




OPEN Right visual field advantage in orientation discrimination is influenced by biased suppression

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Visual input is not equally processed over space. In recent years, a right visual field advantage during free walking and standing in orientation discrimination and contrast detection task was reported. The current study investigated the underlying mechanism of the previously reported right visual field advantage. It particularly tested if the advantage is driven by a stronger suppression of distracting input from the left visual field or improved processing of targets from the right visual field. Combining behavioural and electrophysiological measurements in a mobile EEG and augmented reality setup, human participants ($n = 30$) in a standing and a walking condition performed a line orientation discrimination task with stimulus eccentricity and distractor status being manipulated. The right visual field advantage, as demonstrated in accuracy and reaction time, was influenced by the distractor status. Specifically, the right visual field advantage was only observed when the target had an incongruent line orientation with the distractor. Neural data further showed that the right visual field advantage was paralleled by a strong modulation of neural activity in the right hemisphere (i.e. contralateral to the distractor). A significant positive correlation between this right hemispheric event related potential (ERP) and behavioural measures (accuracy and reaction time) was found exclusively for trials in which a target was presented on the right and an incongruent distractor was presented on the left. The right hemispheric ERP component further predicted the strength of the right visual field advantage. Notably, the lateralised brain activity and the right visual field advantage were both independent of stimulus eccentricity and the movement state of participants. Overall, our findings suggest an important role of spatially biased suppression of left distracting input in the right visual field advantage as found in orientation discrimination.

Keywords Attention, Discrimination, Event related potential, Visual field bias, Walking, Mobile brain imaging

Visual input is not equally processed over space. A number of behavioural studies have shown a right visual field advantage in a local discrimination or a matching task^{1–6}. Others however, using rapid serial visual presentation tasks, have reported a left visual field advantage^{7–10}. What becomes obvious from these divergent results is that the visuospatial bias is not a coherent phenomenon but sensitive to the experimental set-up.

Importantly, visual field bias is not a phenomenon tied to highly controlled laboratory setups but also plays a role in real world settings. A number of studies have highlighted the importance of understanding the visual perception in natural behaviour^{11–15}. In a previous study, using a visual discrimination task during standing and walking, we established a robust right visual field advantage in different movement states including free walking¹⁶.

To better understand the nature of such visual field biases during natural behaviour, the current study aimed to clarify the underlying mechanism through manipulation of distractor status and stimulus eccentricity. A study by Pollmann¹ showed that participants had a faster response to right targets when searching for a conjunction target in the presence of salient distractors. The right visual field advantage was not found when the distractor was absent or when the target was the salient pop-out. They additionally reported that salient distractors led to greater response delays when presented in the right visual field than in the left visual field. These findings indicate the influence of distracting input on the spatial bias. They argued that the right hemisphere processes stimuli in both contra- and ipsilateral locations, whereas the left hemisphere mainly responds to the contralateral

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location¹⁷. Due to this bias, they assumed that a distractor was less processed when it appeared in the left visual field. A later study, with the manipulation of the distractor features (colour vs. orientation) in the singleton search paradigm, replicated the right visual field advantage with varying distractor features and added additional information³. First, for targets in the right visual field, the reaction time difference between with and without a distractor in the opposite hemifield (e.g. the distraction effect), was larger when the distractor had low similarity to the target (e.g. different shapes), compared to when the distractor had high similarity (e.g. different colours but same shape) to the target. A left distractor with a different shape can be viewed as a more salient distractor. Its stronger distraction effect would therefore support the idea that the distractor existence and its salience play an important role in the spatial perceptual bias. Unfortunately, no neural evidence was provided in this study. A second finding to highlight is a stronger distraction effect for right distractors compared to left distractors which was found when the distractor and the target were in different hemifields (the target-distractor distance was 2.75°) but not when they were on the same side of the visual field (the target-distractor distance was 1.67°) (see their Fig. 2). This potentially indicates an effect of the visual field on the right visual field advantage. Other studies confirmed that visual discrimination in general was more strongly interfered by distractors in peripheral (eccentricity 9°) than central locations (eccentricity 1°)^{18,19}. In our previous study showing a right visual field preference, the target and the distractor were both presented at 9° eccentricity. The behavioural right visual field advantage was consistently paralleled by an offset between the neural signals from the left and right occipital electrodes (N2pc component) which additionally showed a correlation with the reaction time¹⁶.

