

Exploring bias in horizontal and vertical spatial representations using mental number lines and the greyscales task

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ABSTRACT

People have a leftward bias when making visuospatial judgements about horizontally arranged stimuli ("pseudoneglect"), and a superior bias when making visuospatial judgements about vertically arranged stimuli. The leftward visuospatial bias in physical space seems to extend to the mental representation of space. However, whether any bias exists in mental representation of vertical space is unknown. We investigated whether people show a visuospatial bias in the mental representation of vertical space, and if any bias in mental representations of horizontal and vertical space related to the extent of bias in physical space. Participants ($n = 171$) were presented with three numbers and asked which interval was smaller/larger (counterbalanced): the interval between the first and middle, or middle and last number. Participants were instructed to either think of the numbers as houses on a street or as floors of a building, or were given no imagery instructions. Participants in the houses on a street condition showed a leftward bias, but there was no superior bias in the floors of a building condition. In contrast, we replicated previous findings of leftward and superior bias on greyscales tasks. Our findings reinforce previous evidence that numbers are represented horizontally and ascending left to right by default.

1. Introduction

On average, neurologically healthy controls tend to bisect horizontally-presented lines slightly to the left of the veridical midline (Bowers & Heilman, 1980; Jewell & McCourt, 2000). This pattern has been termed 'pseudoneglect' due to its resemblance to the larger rightward bisection bias exhibited by people with hemispatial neglect ('neglect') following brain lesions. In addition to physical bisection tasks, pseudoneglect is well-documented in visuospatial tasks that do not require gross movements. For example, in the greyscales task, two horizontal rectangles with the same, but left/right mirrored brightness gradients are presented above each other. Participants must indicate which of the gradients is lighter (or darker) on average. Neurologically healthy people tend to show a slight, but consistent preference to choose the gradient that is lighter (or darker) on the left-hand side (Mattingley et al., 1994).

A prominent explanation for pseudoneglect is that the right-hemisphere dominance for spatial attention leads to greater activation

of the right hemisphere relative to the left hemisphere during spatial attention tasks (such as line bisection), and a subsequent stronger 'push' of attention towards the left visual field (the "activation-orientation hypothesis"; Bultitude & Aimola Davies, 2006; Reuter-Lorenz et al., 1990). Pseudoneglect is larger in males than in females and reverses with age, consistent with sex- and age-related differences in right-hemisphere control of attention (Jewell & McCourt, 2000). Pseudoneglect is also larger when tested under conditions that would increase right- relative to left-hemisphere activation, such as when participants respond with their left hand and when stimuli are placed further into the left visual field (Luh, 1995; Reuter-Lorenz et al., 1990).

Another explanation for pseudoneglect is that it is related to participants' visual scanning patterns. Some authors have found that line bisection errors are more leftward when participants scan the line or page from left-to-right compared to from right-to-left (Brodie & Pettigrew, 1996; Halligan et al., 1991), although others have found no difference (Reuter-Lorenz & Posner, 1990). Habitual visual scanning patterns, for example due to cultural factors such as reading direction,

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might therefore affect pseudoneglect. Most pseudoneglect studies are conducted in countries where the habitual reading direction is from left-to-right, but studies testing the effect of habitual reading direction have found that right-to-left readers' line bisection errors are unbiased or significantly rightward of veridical (Chokron & Imbert, 1993; Halligan et al., 1991), and their greyscales judgements are also unbiased (Friedrich & Elias, 2014). However, when the study sample consists of approximately equal numbers of native left-to-right and right-to-left readers, the overall bias still tends to be towards the left (Rinaldi et al., 2014). This suggests that cultural influences on pseudoneglect moderate an underlying leftward bias.

In addition to a leftward bias in horizontal visuospatial tasks, neurologically healthy controls also tend to show a systematic bias when bisecting vertically-presented lines, erring superior of the veridical midline (Drain & Reuter-Lorenz, 1996; Post et al., 2006; Shelton et al., 1990; van Vugt et al., 2000), and similarly show a superior bias on the vertical greyscales task (Heber et al., 2010; Nicholls et al., 2006; Yamashita, 2021). The precise mechanisms underlying the superior bias for vertical tasks has been less studied than the leftward bias for horizontal tasks. There are some indications that the underlying mechanisms of the leftward and superior bias overlap. Like leftward errors on horizontal bisection tasks, superior bisection errors on vertical bisection tasks increase with more *leftward* line placement (Suavansri et al., 2012), suggesting the superior bisection errors could also be driven by relative left versus right hemispheric activation. Indeed, Fink et al. (2001) observed right posterior parietal lobe activation during both horizontal and vertical line bisection, with no significant difference between the orientations. However, against this explanation, performing bisection with the left hand increases horizontal bisection error and *decreases* superior bisection error (Suavansri et al., 2012). Furthermore, horizontal and vertical errors do not correlate (Nicholls, Mattingley, et al., 2004; van Vugt et al., 2000), even when measured at the same time on two-dimensional stimuli (Churches et al., 2017). In an alternative take on the activation-orientation hypothesis, it has been proposed that line bisection and related spatial judgement tasks are preferentially processed through the ventral visual stream (the 'what' pathway), leading to greater activation relative to the dorsal visual stream (the 'where' pathway). As the upper visual field is processed ventrally, more activation in the ventral stream could therefore result in an upward deviation of attention (Drain & Reuter-Lorenz, 1996; Silson et al., 2018). Overall, the leftward horizontal bias and superior vertical bias in visuospatial performance appear to be related, but distinct.

