statistical analysis was performed according to Bauer et al. (2022) and Jost et al. (2023) using *Linear Mixed-Effects Models* using the *lme4* package (version 1.1–21; Bates, Maechler, et al., 2015). Reaction time and cognitive effort were analyzed using linear mixed models, and accuracy was analyzed using generalized linear mixed models with a binomial distribution. Model parameters were estimated by maximum likelihood estimation using the *bobyqa* algorithm wrapped by the *optimx* package (version 2018–7.10; Nash & Varadhan, 2011) as optimizer. Model fit was calculated using likelihood ratio tests to compare models with and without the fixed effect of interest. The resulting p values were compared to a significance level of 0.05. For multiple comparisons of the same variables, the significance level was Bonferroni corrected. Visual inspection of residual plots did not reveal deviations from homoscedasticity or normality in any model. For the significant effects and main effects, we report the unstandardized effect sizes and the confidence intervals that were calculated using parametric bootstrapping with 1000 simulations, in line with the recommendations of Baguley (2009) and Pek and Flora (2018).

Cognitive effort analysis was additionally conducted using *Cumulative Link (Mixed) Models* using the *Regression Models for the Ordinal Data* package (*ordinal*, version 2019.12–10; Christensen, 2015). Since both analyses of cognitive effort resulted in the same model, we report the results of the *Linear Mixed-Effects Model* for better comparability with the other results.

Model building was based on the research of Barr et al. (2013) and Bates, Kliegl, et al. (2015), starting with a model with random intercepts and slopes for every appropriate fixed effect and reducing the model complexity by dropping non-significant variance components. Non-significant fixed effects were removed stepwise from the model; that is, effects that least decreased the model fit were removed first, and a model only containing significant fixed effects remained. Then, non-significant effects were tested for improving the model fit by including them in the resulting model. Also, significant effects were tested for worsening the model fit by exclusion of the effect. The main effects for significant interactions were tested separately by splitting the interaction (see also Jost & Jansen, 2020). The resulting models for each parameter are described in the results section. In the tables, all results (i.e., partial interactions, test statistics, and confidence intervals) are depicted for effects with $p < 0.05$. For.1 $> p >$ 0.05, the test statistics are also depicted. Furthermore, for $p > 0.1$, only the test statistics for hypothesis-relevant effects (interactions of MF, PP, GEN, and DEG, and selected main effects) are depicted. That means all other effects in the models resulted in $p > 0.1$. As the data were not normally distributed (Shapiro-Wilk test, $W = 0.98$, $p < 0.05$), the TMS scores were analyzed with Mann-Whitney tests in R (R Core Team, 2018). All data were visualized using the *ggplot2* package (Wickham, 2016) in R (R Core Team, 2018).

3. Results

3.1. *Toronto Mindfulness Scale scores*

As a measure of state mindfulness, the TMS scores were analyzed. A Mann-Whitney test indicated that participants' scores without MF (Mdn = 23) differed significantly from those with MF (Mdn = 30.5), U = 499, $p < 0.001$. A similar test revealed no significant difference between men (Mdn = 24.5) and women (Mdn = 28), U = 1102, $p = 0.267$.

3.2. *Effects on the mental rotation performance*

3.2.1. *Reaction time*

For reaction time, model construction resulted in a model with random intercepts and slopes for PP and DEG by participant and DEG by model. PP*MF*GEN*DEG and all respective interactions and main effects were analyzed as fixed effects. Significant differences were found for PP*MF*GEN and DEG*GEN (see Table 2). The three-way interaction of PP*MF*GEN indicates different improvements through mindfulness induction in interaction with gender and pre-post testing. Breaking this interaction into its subparts resulted in no significant interactions or main effects. The interaction DEG*GEN shows a significant increase in reaction time with increasing DEG, with higher increases for men than women. Reaction time increased significantly by DEG and decreased significantly by PP (main effects).

The results did not support our first hypothesis that mental rotation task performance would be better for the mindfulness condition in the posttest (PP*MF *ns*), and the effect of this was neither modified by increasing angular disparity (PP*MF*DEG *ns*).

Regarding reaction time and our other hypotheses, gender differences did not emerge for the main effect (GEN) but for the interaction PP*MF*GEN, indicating different improvements through the mindfulness induction in interaction with gender and pre-post testing. Fig. 3 illustrates the significant three-way interaction of PP*MF*GEN. The mindfulness induction group and the control group improved from pre- to posttest. Males had overall higher average reaction times than women. Visually, for men, the mindfulness group improved less than the control group, and vice versa; for women, the mindfulness group improved more than the control group. However, further analysis showed no significant two-way interactions or main effects.