In the study at hand, we specifically asked how distracting input affects the visual field bias in a spatial visual discrimination task. We investigated the neural responses contra- and ipsi-lateral to targets and distractors, which have been considered as neural markers of visual spatial processing^{20–23}. Previously, lateralised ERP components (calculated by subtracting the neural activity recorded from the electrodes contralateral to the target from the ipsilateral activity) were found to have different functional roles such as target processing and distractor suppression²¹. For example, the N2pc component was shown to reflect target processing^{24–27}. Additionally, there is ample evidence that the N2pc can reflect multiple attentional mechanisms, possibly as a combination of both distractor suppression and target processing^{28–30}. Hickey, et al.²⁸ proposed that the N2pc was a summation of the Pd and Nt component. The Pd component was considered as reflecting a suppression process³¹, and the Nt component was considered a subcomponent which at least partly reflects target enhancement²⁸. Unfortunately, as these components are calculated by subtracting the contralateral from the ipsilateral activity, it cannot be dissociated by means of anatomical preferences if the features of the component are driven by activity contralateral to the target or ipsilateral to the distractor. By comparing the contra- and ipsi-lateral activities separately between conditions, it might be possible to identify the processes that underly such lateralized components. Such an approach is particularly important, when investigating lateralized perceptual processes. To gain a better understanding of the neural mechanism of the visual field bias, we analysed the left and right hemispheric ERP components, separately while considering the position of the target and the distractor. Accordingly, the left ERP could be either contra- or ipsi-lateral to the target or the distractor. The same was true for the right ERP. This approach could, at least partly, distinguish neural activity related to the processing of the target vs. the distractor in both the left and right visual fields, thus helping to understand the relationship of possible underlying neural imbalances. We additionally explored the distribution of the right visual field advantage over visual space by testing at different eccentricities and excluded that the advantage was motor-driven (i.e. independent of the side of the response hand).

The work at hand replicated the right visual field advantage and provided electrophysiological evidence that the advantage is influenced by a biased distractor suppression independent of input eccentricity.

Materials and methods

Participants

A total of 30 healthy adults were recruited from a local participants pool via the SONA system (21 females, 9 males; age: $M = 25.37$, $SD = 3.88$; SONA system: <https://www.sona-systems.com/>). All participants reported normal or corrected-to-normal vision and normal colour vision. They gave written informed consent before the start of the experiment and were compensated with 10 euros per hour after the experiment. The experimental protocol was approved by the Research Ethics Committee at the University of Würzburg, which follows the guidelines of the Declaration of Helsinki and the European data protection law (GDPR). All measures also complied with the COVID related hygiene safety concept for Psychological Experiments at the Institute of Psychology (Division for Cognitive Psychology) of the University of Würzburg.

Experimental task and procedure

A line orientation discrimination task was employed. Participants should always report the line orientation inside a yellow circle (the target) via keypress. The line orientation was either horizontal or vertical. A handheld response box was used to collect the responses. The response box has two buttons convenient for responding with the thumb and the middle finger. Participants pressed the corresponding button to indicate the line orientation as vertical or horizontal (the mapping between the button and the response was counterbalanced between participants). As one goal of the study was to replicate the right visual field advantage while controlling the influence from the hand making responses, the first 15 tested participants were asked to use their right hand for responses, and the next 15 participants were asked to use the left hand. Using a within-participants design, all participants performed the same task in two movement states (standing vs. walking). The stimulus-related manipulations consisted of target location (2 conditions: left vs. right), distractor status (3 conditions: incongruent distractors, congruent distractors, or no distractors), and stimulus eccentricity (3 conditions: 1.3°, 9° and 16°). Each stimulus-related manipulation (18 conditions in total, i.e. $2 \times 3 \times 3$) contained 32 trials, resulting in a total 576 trials in each movement state. The 576 trials in each movement state were presented in a