There is evidence that the leftward visuospatial bias in horizontal space also extends to the mental representation of space. This has been examined by taking advantage of the association between numerical magnitudes and space. Associating or mapping numbers spatially appears universal, although the precise direction and orientation of the "mental number line" line is strongly influenced by directional cultural activities, such as reading or counting direction (Göbel et al., 2011). Evidence that numbers are represented horizontally and ascending from left to right for Western participants has been replicated across a range of tasks involving magnitude or relative distance judgements about numbers (Dehaene et al., 1993; Fischer, 2003; Fischer et al., 2004; Umiltà et al., 2009; Zorzi et al., 2002), as well as other ordered sequences such as the letters of the alphabet (Nicholls & Loftus, 2007) and time (Bonato et al., 2012). Thus, for Western participants, a horizontal arrangement seems to be the default when thinking about numbers (Toomarian & Hubbard, 2018). Loftus et al. (2009) presented participants with number triplets (e.g., 16, 36, 55) and asked them to indicate whether the numerical distance was greater on the left or right side of the inner number. Participants tended to over-estimate the numerical extent on the "left" side of the mental number line (i.e., the distance between the numerically lower numbers). This indicates that Western participants pay greater attention to, or have a greater representation of, the left extent of mental space. Longo and Lourenco (2010, 2007) showed that biases on physical line bisection and mental number

bisection correlated, and were similarly influenced by length of line or numerical interval and the distance (near/far) at which the lines/numbers were presented to the participants. These findings suggest that the extent of visuospatial bias is closely related to bias on mental number processing. Furthermore, the extent of bias for visual bisection and mental number bisection can be influenced by the other modality. For example, bias on the greyscales task increased or decreased in line with participants' reports of whether overlaid numerical stimuli were high (decreasing leftward bias) versus low (increasing leftward bias; Loftus et al., 2008). However, bias on physical visuospatial judgements and mental number bisection dissociated in several clinical populations (English et al., 2017; Tian et al., 2011), as well as following TMS to the left cerebellar hemisphere (Ciricugno et al., 2020), indicating at least partly separable mechanisms.

Despite evidence that Western participants have a leftward horizontal bias in the mental representation of space, similar to their bias in physical spatial judgements, it is less clear whether there is also a superior vertical bias in the mental representation of space, similar to their bias in physical spatial judgements. This could also be explored using number bisection tasks. Although a horizontal left-to-right mental representation of numbers appears to be the default for Western participants, there is also evidence for a vertical spatial-numerical mapping, with numbers ascending from bottom to top (see Winter et al., 2015, for a review). Furthermore, it appears it is possible to manipulate whether the mental number line is represented horizontally or vertically in a given task. Cappelletti et al. (2007) administered a number bisection task to five neglect patients with instructions phrased in terms of reporting the middle house number between two houses on a street, or the middle floor number between two floors of a building. All five patients gave larger than accurate numbers in the street condition (consistent with a rightward bias), but only three gave larger than accurate numbers in the building condition (consistent with a superior bias). This pattern corresponded to the patients' performance on horizontal and vertical line bisection tasks, suggesting that the mental representations of horizontal and vertical space are analogous to the representations of physical space, and that horizontal and vertical representations are separable. However, one limitation of this study is that the type of errors that would be produced by an upward bias in vertical mental space is the same as what would be produced by a rightward bias in horizontal mental space (i.e., erring towards larger numbers). Therefore, it is not possible to be certain that those patients who showed errors in the 'vertical' mental number bisection tasks were using the required strategy of representing floors of a building, or if they were simply employing a normal mental number bisection strategy, in which case they likely would have used the default horizontal representation.

If biases in mental representations really do match those present for physical bisection, it could be possible to address this limitation by studying horizontal and vertical mental number bisection in neurologically healthy controls. The leftward biases shown by Western neurologically healthy controls in physical horizontal bisection would lead to a negative bias if it also manifests in the 'houses on the street' task, whereas the superior bias shown by Western neurologically healthy control in physical vertical bisection would lead to a positive bias if it also manifests in the 'floors of a building' bisection task. In other words, if there is a positive bias in a task where participants imagine numbers being 'floors of a building', this cannot be explained by the default left-to-right arrangement of the mental number line.

The aim of this study was to investigate if neurologically healthy controls recruited in a Western setting have a visuospatial bias in the vertical dimension of their mental representation of space. A secondary aim was to investigate if the extent of bias in mental representations of horizontal and vertical space relate to the extent of bias in physical space. We adapted the numerical distance judgement task of Loftus et al. (2009) such that the participants were encouraged to adapt a horizontal or a vertical representation of the numbers. Participants were informed that the number triplets represented houses on a street (horizontal

dimension) or floors on a building (vertical dimension). In the horizontal dimension, we expected that participants would over-estimate the distance between the numerically lower numbers, consistent with their previously documented mental number line bisection bias, and replicating the findings of Loftus et al. (2009). If the superior visuospatial bias in vertical space would extend to the mental representation of space, we expected that participants would *under*-estimate the distance between the numerically lower numbers in the vertical dimension, consistent with the previously documented superior visuospatial bias on vertical line bisection tasks. We administered horizontal and vertical versions of the greyscales task to see if participants' judgements on these (i.e., visuospatial bias in physical space) correlated with their numerical distance judgement biases (i.e., visuospatial bias in mental space).

2. Materials and methods

2.1. Participants

Participants consisted of healthy controls who completed the task as part of a teaching exercise for an undergraduate psychology class at the University of Bath in the United Kingdom. Inclusion criteria were being aged between 16 and 30 years, having no history of neurological illness or injury, and having normal or corrected-to-normal vision. Participants who completed the study could choose to either receive research participation credits or participate in a prize draw. The protocol was approved by the ethical committee at the University of Bath (protocol number 21-223). The study was preregistered on the OSF (https://osf.io/tu8wh/?view_only=ec1bd2c5cab8456286154764675b7523).