The results aligned with the mental rotation paradigm, showing increasing reaction times with increasing angular disparity. Our hypothesis that higher improvements would show for larger angles in the posttest was not confirmed (PP*DEG *ns*). However, PP and DEG both showed significant main effects, indicating an overall improvement from pre- to posttest, as well as the general negative effect of increasing angular disparity on reaction times. Additionally, the interaction DEG*GEN indicates that overall test increases in angular disparity affected the performance of men significantly more than women.

3.2.2. *Accuracy*

Like reaction time, model construction for ACC resulted in a model with random intercepts and slopes for PP and DEG by participant and DEG by model. PP*MF*GEN*DEG and all respective interactions and main effects were analyzed as fixed effects. Significant differences were only found for DEG and PP (see Table 3). Accuracy decreased significantly by DEG and increased significantly by PP.

Similar to reaction times, the results for accuracy did not support our first hypothesis that mental rotation task performance would be better for the mindfulness condition in the posttest (PP*MF *ns*), and the effect of this was neither modified by increasing angular disparity (PP*MF*DEG *ns*).

Regarding accuracy and our other hypotheses, gender differences emerged neither for the main effect (GEN) nor for the

Table 2
Statistical Analysis of Reaction Time (in Seconds).

Variable	Estimate	SE	Test Statistic	*p* value	95 % CI
Intercept	1.49	0.13			1.25, 1.73
MF*PP*GEN*DEG			$\chi^2(1) = 0.01$	0.974	
MF*PP*DEG			$\chi^2(1) = 1.18$	0.279	
MF*PP*GEN	0.43	0.20	$\chi^2(1) = 4.58$	0.032	0.02, 0.81
MF*PP			$\chi^2(1) = 0.17$	0.677	
PP*GEN			$\chi^2(1) = 0.09$	0.869	
MF*GEN			$\chi^2(1) = 0.11$	0.735	
DEG*PP			$\chi^2(1) = 0.13$	0.719	
DEG*GEN			$\chi^2(1) = 4.16$	0.041	
DEG*GEN(m)	1.40	0.11			1.18, 1.62
DEG*GEN(w-m)	−0.26	0.13			−0.53, −0.08
DEG(0°)*GEN(w-m)	−0.03	0.17			−0.39, 0.32
DEG(100°)	1.28	0.08	$\chi^2(1) = 35.17$	<0.001	1.09, 1.46
PP(pretest)	0.28	0.09	$\chi^2(1) = 7.57$	0.006	0.09, 0.46

Note. The intercept in this model represents the estimate for gender (GEN) = men, angular disparity (DEG) = 0°, pre-posttest (PP) = post, and no mindfulness (no MF). The effect of GEN represents the difference between women (w) and men (m). Effects of angular disparity (DEG) represent changes of 100°.