random order in 4 blocks (each block containing 144 trials). The standing blocks and the walking blocks were presented alternately with a break after every 2 blocks (order counterbalanced between participants). In the with distractor manipulation (incongruent and congruent distractors), the visual search array consisted of the yellow target circle and a green or red circle serving as the distractor opposite to the target circle. Distractor and target circles were presented with equal eccentricity to the left and right side of the fixation cross. Each circle contained a grey line with a horizontal or vertical orientation (balanced between manipulations). When the line orientation was the same in target and distractor circles (both are horizontal or vertical), it is a congruent trial. Conversely, when the target circle had a different line orientation with the distractor circle, it is an incongruent trial. In the no distractor manipulation, only the target (the yellow circle with a grey line inside) was presented in the search array either on the left side or right side of the fixation cross at one of the defined eccentricities. All circles were 2.2° in diameter with the eccentricity (the distance between the fixation cross and the centre of the circle) being 1.3°, 9° or 16°. Two example trials are illustrated in Fig. 1. Note that the background was not black as shown in the figure. The stimuli were superimposed onto the real-world scene using AR glasses, meaning that participants could see the stimuli floating in the air while simultaneously being able to see the floor, walls, and furniture in the room.

The recordings were conducted in a spacious room of approximately 5*6 m. Room windows were covered with blackout paper and curtains to create a dim environment, which helped to keep the light relatively constant despite the movement of participants. In order to investigate the spatial visual bias in a natural scenario, we presented the visual stimuli with a pair of augmented reality glasses with a 60 Hz refresh rate (DreamWorld AR, Dream Glass 4 K edition; San Mateo, CA). The AR glasses allowed participants to see through the transparent glasses while the task related stimuli were projected onto the real-world scene (as if floating in the air). Please note there were two windows in the room facing to the south and the west. Dependent on the time of the day the experiment was conducted, the brightness distribution (if at all) would vary. Additionally, all participants were asked to walk freely in the experimental room while performing the task. Therefore, even if there was a slight imbalance of light distribution, the influence of light should be theoretically averaged out among the 1152 trials and 26 subjects included in the final analysis. Similarly, for standing, participants could stand anywhere in the room at each block. Participants were asked to report the line orientation inside the yellow target circle.

Two natural movement states were included - standing and walking. In the standing condition, participants were asked to stand still while doing the discrimination task without any restriction of location within the room or body posture. In the walking condition, participants walked freely without any path or direction restrictions. The walking speed should be in the normal range (around 0.8 m/s, trained for each participant before the data recording). The walking speed was demonstrated by the experimenter before the experiment started. The experimenter monitored the walking performance of the participant during the whole testing period.

Data recording

We used a Smarting mobile EEG system (mBrainTrain LLC, Serbia) to record the electroencephalogram (EEG) data. The EEG system has 24 recording electrodes with a sampling rate of 500 Hz. Among the 24 electrodes, 16 electrodes were used for EEG recording referenced to a common mode sense electrode placed between Fz and Cz. 2 channels were attached to earlobes for possible re-referencing. Another 6 electrodes, which were placed around the eyes (3 electrodes for each eye: one above and one below the eyes, one near the outer canthus), were used for electrooculogram (EOG) recording. The signals from the EOG electrodes were included to remove ocular artefacts in the independent component analysis (ICA). The EEG signal amplifier and the data transmitter of the mobile EEG system were integrated into a little box (82 × 51 × 12 mm; 60 g), which was attached tightly and stably to the back of the EEG cap. Wireless data transmission (via Bluetooth) was applied in the EEG system. The software Lab Streaming Layer (<https://github.com/scn/labstreaminglayer>) was implemented to collect and synchronize all data streams (EEG, behavioural responses, and stimulus triggers). Stimulus generation and presentation were coded in MATLAB (The Mathworks Inc, R2019b) with the Psychtoolbox³². A Dell laptop (model: Latitude E7440) was used for the experiment, which was carried in a rucksack by participants during the experiment.