We used G*Power (version 3.1) to compute the minimum required sample size for a 2×2 between-subjects ANOVA comparing dimension (horizontal, vertical) and instruction type (neutral, imagery). With an alpha of 0.05 and a power of 0.80, it was estimated that at least 128 participants in total (32 per group) were needed to detect a small effect size ($f = 0.25$). As the study was being used as part of a teaching exercise, we anticipated that the sample size might be larger, but not exceeding 300 participants.

2.2. Procedure

The experiment was conducted online, performed at the participant's home or any other location of their choice on a laptop or desktop computer with a screen size of at least 12 in. (25 cm wide * 14 cm high). Participants opened the experiment by clicking on a link, after which Inquisit Player 6 was installed. The experiment started with information about the study and an informed consent form. Participants answered questions about inclusion criteria and demographic information (i.e., age, sex, handedness). In addition, a control question was included in which participants were instructed to select a specific answer, to ascertain that participants were reading the questions properly. Subsequently, the screen size and number of pixels per cm were computed by asking participants to adjust the size of a rectangle on the screen to match with the size of a bank or credit card.

Participants were randomly assigned to one of two dimensions (horizontal, vertical) and instruction types (neutral, imagery), resulting into four groups. The experiment consisted of a mental number line task and greyscales task. After each task, participants were asked whether the instructions beforehand had been clear, whether they had 'cheated' during the task (for example by using aids), and how difficult they found the task on a scale from 0 ("very easy") to 10 ("very difficult"). Next, participants filled out the Vividness of Visual Imagery Questionnaire (VVIQ) and Edinburgh Handedness Inventory. At the end, participants were debriefed about the aim of the study. Stimuli and experiment scripts can be found at https://osf.io/tu8wh/?view_only=ec1bd2c5cab8456286154764675b7523.

2.3. Mental number line task

The mental number line task was administered to assess whether participants showed a visuospatial bias in their mental representation of space. The task was based on Experiment 1 (Configuration 3) of Loftus et al. (2009). Participants were presented sequentially with three two-digit numbers (Arial font, black, 0.5×0.8 cm per digit), 1000 ms each, overlaying the centre of an image (6.58×6.58 cm, blue) that was either a square (horizontal or vertical dimension groups, neutral instructions), represented houses on a street (horizontal dimension group, imagery instructions), or floors on a building (vertical dimension group, imagery instructions; Fig. 1). To control for potential visuospatial cueing effects in the two imagery groups, the images were flipped horizontally for half of the participants (i.e., in the horizontal group the "chimneys" were either on the left or right side; in the vertical group the "balconies" were either on the left or right side).

In the neutral groups, participants were instructed that they would be presented with three numbers in the centre of a square, one after the other. In the imagery groups, participants were instructed to imagine numbers that represent houses on a street that are numbered from left to right (horizontal dimension), or floors on a building that are numbered from bottom to top (vertical dimension). Participants in the imagery groups were informed that they would be presented with three house/floor numbers, one after the other, in the centre of an image of houses/floors. Depending on the group, the image of a square, houses, or floors was provided alongside the instructions. In both groups, participants would be asked which interval was smaller/larger: the first or the second. Participants were instructed to not compute the differences between intervals but instead to try and guess the differences and respond as fast as possible.

Numbers were presented sequentially in ascending order overlaying the centre of the image, instead of left/right or up/down, to avoid visual

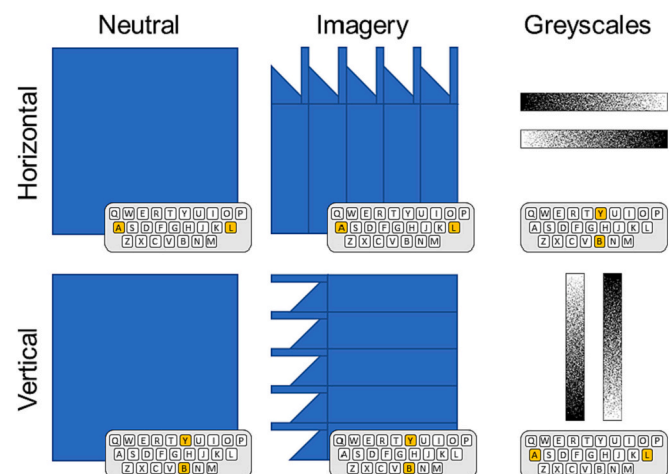


Fig. 1. Stimuli and response keys used in the mental number line task (left and central figures) and greyscales task (right figures). In the mental number line task, the numbers were presented on top of one of the images, which was kept consistent within participants. Stimuli were squares in the neutral groups (top left and bottom left), houses on a street in the horizontal imagery group (top centre), and floors on a building in the vertical imagery group (bottom central). The images in the imagery groups were flipped horizontally for half of the participants (i.e., in the horizontal group the "chimneys" were either on the left or right side; in the vertical group the "balconies" were either on the left or right side) to control for potential visuospatial cueing effects. In the greyscales task, participants had to indicate which of two bars was lighter or darker. Example stimuli and response keys are depicted for the horizontal dimension (top right) and vertical dimension (top left). Note that the response keys in the mental number line task were aligned with the dimension (horizontal or vertical), whether the response keys in the greyscales task were opposite to the dimension.

cues from the stimulus display. By presenting the numbers sequentially, there was a strong memory component which could lead to primacy or recency effects, i.e., a tendency to select the first or second interval. To control for this, whether participants had to indicate the smallest or largest interval was counterbalanced between participants. Participants either had to press “A” for the first, and “L” for the second interval (horizontal dimension groups); or “B” for the first, and “Y” for the second interval (vertical dimension groups). We matched the key alignment (horizontal or vertical) with the dimension that was tested, to control for potential effects of physical key alignment on the mental number line bias in a similar way.