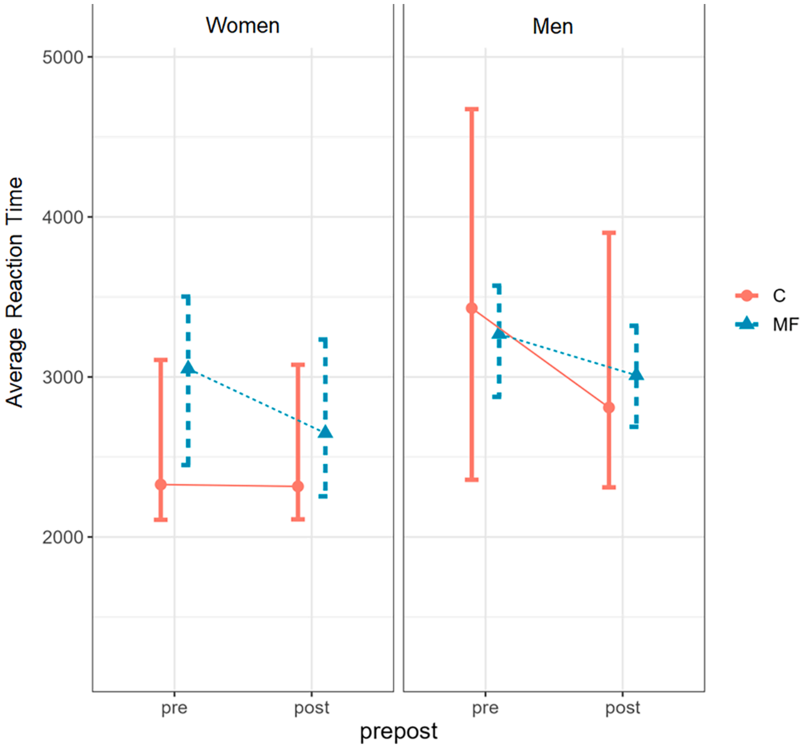

Fig. 3. *Average Reaction Time Plotted For Gender, Condition, and Pre-Post Test.* C = control condition, MF = mindfulness condition, pre = pretest, post = posttest. Whiskers depict the Interquartile Range of the 75th percentile (upper) and 25th percentile (lower) of the data; the dots connected with a ghost line depict the median.

interactions. The results aligned with the mental rotation paradigm, showing decreasing accuracy rates with increasing angular disparity. Our hypothesis that higher improvements would show for larger angles in the posttest was not confirmed (PP*DEG *ns*). However, PP and DEG both showed significant main effects, indicating an overall improvement from pre- to posttest, as well as the general negative effect of increasing angular disparity on accuracy rates.

3.3. Effects on subjective cognitive effort

The model building for cognitive effort resulted in a model with random intercepts by participants. PP*MF*GEN, all respective interactions, main effects, and RT-Sum were analyzed as fixed effects. The cognitive effort decreased significantly by PP and increased significantly by RT-Sum (see Table 4). About the inclusion of RT-Sum in the model, we inspected the data for possible collinearity problems. All variance inflation factors were more minor than three (maximum of 1.03), which means collinearity was not an issue (see Zuur et al., 2010).

With the variable RT-Sum having an impact on cognitive effort, we exploratively analyzed this variable more. It is important to note that this analysis differs from the analysis of reaction times by item, which is only conducted for non-mirrored and correctly answered

Table 3
Statistical Analysis of (Logarithmic Odds of) Accuracy.

Variable	Estimate	SE	Test Statistic	*p* value	95 % CI
Intercept	3.89	0.17			3.54, 4.26
MF*PP*GEN*DEG			$\chi^2(1) = 0.12$	0.725	
MF*PP*DEG			$\chi^2(1) = 0.08$	0.781	
MF*PP*GEN			$\chi^2(1) = 0.47$	0.496	
MF*PP			$\chi^2(1) = 0.01$	0.969	
PP*GEN			$\chi^2(1) = 0.04$	0.848	
DEG*GEN			$\chi^2(1) = 1.04$	0.308	
DEG(100°)	−1.26	0.10	$\chi^2(1) = 31.43$	<0.001	−1.45, −1.06
PP(pretest)	−0.45	0.18	$\chi^2(1) = 4.86$	0.028	−0.83, −0.07

Note. The intercept in this model represents the estimate for the logarithmic odds for gender (GEN) = men, angular disparity (DEG) = 0°, pre-posttest (PP) = post, and no mindfulness (no MF). The effect of GEN represents the difference between women and men. Effects of angular disparity (DEG) represent changes of 100°.

ones. The total sum of reaction time describes the time per block (pre- or posttest) for participants to respond to all 150 items. Statistical analysis showed significant main effects for PP and GEN. Both genders have smaller sums of reaction times in the posttest than in the pretest. Additionally, men have overall higher values than women in both pre- and posttests. For this analysis, collinearity did not exist, as all variance inflation factors were smaller than one (see Zuur et al., 2010).

In the results for subjective cognitive effort, there was no evidence for our second hypothesis that self-reported cognitive effort would be influenced by mindfulness induction and be lower in the posttest (PP*MF and MF *ns*). Our third hypothesis was confirmed, as subjective cognitive effort decreased overall from pre- to posttest (PP sign.). In our fourth hypothesis, we expected subjective cognitive effort for pre- and posttests to be linked to the overall sum of reaction times. This was confirmed, as increasing overall response time led to higher values in subjective cognitive effort (RT-Sum sign.).

Regarding subjective cognitive effort and our other hypotheses, no gender differences emerged either for the main effect (GEN) or for the interactions. In the explorative analysis of the variable RT-Sum, the sums of reaction times decreased from pre- to posttest for all groups, and a significant main effect of gender indicated that women had overall lower reaction time sums in both tests.