Data analysis

Subject exclusion

The final data analysis included 26 participants for behaviour and 25 participants for EEG. In the behaviour analysis, 1 participant was excluded due to data transmission error. For the remaining 29 participants, a correct response trial was counted if a correct indication of the target line orientation was given within 1500 ms after the stimulus onset. Based on the accuracy data, we further excluded 3 participants who had a low response accuracy (<0.60). The average accuracy of the remaining 26 participants was 0.87 (ranging from 0.72 to 0.95; SD = 0.07). In the EEG analysis, 1 more participant was excluded due to strong artefacts in the channel of interest (P7).

Behaviour analysis

A four-way (movement states: standing vs. walking; target location: left vs. right; eccentricity: 1.3° vs. 9° vs. 16°; distractor status: no distractor vs. congruent vs. incongruent) repeated-measures ANOVA was performed separately with the accuracy and reaction time. Reaction time data (from stimulus onset to response) were only calculated with correct response trials. Throughout the manuscript, a Greenhouse-Geisser correction was performed for ANOVA results where necessary. Statistical results are reported as significant when the *p* value was below 0.05.

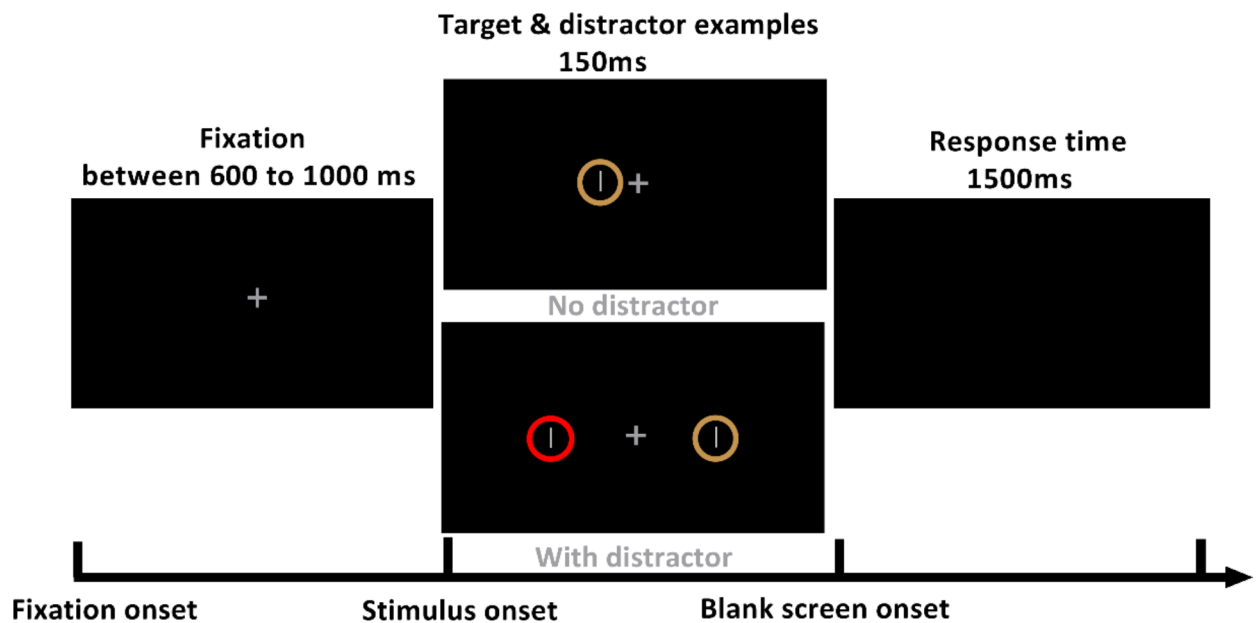


Fig. 1. A fixation cross with a random duration between 600 and 1000 ms was followed by the briefly presented visual search array (150 ms), which includes a yellow circle (the target) with a grey line inside. The target was either displayed alone (no distractor manipulation) on either side (left vs. right) of the fixation cross or was accompanied by a distractor (red or green circle with a grey line inside; with distractor condition) on the opposite visual field. Stimulus eccentricity (the distance between the fixation cross and the centre of the target /distractor circle) could be 1.3°, 9° or 16°. In this example, a left target (no distractor condition, eccentricity: 1.3°) and a right target (with distractor, eccentricity: 9°) are shown. A blank screen was presented for 1500 ms after the offset of the search array, during which participants should report the line orientation (vertical or horizontal) inside the yellow circle with a keypress. Both the speed and accuracy were emphasised.