These keyboard response instructions were all that differentiated the two neutral instructions groups, and in this way each imagery instructions group had a neutral instruction group that was matched to it in terms of arrangement of response keys. In this way, we controlled for any possible effects of response key arrangement.

Participants started with a block of 20 practice trials. Practice trials were randomly selected from four different sets of flankers (2_92, 12_98, 3_89, and 5_93), which defined four different numerical lengths (90, 86, 86, and 88, respectively). The inner number was shifted by 30 points below, or 40 points above the true arithmetic centre. Feedback on speed and accuracy was provided after the practice block. This block was repeated if the accuracy was below 75 %, up to three times maximum. The response window in the practice trials was 5000 ms.

In the main task, four different sets of flankers (19_55, 53_99, 42_98, and 17_83), which defined four different numerical lengths (36, 46, 56, and 66, respectively) were used. The inner number was shifted by 1, 2, or 5 points below or above the true arithmetic centre. The factorial combination of numerical length (4 levels) and inner number shift (6 levels) produced 24 number triplet combinations that were randomized within one block. Eight blocks of 24 trials were presented, resulting in 192 trials. A trial was terminated after a response was given, or after 2000 ms. In the latter case, the text “Too slow, press space to continue” appeared. In this way, the experiment would pause automatically if participants would stop responding. Per trial, the response and response time (RT) were recorded.

First, we computed the percentage of trials in which a correct response was provided separately for trials in which the lower interval was smaller, and for trials in which the higher interval was smaller, only including valid trials (i.e., RT < 2000 ms). Next, a bias score was computed [bias score = % correct lower interval smaller - % correct higher interval smaller]. Presuming our mental imagery manipulation was successful, a negative value would correspond to a leftward/inferior spatial bias (i.e., the distance between the lower two numbers is estimated to be larger than the distance between the higher two numbers), and a positive value would correspond to a rightward/superior spatial bias (i.e., the distance between the higher two numbers is estimated to be larger than the distance between the lower two numbers). However, given that there is no way of objectively measuring the success of the mental imagery manipulation, we simply refer to negative or positive bias scores when referring to these data. A score of 0 would indicate no spatial bias.

2.4. Greyscales task

The greyscales task was used to assess visuospatial attention bias in physical space (Mattingley et al., 1994; Nicholls et al., 2006). For participants in the horizontal dimension groups, only left-right lateralized visuospatial attention bias was assessed using a horizontal version of the greyscales task. For participants in the vertical dimension groups, only superior-inferior visuospatial attention bias was assessed using a vertical version of the greyscales task. A trial started with a central fixation cross (black, 1*1 cm), presented for 500 ms. Next, two gradients (i.e., greyscales; Fig. 1) were presented for 200 ms. In the horizontal dimension, the gradients were presented 1.78 cm above each other, had a height of 1.78 cm, and a width of 12.76 cm. In the vertical dimension, the

greyscales were rotated by 90 degrees. Stimuli were presented on a white background. The inter-trial interval was 500 ms.

Participants were asked to choose which gradient was lighter or darker by pressing “Y” with the index finger of the right hand for the upper gradient, and “B” with the index finger of the left hand for the lower gradient (horizontal dimension); or “A” with the index finger of the right hand for the left gradient, and “L” with the index finger of the right hand for the right gradient (vertical dimension). The requested target (i.e., lighter/darker) was counterbalanced between participants.

Participants started with a block of 6 practice trials, in which one of the two gradients was darker than the other (i.e., 75 % black/25 % white, versus 50 % black/50 % white). The response window in the practice trials was 5000 ms. Feedback on speed and accuracy was provided after the block. This block was repeated if the accuracy was below 75 %, up to three times maximum.

The main greyscales task consisted of one block of 72 trials. The two gradients were mirror-image versions of the same gradient that contained an equal amount of black and white pixels. As there was no correct or incorrect answer, no feedback on accuracy was given. A trial was terminated after a response was given, or after 2000 ms. In the latter case, the text “Too slow, press space to continue” appeared. In this way, the experiment would pause automatically if participants stopped responding.

Responses were categorised as ‘right’ and ‘left’; or ‘down’ and ‘up’, according to whether participants selected the bar that with the target (i.e., lighter or darker) on that side. A bias score was computed using Eq. (1) for the horizontal dimension, and Eq. (2) for the vertical dimension, based upon Eq. (1) in Nicholls and Roberts (2002).

$$\text{Horizontal bias} = \frac{(N_{\text{right}} - N_{\text{left}})}{N_{\text{total}}} \times 100 \quad (1)$$

$$\text{Vertical bias} = \frac{(N_{\text{down}} - N_{\text{up}})}{N_{\text{total}}} \times 100 \quad (2)$$

Scores ranged between -100 to +100, with positive scores reflecting a bias towards the left side (horizontal dimension) or superior side (vertical dimension) and negative scores reflecting a bias towards the right side (horizontal dimension) or inferior side (vertical dimension). Values of zero would indicate no spatial bias.

2.5. Questionnaires

We included two questionnaires measuring variables that might influence the effectiveness of the mental imagery manipulations and the extent of visuospatial biases. These were to enable us to confirm that the groups were matched on these influential characteristics, or to use as covariates in our main analyses if the groups were not matched.