4. Discussion

4.1. *Manipulation Check: Toronto Mindfulness Scale scores*

All participants had to fill out a TMS questionnaire. The TMS scores were then analyzed to determine whether the mindfulness induction had the desired effect. The participants of the mindfulness groups showed overly high scores for state mindfulness in the experiment (see Lau et al., 2006). These scores are similar to the ones Weger et al. (2012) reported for their mindfulness groups. The participants of the control groups showed significantly lower scores. Therefore, the twenty-minute mindfulness induction elicited a significant effect on state mindfulness.

4.2. *Effects of the mindfulness induction on mental rotation performance*

Based on our hypotheses, the focus was on the interaction between mindfulness and pre-post testing, which would illustrate the changes in behavioral performance resulting from the treatment.

In the analysis for reaction time, the interaction between pre-post testing, mindfulness, and gender was significant. This indicates that in interaction with the mindfulness induction or control condition, men and women showed significantly different changes between the pre- and posttest. Visual inspection of the reaction time averages (see Fig. 3) might indicate that only women benefitted from the mindfulness induction. Additionally, men seem to improve more in the control condition. Nevertheless, dividing this three-way interaction into its subparts resulted in no significant effects. Due to the filtering of many participants, the explorative analysis of this three-way interaction was underpowered. The effect size of this interaction could be considered for future studies for sample size estimations.

However, another significant interaction was that gender interacted with changes in angular disparity. This means that in both tests, reaction time increased more for men with higher levels of angular disparity than for women. Hence, in both conditions, women seemed less susceptible to the increasing difficulty due to larger rotation angles between the figures.

For accuracy, no interactions between pre-post testing and mindfulness emerged as significant, indicating no effects regarding mindfulness induction can be observed. In the model, angular disparity and pre-post testing were the only significant variables. This could be explained by the actuality that in mental rotation tasks, a speed-accuracy-tradeoff always happens. Here, accuracy undergoes more minor changes than reaction time and is therefore less influenced by different variables (see, e.g., Hertzog et al., 1993; Wickelgren, 1977).

About our first hypothesis, no significant differences in the performance manifested between the two treatment conditions. Only with the addition of gender in the interaction the groups differed significantly in the model. This is interesting, as other chronometric mental rotation studies (e.g., Jansen-Osmann & Heil, 2007; Voyer et al., 2006) reported no gender differences in the mental rotation performance of 3D cube figures. Considering the effective change in state mindfulness, the embodied meditation treatment could have had more impact on attentional control for the women. In contrast, the men may have profited more from the control condition (see Lutz et al., 2008). This could mean that the embodiment effects were less beneficial for the men. Another possibility is that listening to the prosodic reading lead to lower arousal (see Jürgens et al., 2018) and thus improvements in attentional control and that this was

Table 4
Statistical Analysis of Subjective Cognitive Effort.

Variable	Estimate	SE	Test Statistic	p value	95 % CI
Intercept	3.69	0.26			3.19, 4.17
MF*PP*GEN			$\chi^2(1) = 0.16$	0.691	
MF*PP			$\chi^2(1) = 0.54$	0.463	
PP*GEN			$\chi^2(1) = 0.28$	0.596	
PP(pretest)	0.67	0.13	$\chi^2(1) = 24.37$	<0.001	0.44, 0.94
RT-Sum	0.08	0.03	$\chi^2(1) = 6.75$	0.009	0.02, 0.14

Note. The intercept in this model represents the estimate for gender (GEN) = men, pre-posttest (PP) = post, and no mindfulness (no MF). The effect of GEN represents the difference between women and men.

easier for men to listen to and focus on than focusing on the body scan. However, as no further interactions or main effects regarding these interactions with gender emerged, the conclusions of this three-way interaction are limited. Future research could analyze this further to determine more details.

Altogether, our results did not confirm our hypothesis that task performance would be better after the mindfulness induction. Within the three-way interaction, there is only a visual indication that women might have benefited more from the mindfulness induction than men. One explanation could be that, generally, higher levels of anxiety lead to reduced task performance (Eysenck et al., 2007). In navigation and mental rotation, women show greater spatial anxiety than men (Lawton & Kallai, 2002; Malanchini et al., 2017), which to some degree can influence women performing worse than men in mental rotation tasks (Alvarez-Vargas et al., 2020; see Lourenco & Liu, 2023). Anxiety may deplete cognitive mechanisms like working memory (Eysenck et al., 2007; Maloney et al., 2014), which can lead to rumination processes that compete for working memory resources necessary for task completion (Moran, 2016; see Lourenco & Liu, 2023). Mindfulness improves attention regulation (Lutz et al., 2008), emotion regulation, body awareness, and a change in perspective (Hölzel et al., 2011; see Portele & Jansen, 2023). Therefore, as women are more anxious generally, they might benefit more from mindfulness interventions and inductions.