Response hand

To check if the right visual field advantage was motor-driven, we tested whether participants using the left hand for responses and those using the right hand for responses showed similar right visual field advantage. Two-sample t-tests were performed to compare the right visual field advantage between the two subgroups with accuracy and reaction time data.

EEG - ERP analysis

Preprocessing

The EEG datasets ($n=25$) were pre-processed and analysed in Matlab (The MathWorks Inc., USA) with the Fieldtrip toolbox³³ and in-house scripts. A band-pass filter between ([1 30]) Hz using a windowed sinc FIR filter was performed as the first-step pre-processing. The filtered data (with all 24 channels) were then epoched into trials ([-1000 1500] ms, time locked to the stimulus onset at time 0). Artefact rejection was implemented in two steps. First, all trials for each participant were checked by visual inspection, and trials with strong and prominent noise were manually excluded based on the variance across channels. Second, ICA was applied to correct for eye movements, heartbeat, and muscle related artefacts after a dimension reduction to 16 with principal component analysis. An average of 12.17 trials ($SD=8.21$; out of the total 1152 trials) and 2.77 artefact components ($SD=1.52$; out of the total 16 components) were rejected. For all subsequent EEG data analyses, the data from standing and walking conditions were collapsed, since no significant difference in the visual field bias was found between the two movement states.

Identifying the time window with imbalanced neural activity between hemispheres

To investigate the underlying neural mechanism of the visual field bias, we first compared the neural responses between left and right hemispheres. Due to the hemispheric lateralisation of visual spatial information processing, the visual field bias in behavioural results may have a correlate in a hemispheric difference of neural responses. Specifically, we compared the ERPs from left (P7) and right (P8) parietal electrodes, separately for trials with a left target and trials with a right target. For this comparison, we only used trials with incongruent distractors as the behavioural data only indicated a visual field bias in this case. The parietal electrodes were often used in previous studies that analysed lateralized ERP components of visual processing, which correspond to the P7 and P8 electrodes in our mobile EEG system. The comparison was made with paired-sample tests between the time window ([0 1000] ms), and multiple comparisons were corrected using the cluster-based permutation approach

(as implemented in fieldtrip)³⁴. For the permutation, the neural responses from P7 and P8 electrodes were randomly assigned to each electrode for 1000 times to estimate a ‘null’ distribution of the difference between P7 and P8 electrodes based on cluster-level statistics (cluster-defining threshold: $p < 0.05$)³⁴. The time window with a significant difference was identified for further analysis. Baseline correction to ERPs was performed using a 300 ms pre-stimulus time window (averaged over -300 to 0 ms).

Correlation analyses between the left and right hemispheric ERP and behaviour

In order to directly test the relationship between the ERP amplitude and behaviour with respect to hemisphere and hemifield, we performed two sets of correlation analyses. The first set aimed to determine the functional properties of the hemispherically imbalanced ERP as identified in the previous step. Our reasoning is that the ERP signal from one hemisphere could reflect a suppression of distractor processing or an enhancement of target processing. If the ERP from the hemisphere contralateral to the target contributes to the behavioural responses (higher detection rate, lower reaction time), the ERP is likely related to target enhancement, whereas if the ERP from the hemisphere contralateral to the distractor contributes to behavioural responses, the ERP is more likely related to distractor suppression. We extracted the ERP amplitude in the previously identified time window showing the significant hemispheric difference (around 300 ms): Trials were grouped based on the target location (left vs. right) and the distractor status (congruent distractors, incongruent distractors, no distractors), thus giving 6 trial groups. The activity from the P7 and P8 electrode were then averaged within each trial group (averaging over the trial within the group), thus giving 12 ERP responses. Each ERP response had its own corresponding behavioural responses (accuracy and reaction time) calculated from the same trials. Correlation analyses were performed between each ERP response and its corresponding behavioural responses (separately for accuracy and reaction time), thus giving a total of 24 correlation results.