The VVIQ (Marks, 1973, 1995) measures individual differences in vividness of visual imagery. The full version consists of 32 questions, however Campos and Pérez-Fabello (2009) demonstrated that scores from only the first 16 items correlate highly with the total score and has high Cronbach α reliability. We therefore used only the first 16 items to minimize the total study time. Participants were asked to close their eyes and imagine characteristics of a relative or friend, natural phenomena, a shop, and a country scene, and rate the vividness of each characteristic on a scale from 1 (“No image at all”) to 5 (“Perfectly clear and vivid as if I was actually seeing it”). Total scores ranged from 16 to 80, with higher scores indicating more vivid mental imagery.

The Edinburgh Handedness Inventory (Oldfield, 1971) measures the extent to which a person uses their left, right, or both hands for everyday activities. Scores range from -100 to 100, and participants can be classified as left-handed (score -100 to -40), right-handed (score 40 to 100), or ambidextrous (score -39 to 39).

2.6. Statistical analysis

Analyses were performed using JASP 0.16.2 (JASP Team, 2022). Normality of the data were checked per group by visually inspecting Q-Q plots and using Shapiro-Wilk tests. Homogeneity of variance was checked using Levene's test. All data were normally distributed and therefore, parametric tests were used. A significance level of $\alpha = 0.05$ was used. Effect sizes for pairwise comparisons were expressed as Cohen's d (the mean difference between groups divided by the standard deviation) and were interpreted as small (0.2), medium (0.5), or large (0.8).

In addition to the frequentist statistics, we computed Bayes Factors (BF) to indicate whether there was more evidence in favour of the null hypothesis versus the alternative hypothesis based on the observed data. We reported BF_{10} , the evidence in favour of the alternative hypothesis, or BF_{01} , the evidence in favour of the null hypothesis. We interpreted a BF of 1–3 as providing anecdotal, 3–10 moderate, 10–30 strong, 30–100 very strong, and > 100 extreme evidence (Wagenmakers et al., 2018).

For all experiments, data and analysis scripts can be found at https://osf.io/tu8wh/?view_only=ec1bd2c5cab8456286154764675b7523.

2.6.1. Effect of mental imagery on spatial attention bias in the mental number line task

First, we assessed whether there were attention biases in any of the four groups (neutral/imagery, horizontal/vertical) using one sample t -tests comparing the bias scores obtained from the mental number line task with 0.

The main analysis was a 2×2 ANOVA with the between-subjects factors dimension (horizontal, vertical) and instruction type (neutral, imagery). The dependent variable was the bias score obtained from the mental number line task. We expected a two-way interaction, with lower bias scores (reflecting a leftward bias on the presumed horizontally represented mental number line) for the horizontal neutral group, vertical neutral group, and horizontal imagery group, and higher bias scores (reflecting a superior bias in the vertical mental representation of space) for the vertical imagery group.

Planned independent samples t -tests were conducted to directly compare the neutral and imagery groups per dimension (horizontal, vertical). If there would be a more superior spatial bias when participants imagined 'floors on a building' compared to no imagery, we expected the bias in the vertical imagery group to be higher/more positive than the bias in the vertical neutral group (which would presumably use a normal horizontal representation of the mental number line).

Regarding the horizontal groups, it would be possible that the normal presumed horizontal representation of the mental number line would be strengthened by the imagery instructions ('houses on a street'). Therefore, we compared the bias in the horizontal imagery group to the bias in the horizontal neutral group. If the spatial bias in the horizontal dimension of mental representation was strengthened by 'houses on a street' instructions, we expected the bias score to be lower/more negative in the horizontal imagery group than the bias score in the horizontal neutral group.

2.6.2. Spatial attention bias in the greyscales task

For each of the four groups (neutral/imagery, horizontal/vertical), we assessed whether there was a visuospatial bias on the greyscales task. We conducted one-sample t -tests to evaluate whether the bias scores differed from zero. Note that there was no difference regarding the greyscales task for the neutral versus imagery group, however, to assure that similar biases were present in all four groups, data was analyzed per group.

2.6.3. Correlation between mental number line and greyscales

To assess whether there was a relation between the visuospatial bias in the mental imagery task (mental representation of space) and the

visuospatial bias in the greyscales task (physical space), non-parametric Spearman correlations were conducted between the mental imagery and greyscales bias scores for each of the four groups (horizontal/vertical, neutral/imagery). Spearman's ρ was interpreted as small (>0.10), moderate (>0.30), large (>0.50), or very large (>0.70 ; Dancey & Reidy, 2004).

3. Results

3.1. Demographic characteristics

The experiment was completed by 305 participants. We excluded participants who did not correctly answer the control question ($n = 4$), did not adjust the size of the rectangle to match a credit card size ($n = 16$), had a completion time that exceeded 90 min ($n = 6$), for whom less than half of the practice trials was valid (i.e., RT below 2000 ms) or a score below 75 % was obtained in the final practice block (mental imagery: $n = 51$; greyscales: $n = 14$), self-reported to have cheated (mental imagery: $n = 8$; greyscales: $n = 10$), did not complete all blocks of the mental imagery task ($n = 1$), and/or indicated after completing the mental imagery task that they had not understood the instructions beforehand ($n = 77$). This left us with 171 participants. We ran the analyses again without excluding people who indicated they did not understand the instructions, and results were qualitatively the same (see supplementary materials).

Demographic characteristics and scores on the questionnaires per group are shown in Table 1. There were no differences between groups in the percentage of females, $\chi^2(3) = 2.41, p = .491, BF_{01} = 66$, self-reported right-handedness, $\chi^2(3) = 2.97, p = .397, BF_{01} = 68$, age, F

Table 1
Demographic characteristics and scores on the questionnaires, split for the horizontal and vertical dimension and for the neutral and imagery instructions groups. Frequencies (%) and means (SD) are depicted.