The implications of the three-way interaction stand in contrast to the findings of Weger et al. (2012), on which our hypothesis was based. In the study with mathematical tests, the authors reported a significant main effect of a brief five-minute mindfulness intervention (eating two raisins) versus a control condition. Similarly, in their recent study with psychometric mental rotation tasks, Rahe and Jansen (2023) reported a significant effect of a five-minute mindfulness intervention (eating two candies). A professional instructor recorded our induction. It lasted longer (i.e., twenty minutes) than the ones Weger et al. (2012) and Rahe and Jansen (2023) induced (i.e., five minutes). With the TMS scores demonstrating a significant difference in elicited state mindfulness in the induction group compared to the control group, the different results regarding the (non–)existence of mindfulness effects are noteworthy. These differences might not only derive from the different treatment durations in the studies but also from the different forms of focused attention meditation. The body scan and the raisin-/candy-eating both involve aspects of embodiment. According to the embodied cognition approach, they would thus elicit respective embodiment effects. By design, the body scan incorporates more of the whole body and the sensations regarding several body areas.

In contrast, eating meditations focus more on the hands and the mouth, and respectively touch and taste. This tactile and taste sensory information could lead to more pronounced or different embodiment effects, which seem to influence cognitive performance more impactfully. As brief mindfulness inductions can influence the working memory (e.g., Beilock et al., 2007), the effects may be more pronounced for the eating treatment than the body scan.

In line with the paradigm for chronometric mental rotation tasks, changes in angular disparity significantly influenced behavioral data. Higher angular disparity between the two pictures resulted in higher reaction times and lower accuracy. Differences between the reaction times of pre- and posttest can be observed, with worse performance values in the pretest. These outcomes can be explained as typical learning effects in a pre-post experimental design.

4.3. *Effects on subjective cognitive effort in the mental rotation task*

Regarding the analysis of subjective cognitive effort, in our third hypothesis, we expected reduced effort for the mindfulness condition in the posttest. This hypothesis was based on the effects of embodied mindfulness (such as the body scan meditation used here) to influence the brain's introspective systems (underlying conscious experience of emotion, motivation, and cognitive operations) to elicit improvements in cognitive tasks (see Niedenthal et al., 2005) and reduce subjective cognitive effort. However, our analysis showed no evidence in support of this hypothesis. The mindfulness induction and the control condition did, therefore, not differ significantly in their effect on subjective cognitive effort. However, for all groups, the subjective cognitive effort decreased from the pretest to the posttest, confirming our third hypothesis. First, this result could be explained by learning and habituation effects, which could lead participants to ascertain task difficulty and resulting cognitive strain to be lower in the second mental rotation part of the experiment. Second, both conditions involved listening to a voice for twenty minutes. While the TMS scores indicate that there was a difference in elicited state mindfulness induction between the condition groups, possible effects of just concentrating and listening to a recording can still influence both groups. For instance, participants could have experienced both conditions to calm the mind and thus reduce arousal. This notion could be supported by the findings of Jürgens et al. (2018). In their study, they measured arousal differences via pupillometry for different levels of affective prosodic utterances. In presenting neutral prosodic stimuli, the pupil sizes were significantly lower than for joyful or angry ones. Similarly, in our study, the control condition was chosen to be neutral, which could mean that the control condition could lead to lower levels of cognitive effort. Thus, aside from the other effects of the embodied meditation practice, both conditions could, therefore, have led to lower overall estimations of subjectively perceived cognitive effort, whose range of possible differences resulted as non-significant.

In our fourth hypothesis, we expected participants' subjective cognitive effort for pre- and posttests to be linked to their overall sums of reaction times. The significant main effect of the reaction time sums confirmed this hypothesis. This means that with increases in the summed reaction times, participants would rate their subjective cognitive effort higher. As this variable was only measured twice, that is, every time after completing the whole test block in pre- and posttest, the longer perceived time to complete these blocks seems to influence the subjective rating of cognitive effort. This could also be partly due to familiarization with the mental rotation test. Notably, changes in subjective cognitive effort were not fully explained by the effects of pre-post testing. However, the sums of the reaction times still predicted a significant portion of the changes in subjective cognitive effort in the statistical model.