In the second set of correlation analyses, we checked whether the right hemispheric ERP component was related to the behavioural right visual field advantage. The right visual field advantage was calculated separately for congruent trials, incongruent trials, and no distractor trials, using the accuracy difference between target locations (calculated as right targets – left targets) and the reaction time difference between target locations (calculated as left targets – right targets). Since the right visual field advantage was only found in incongruent trials, a significant correlation between the right visual field advantage and the right hemispheric ERP component was only expected for incongruent trials. Please note that for both the first and the second sets of correlational analyses, multiple comparison corrections were not performed. Therefore, the results should be interpreted with this information in mind.

As outliers in correlation analyses can inflate or deflate the correlation coefficient, potentially limiting the reliability of the findings, we excluded all outliers before the correlation analysis. In a first step, we identified grand-level outliers based on the average level of the behavioural index (averaged across target locations) and two hemispheric ERP responses (averaged across electrode sides and target locations). To identify the outlier, the Robust Correlation Toolbox³⁵ was used. This toolbox estimates the true association with accurate false positive control and without loss of power, which provides the output of the outlier identifications. A data point is considered an outlier if its deviation from the median exceeds $2.2414 (\sqrt{\chi^2_{inv}(0.975,1)})$ times the Median Absolute Deviation (MAD). As a result, 2 outliers were identified when measuring the relationship between the average accuracy and average ERP response: 1 of them was a univariate outlier from the ERP component which had a high ERP amplitude, 1 of them was a univariate outlier with a low accuracy. For the second step, we identified grand-level outliers of the right visual field advantage (averaged across congruency status) and two hemispheric ERP responses (averaged across electrode sides and target locations). 1 univariate outlier from the ERP component which had a high ERP amplitude was identified when measuring the relationship between average ERP and right visual field advantage calculated by both accuracy and reaction time. Throughout our manuscript, we report the Pearson correlation coefficient (r) as the measure of correlation strength.

To further confirm the relationship observed in the cross-participant correlation, we performed a within-participant analysis using the half-split method. Outliers identified in the previous cross-participant correlation analysis remained excluded. For each participant, trials from the specific trial group(s) which showed significant correlation(s) (e.g. trials with right target and an incongruent left distractor) were classified into a low ERP group (50%) and a high ERP group (50%). We calculated the average accuracy for both the low and high ERP groups for each participant, resulting in 23 values in the high ERP group and 23 values in low the ERP group. A t-test was then performed to check whether the accuracy difference between the two ERP groups was significant. A similar analysis was performed with the reaction time data. As a manipulation check, the same analyses based on trials with a left target and an incongruent right distractor were performed.

Results

Incongruent distractor presence was crucial to the right visual field advantage

The accuracy and reaction time data were separately subject to a four-way (movement states: standing vs. walking; target location: left vs. right; eccentricity: 1.3° vs. 9° vs. 16° ; distractor status: incongruent vs. congruent vs. no distractor) repeated-measures ANOVA.

With accuracy, a significant main effect of target location was found ($F(1, 25) = 7.13$, $p = 0.013$, $\eta^2_p = 0.22$), the accuracy for right targets ($M = 0.88$, $SD = 0.07$) was significantly higher than for left targets ($M = 0.86$, $SD = 0.06$). In addition, a significant main effect of distractor status was found ($F(2, 50) = 4.19$, $p = 0.047$, $\eta^2_p = 0.14$; incongruent: $M = 0.84$, $SD = 0.07$; congruent: $M = 0.88$, $SD = 0.06$; no distractor: $M = 0.88$, $SD = 0.07$). Importantly, the interaction between target location and distractor status was significant ($F(2, 50) = 4.19$, $p = 0.025$, $\eta^2_p = 0.14$). A higher right visual field advantage was only found in incongruent condition ($t(25) = 3.44$, $p = 0.002$) but not in congruent ($t(25) = 1.00$, $p = 0.323$) and no distractor conditions ($t(25) = 0.64$, $p = 0.524$). The above results showed that the congruency of a distractor is relevant for the right