	Horizontal, neutral	Horizontal, imagery	Vertical, neutral	Vertical, imagery
<i>N</i>	51	38	45	37
Age, years	18.55 (0.70)	18.55 (0.98)	18.42 (0.75)	18.49 (0.73)
Sex ^a , % female	46 (90.2 %)	31 (81.6 %)	40 (88.9 %)	30 (81.1 %)
Handedness ^b , % right	43 (84.3 %)	32 (84.2 %)	42 (93.3 %)	34 (91.9 %)
Edinburgh Handedness Inventory, –100 to 100	68.12 (60.18)	71.47 (61.84)	80.53 (49.91)	81.11 (47.74)
Vividness of Visual Imagery Questionnaire, 16 to 80	56.31 (12.60)	62.13 (11.51)	58.60 (10.68)	60.70 (7.94)
Experiment completion time, minutes	33.63 (8.45)	34.69 (10.09)	35.52 (9.02)	36.96 (12.97)
Mental number line task difficulty (0 = very easy, 10 = very difficult)	7.29 (1.93)	7.68 (1.58)	6.80 (1.69)	7.08 (2.03)
Mental number line bias ^c , –100 to 100	–2.04 (19.00)	–12.20 (18.35)	–4.07 (19.36)	–3.88 (17.18)
Greyscales bias ^d , –100 to 100	–17.49 (32.54)	–13.62 (28.77)	–16.85 (39.93)	–18.08 (43.24)

^a Three participants in the horizontal imagery group indicated 'other' when asked to indicate their sex, and the remaining non-female participants were male.

^b One participant in the horizontal neutral group indicated 'ambidextrous' when asked to indicate their handedness, and the remaining non-right handed participants were left-handed.

^c Bias scores of <0 in the mental number line task indicate a leftward/inferior bias.

^d Bias scores of <0 in the greyscales task indicate a leftward/superior bias.

(3,167) = 0.27, $p = .847$, $BF_{01} = 24$, Edinburgh Handedness Inventory scores, $F(3,167) = 0.61$, $p = .609$, $BF_{01} = 16$, VVIQ scores, $F(3,167) = 2.35$, $p = .074$, $BF_{01} = 1.93$, experiment completion times, $F(3,167) = 0.83$, $p = .479$, $BF_{01} = 12$, and self-rated difficulty of the mental number line task, $F(3,167) = 1.72$, $p = .165$, $BF_{01} = 4.26$.

3.2. Effect of mental imagery on spatial bias in the mental number line task

The bias scores on the mental imagery task are depicted for each group in Fig. 2. First, we assessed whether there were visuospatial attention biases in the mental number line for any of the four groups by comparing the bias scores with zero. There was moderate evidence for the absence of a bias in the horizontal neutral group, $t(50) = -0.77$, $p = .448$, $d = -0.11$, $BF_{01} = 4.97$. There was extreme evidence for a leftward bias in the horizontal imagery group, $t(37) = -4.10$, $p < .001$, $d = -0.67$, $BF_{10} = 121$, with a medium effect size. There was no bias in the vertical neutral group, $t(44) = -1.41$, $p = .166$, $d = -0.21$, $BF_{01} = 2.46$, and the vertical imagery group, $t(36) = -1.38$, $p = .178$, $d = -0.23$, $BF_{01} = 2.38$. However, the evidence for the absence or presence of a bias was inconclusive.

The main analysis showed moderate evidence for the absence of an interaction effect of instruction type * dimension, $F(1, 167) = 3.26$, $p = .073$, $BF_{01} = 3.42$ (Fig. 2). Planned contrasts showed that in the horizontal dimension, there was moderate evidence for a difference between the neutral and imagery instructions, $t(87) = 2.53$, $p = .013$, $d = 0.54$, $BF_{10} = 3.53$, which was a medium effect. Participants who were instructed to imagine a row of houses (imagery group), had a larger leftward spatial bias than people who were not instructed to imagine a row of houses (neutral group). In the vertical dimension, there was moderate evidence for the absence of a difference between the neutral and imagery instruction types, $t(80) = -0.05$, $p = .964$, $d = -0.01$, $BF_{01} = 4.33$.

There was moderate evidence for no difference between the horizontal and vertical dimension in the neutral conditions, $t(94) = 0.52$, $p = .606$, $d = 0.11$, $BF_{01} = 4.55$, showing that there was no effect of key arrangement on visuospatial attention biases in the mental number line.

To summarize, across groups, there was a tendency to overestimate the distance of the lower numerical interval compared to the higher

numerical interval, which was only significant for participants who were instructed to imagine the numbers being house numbers on a row of houses.

3.3. Spatial attention bias in the greyscales task

In the horizontal dimension, there was very strong evidence for a leftward bias in the neutral group with a greyscales bias score of -17.49 ($SD = 32.54$), $t(50) = -3.84$, $p < .001$, $d = -0.54$, $BF_{10} = 72.87$, with a medium effect size. There was moderate evidence for a leftward bias in the imagery group with a greyscales bias score of -13.62 ($SD = 28.77$), $t(37) = -2.92$, $p = .006$, $d = -0.47$, $BF_{10} = 6.49$, with a small effect size. Thus, in both groups in the horizontal dimension, there was a clear leftward visuospatial perceptual bias in physical space.