As the sums of all the reaction times resulted in a significant effect, we further analyzed this variable exploratively. In the analysis, these sums decreased from pre- to posttest for all groups, illustrating possible learning effects. Furthermore, a significant main effect of gender emerged, indicating that women had overall lower sums of reaction times in both tests. This is interesting, as no main effect of gender differences emerged in any other analysis of the dependent variables. One minor difference is only the lower variance in the cognitive effort data for men.

In the analysis of gender differences for subjective cognitive effort, no interaction or main effects were significant. Overall, both genders rated the pre- and posttest similarly. Males only show a more minor variance compared to women. As part of their study on the link between mental rotation and physical exercise, Jost et al. (2023) analyzed subjective cognitive effort for mental rotation task blocks. In their analysis of 22 females and 19 males, they found a significant main effect of sex, with subjective cognitive effort being significantly lower for females than males. On the other hand, in the pupillometric study of Campbell et al. (2018), females showed higher cognitive load—or used more attentional resources—than males in mental rotation tasks of abstract figures. Considering that the measures of cognitive effort differ between this study and Campbell et al. (2018), our findings did neither confirm their results nor those of Jost et al. (2023), as no differences emerged.

In conclusion, both genders solved mental rotations tasks with cube figures of similar difficulty and rated their subjective cognitive effort similarly. Our last studies showed corresponding results regarding the gender differences in cognitive effort objectively measured via pupillometry (see Bauer et al., 2021, 2022). Hence, our findings in this study provide further evidence that women and men perceive (and probably need) the same cognitive effort for solving cube figure tasks.

5. Limitations

Instead of the option to measure subjective cognitive effort after every item, we chose only to measure it after each block. On the one hand, the results are less detailed and imply a more significant internal variance for each participant. On the other hand, the standard chronometric mental rotation task design was maintained, and the overall experiment duration was kept to a reasonable participation time. However, for future research, more detailed measurements per item could be considered.

One more limitation is the short mindfulness induction. As it was the objective to research the effects of a single brief mindfulness induction, it is still important to consider that mindfulness generally works best through daily practice routines over a more extended period (Cahn & Polich, 2006; Rahe & Jansen, 2023). In this regard, a possible terminological distinction between longer and brief treatments could be considered. For that reason, we described the brief body scan as a mindfulness induction instead of an intervention. Future research could create, vary, and compare different practices and techniques to establish an impactful one-time induction to elicit significant effects.

As mentioned in the discussion, the filtering in the preprocessing led to a final sample size that was smaller than estimated beforehand, resulting in an underpowered explorative analysis of gender differences.

As this study was run as a web experiment, possible influences had to be considered. The participants received clear instructions for a mental rotation experiment conducted on a computer. We also defined means to filter the data appropriately afterward. Lacherez (2008) pointed out that the online character of an experiment does not threaten the internal validity of the findings but may potentially result in less power of the analyses to detect differences, which may also apply to this study.

6. Conclusion

In this online study, the twenty-minute mindfulness induction resulted in an elevated state of mindfulness for the mindfulness condition, significantly different from the control condition. The most important effect was the three-way interaction between pre-post testing, mindfulness, and gender for reaction times. This interaction for the reaction time measurement indicated that women might have benefited more from the mindfulness induction. The underlying mechanism for this must be investigated in further studies; for example, it could be investigated if women’s spatial anxiety is reduced and if this is related to better mental rotation performance.

7. Ethical standards

The experiment was conducted according to the ethical declaration of Helsinki. Ethical approval for this study was not required following the conditions outlined by the German Research Society (DFG), where research that carries no additional risk beyond daily activities does not require Research Ethics Board Approval. We communicated all considerations necessary to assess the question of ethical legitimacy of the study.

8. Code availability

The OpenSesame (Mathôt et al., 2012) and R (R Core Team, 2018) codes used for this study are available from the corresponding author upon reasonable request.

9. Authors’ contributions

Both authors contributed to the study’s conception and design. Material preparation, data collection, and analysis were performed by Robert Bauer. Petra Jansen supervised the study. The first draft of the manuscript was written by Robert Bauer, and Petra Jansen commented on previous versions of the manuscript. Both authors read and approved the final manuscript.

Informed consent

Informed consent was obtained from all individual participants included in the study.

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CRediT authorship contribution statement

Robert Bauer: Writing – review & editing, Writing – original draft, Software, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Petra Jansen:** Writing – review & editing, Supervision, Project administration, Methodology, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

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

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Alexander Kalus (University of Regensburg) wrote the OpenSesame (Mathôt et al., 2012) script.

Appendix A. Supplementary material

Supplementary data to this article can be found online at https://doi.org/10.1016/j.concog.2024.103721.

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