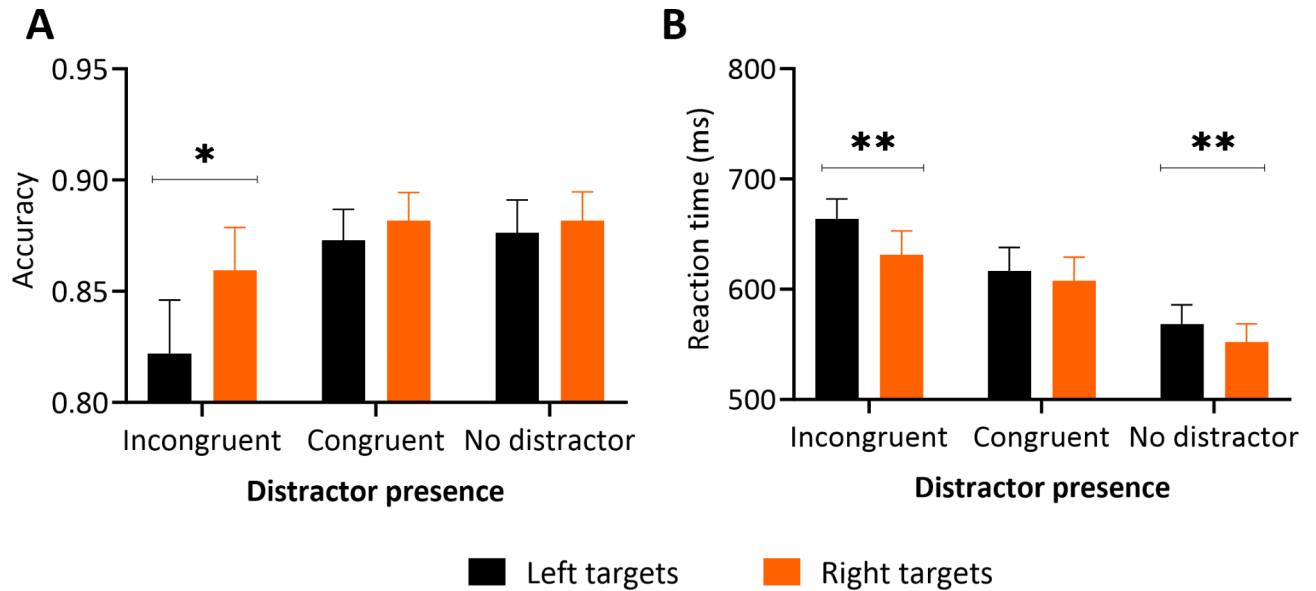


Fig. 2. Behavioural performance indicated a right visual field advantage. (A) The accuracy was higher for trials with a right target (orange) compared to trials with a left target (black) however only when the line orientation between the distractor and target was incongruent but not when the line orientation between distractor and target was congruent. The right visual field advantage was not found when there was no distractor. (B) The reaction time was faster for trials with a right target compared to trials with a left target when the line orientation between the distractor and target was incongruent but not when the line orientation between distractor and target was congruent. A faster reaction time was also found when there was no distractor. Data were collapsed between standing and walking conditions.

visual field advantage. The right visual field advantage was only found when the line orientation was incongruent between the target and the distractor, i.e. the information of the distractor was detrimental to the processing of the target. If the distractor was congruent, i.e. the information was in line with the target input, or if there was no distractor, no right visual field advantage in accuracy was found (Fig. 2A).

With accuracy, other significant main effects include a main effect of movement state ($F(1, 25) = 4.27$, $p = 0.049$), with standing ($M = 0.88$, $SD = 0.08$) leading to a higher accuracy compared to walking ($M = 0.85$, $SD = 0.07$) and a significant main effect of eccentricity ($F(2, 50) = 11.71$, $p < 0.001$, $\eta_p^2 = 0.319$; $M = 0.88$, $SD = 0.07$; 9° : $M = 0.88$, $SD = 0.07$; 16° : $M = 0.85$, $SD = 0.07$). Additionally, the interaction effect between movement state, eccentricity and distractor status was significant ($F(4, 100) = 2.89$, $p = 0.034$, $\eta_p^2 = 0.103$). This effect indicated that when there was no distractor or when the distractor was congruent, the behavioural performance increased during walking when stimuli were at a peripheral location (especially at the eccentricity of 9°) compared to central location (1.3°).