In the vertical dimension, there was moderate evidence for a superior bias in the neutral group with a greyscales bias score of -16.85 ($SD = 39.93$), $t(44) = -2.83$, $p = .007$, $d = -0.42$, $BF_{10} = 5.33$, with a small effect size. There was anecdotal evidence for a superior bias in the imagery group with a greyscales bias score of -18.08 ($SD = 43.24$), $t(36) = -2.54$, $p = .015$, $d = -0.42$, $BF_{10} = 2.90$, with small effect size. Thus, in both groups in the vertical dimension there was a superior visuospatial perceptual bias in physical space, although there was only anecdotal evidence in the imagery group.

3.4. Relation between attention bias in the mental number line and greyscales task

There were no significant correlations between the bias scores in the mental number line task (mental representation of space) and the greyscales task (physical space) for the horizontal neutral group, $r = -0.19$, $p = .181$, $BF_{01} = 2.08$, the horizontal imagery group, $r = -0.19$, $p = .264$, $BF_{01} = 2.37$, the vertical neutral group, $r = 0.11$, $p = .478$, $BF_{01} = 3.67$, nor the vertical imagery group, $r = 0.10$, $p = .552$, $BF_{01} = 3.58$. Note that the evidence for the absence of relations was inconclusive for the horizontal groups.

3.5. Supplementary analyses

We ran unplanned analyses to test potential explanations for our results. First, we tested whether bias scores on the mental number line task for people in the imagery groups related to VVIQ scores. There was moderate evidence for a lack of correlations between the mental number line bias scores and VVIQ scores in the horizontal imagery group, $r = 0.09$, $p = .611$, $BF_{01} = 4.20$, and the vertical imagery group, $r = -0.09$, $p = .612$, $BF_{01} = 4.18$. Thus, in the imagery groups, people who self-reported to have more vivid mental imagery did not show a larger mental number line bias than people who self-reported to have less vivid mental imagery.

Second, we ran our main analysis of mental number line bias scores on only those participants who self-reported to have most vivid mental imagery, defined as VVIQ scores higher than the median (61, $n = 79$). We found moderate evidence for the absence of an interaction effect of instruction type * dimension, $F(1, 75) = 0.004$, $p = .951$, $BF_{01} = 4.74$. That is, there was no effect of imagery instructions even when our analysis only considered those participants with the most vivid mental imagery (i.e. those participants who were most likely to be able to visualize houses on a street or floors on a building).

4. Discussion

The aim of this study was to investigate if healthy controls have a spatial bias in the vertical dimension of their mental representation of space. We replicated previous findings that neurologically healthy participants base their judgements of the brightness (or darkness) of greyscales stimuli more on the left than the right side of horizontally presented stimuli, and more on the superior than the inferior half of

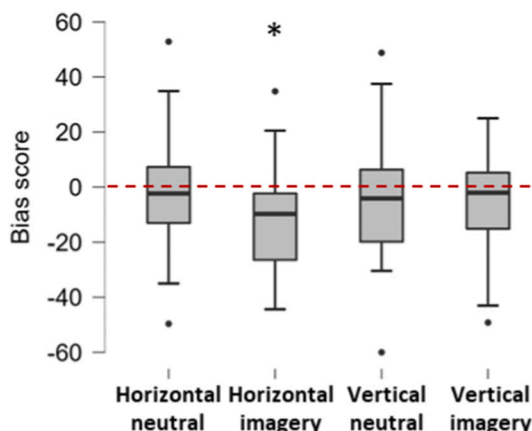


Fig. 2. Mental imagery bias scores split per group, differing regarding dimension (horizontal, vertical) and instruction type (neutral, imagery). Boxplots depict the median (thick line in the middle), the first and third quartiles (top and bottom box lines), and the minimum and maximum values (whiskers), with the exception of outliers (black dots). More positive values indicate a rightward bias in the horizontal dimension and a superior bias in the vertical dimension. More negative values indicate a leftward bias in the horizontal dimension and an inferior bias in the vertical dimension. The dotted line at value 0 indicates no bias. The asterisk indicates that the bias score was significantly different from zero.

vertically presented stimuli (Heber et al., 2010; Nicholls et al., 2006; Yamashita, 2021). However, our main analysis showed no evidence of any difference between mental number bisection judgements of people who were instructed to imagine the numbers as houses on a street, floors of a building, or who were given no imagery instructions. Furthermore, a direct contrast showed that the group who judged floors of a building (vertical imagery) did not have more positive errors (which would reflect a superior spatial bias) compared to the equivalent vertical neutral group that presumably used the 'default' horizontal mental number line.

There are two possible interpretations of the lack of effect of vertical imagery on mental number bisection. The first is that neurologically healthy participants have an inferior, rather than superior, spatial bias when representing vertical dimensions. This seems unlikely, given that neurologically healthy participants show a superior spatial bias when bisecting vertical lines and when judging visually presented stimuli (Heber et al., 2010; Nicholls et al., 2006; Nicholls, Hughes, et al., 2004; Yamashita, 2021). Indeed, the participants in the present study had a significant superior bias on the vertical greyscales task. Furthermore, there is no previous evidence for opposite spatial biases in perception and mental representations at a group level in normal cognition, therefore it is unlikely that our results can be explained by an inferior bias in the representation of vertical space simultaneous to a superior bias in the representation of visual space.

The second, and more likely, reason for the neutral bias scores that we attained in the vertical imagery group is that our participants, who were recruited and tested in a Western setting, did not represent the mental number line vertically, despite our mental imagery manipulation. This could be because participants were not able to keep the 'floors of a building' arrangement in mind while also doing the mental number line bisection task, or because thinking about floors of a building simply does not rearrange the 'default' horizontal mental number line for Western participants. If participants in the vertical imagery group instead used a horizontal mental number line, then the trend for negative bias scores that this group showed would correspond to overestimating the left side (i.e., pseudoneglect). In our study, there were no differences between groups in the reported difficulty of the mental number line task, with all groups finding it about equally hard (mean ratings $\sim 7/10$). The fact that they did not find the mental number line task harder than the other groups, in combination with the lack of superior spatial bias, could suggest that they defaulted to using a horizontal mental number representation. This conclusion is also supported by our supplementary analyses showing that the extent of number bisection bias did not relate to visualisation ability, and our results were similar even if we analyzed data from only those people with stronger visualisation ability.

We did not replicate findings that neurologically healthy Western participants tend to state that the numerical distance between the smallest and a middle number of a triad is larger than the numerical distance between a middle and the largest number (Loftus et al., 2009). Although all groups showed a tendency towards a leftward visuospatial bias, this was only significant for participants who were instructed to imagine the numbers as houses on a street (horizontal dimension imagery instructions). Loftus et al.' (2009) instructions were to indicate which of the two flankers was furthest away (numerically) from the inner number. It is possible that the explicitly spatial wording was more effective in letting people mentally represent a mental number line compared to our instructions, which were to indicate whether the first or second interval was smaller/larger. It is also possible that the online format of our study elicited greater variability in the data, although this would likely be offset by our sample size, which was more than three times that of Loftus et al. (2009). Indeed, studies directly comparing performance on online compared to in-person tests of cognitive functions such as perception, memory, and attention have generally shown that mode of delivery does not significantly impact results (Backx et al., 2020; Uittenhove et al., 2023), with the potential exception of slower

reaction times for online studies (Backx et al., 2020). Unlike the vertical mental imagery group, the mental number bisection performance of the horizontal mental imagery group did differ significantly from their equivalent neutral group. This was only when considering the direct a priori contrast between the imagery and neutral horizontal conditions, and therefore should be interpreted with caution. One possibility is that the instructions to envisage the numbers as houses on a street increased the spatial bias through non-specific effects such as improving concentration or task engagement. We also speculate that horizontal imagery could have strengthened the 'default' horizontal mental representation of numbers, even if it was not possible to force a complete switch away from this default representation to a vertical one using vertical imagery instructions. That is, mental imagery might be able to influence the mental representation of numbers, but not enough to completely change the underlying arrangement of the representation itself.

A possible future direction would be to measure horizontal and vertical pseudoneglect using a mental representation task that is not subject to strong default spatial mapping. Drummond and Tlauka (2012) asked participants to learn the location of objects depicted in six locations relative to a pictured person (left/right, up/down, front/back). Participants were faster to recall the locations of objects that had been positioned upward of the person compared to downward, consistent with vertical pseudoneglect. However, there was no difference in their response times for recalling the locations of left versus right objects, which calls into question whether this is a good test of pseudoneglect. Another future direction could be to repeat our study with participants from a culture where the default reading and counting direction is not left-to-right, and who therefore could be more susceptible to our manipulation. A limitation of our study is that we did not record participants' cultural background or language experience, however we can be confident that our participants were mostly Western, and that all participants had extensive experience of left-to-right reading.

A secondary aim of this study was to investigate if the mental representations of horizontal and vertical space are analogous to the representations of physical space. Dissociations have been reported between visual and representational neglect (Ortigue et al., 2006). Indeed, Beschin et al. (2000) reported a patient with damage to both hemispheres who showed right personal and visual neglect simultaneous to left neglect in mental imagery tasks, demonstrating that perception and mental representations are not only dissociable, but can have opposing biases. However, it is likely that this unique pattern resulted from distinct lesions in the patient's left and right hemispheres. In neurologically healthy participants, Longo and Lourenco (2007) found that people who had lower compared to greater pseudoneglect on a manual bisection task also showed lower or greater bias on a task that involved mentally bisecting two numbers that had been visually presented on either side of a horizontal line. However, when Rotondaro et al. (2015) presented numbers verbally to eliminate associated visuospatial cues, mental number bisection errors did not relate to manual pseudoneglect. This would explain why in the current study, where any visuospatial cues were eliminated, no significant correlations between bias scores on the mental number line bisection and greyscales tasks were found for any of our four groups. Overall, it appears that, while related, attention to these domains may be governed by different mechanisms. Given that there is poor correlation between different methods of measuring (visual) pseudoneglect (including the greyscales task; Learmonth et al., 2015, 2018), any single, underlying influence on performance might also be outweighed by variations in task demands.

5. Conclusions

In conclusion, our study failed to demonstrate that neurologically healthy controls show a superior bias in the mental representation of vertical space. The most likely interpretation of our results is that healthy controls were not able to reorient the 'default' horizontal mental number line to a vertical arrangement. This suggests that the horizontal

arrangement of the mental number line is not easily disrupted in neurologically healthy controls. Previous evidence suggested that at least some brain-lesioned patients with neglect used vertical number representations when the task instructions encouraged such an orientation (Loftus et al., 2009). Overall, these findings could indicate that when mental spatial representations are disrupted by brain damage, they are more malleable to further perturbation than is possible in normal cognition. Future research using tasks that do not involve ordinal sequences may yet be successful in determining if there is an upward bias in the representation of vertical space.

CRedit authorship contribution statement

Janet H. Bultitude: Conceptualization, Investigation, Methodology, Project administration, Writing – original draft, Writing – review & editing. **Antonia F. Ten Brink:** Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Visualization, Writing – original draft, Writing – review & editing.

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

We have shared a link to the data within the attached manuscript

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Appendix A. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.actpsy.2023.104115>.

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