Similarly, with reaction time, a significant main effect of target location was found ($F(1, 25) = 16.36$, $p < 0.001$, $\eta_p^2 = 0.40$). The right targets ($M = 596.94$ ms; $SD = 100.42$ ms) led to a faster response than the left targets ($M = 616.26$ ms; $SD = 95.60$ ms). The main effect of distractor status was also significant ($F(2, 50) = 147.70$, $p < 0.001$, $\eta_p^2 = 0.86$: incongruent: $M = 647.54$ ms, $SD = 99.57$ ms; congruent: $M = 612.08$ ms, $SD = 107.88$ ms; no distractor: $M = 560.20$ ms, $SD = 86.71$ ms). We again observed a significant interaction between target location and distractor status ($F(2, 50) = 6.78$, $p = 0.003$, $\eta_p^2 = 0.21$): a faster reaction time was found with right targets compared to left targets in the incongruent condition ($t(25) = -4.71$, $p < 0.001$) but not in the congruent condition ($t(25) = -1.32$, $p = 0.199$). Interestingly, a faster reaction time with right targets compared to left targets was also found in the no distractor condition ($t(25) = -4.29$, $p < 0.001$) (Figure R1B). Additionally, the main effect of eccentricity was also significant ($F(2, 50) = 95.99$, $p < 0.001$, $\eta_p^2 = 0.79$: 1.3° : $M = 586.02$ ms, $SD = 94.86$; 9° : $M = 595.83$ ms, $SD = 96.21$ ms; 16° : $M = 637.96$ ms, $SD = 102.63$ ms) (Fig. 2B). No other effects were statistically significant.

The above results showed that the congruency of a distractor (congruent distractor vs. incongruent distractor) is relevant for the right visual field advantage. The right visual field advantage was only found when the line orientation was incongruent between targets and distractors, i.e. the information of the distractor was detrimental to the processing of the target. If the distractor was congruent, i.e. the information was in line with the target input, no right visual field advantage was found. However, it is unclear if the better performance is more related to a stronger suppression of distracting input from the left side or to an improved processing of the right target input. To address this question, the neural response contralateral and ipsilateral to target and distractor input was investigated.

The right hemispheric ERP component reflected a suppression process

In a first step, we identified the time period in which the neural signal from the left and right hemisphere was affected by the location of the target. We focused on the left parietal (P7) and right parietal (P8) electrodes, which are commonly used in visual studies that do not focus on primary visual processing but higher cognitive visual processes such as attention. Only trials with an incongruent line orientation between target and distractor were included in this comparison, as those trials demonstrated the strongest biased processing between left and right targets in accuracy (see above). A cluster-corrected sliding t-test was performed comparing the ERP between left and right electrodes. This was done separately for trials with a left target and trials with a right target. For trials with a left target, a significantly higher right ERP component was identified in the time window between ([248 334] ms, $p=0.004$) (Fig. 3A). Also for trials with a right target, a significantly higher right ERP component was identified in the time window between ([234 326] ms, $p=0.010$) (Fig. 3B). The lateralisation of the ERP around 300 ms can be further appreciated in the topography (Fig. 3A,B).

In order to determine the functional properties of the imbalanced ERP identified in the previous step, we examined their relationship with behaviour. Specifically, we separately looked at the ERP component when it was contralateral to the target and when it was contralateral to the distractor. If the ERP contralateral to targets contributes to behavioural responses (higher detection rate, lower reaction time), the ERP is related to target enhancement. Whereas if the ERP contralateral to distractors contributes to behavioural responses, the ERP is related to distractor suppression. We averaged the ERP amplitude of the different trial groups in the time window showing a significant hemispheric difference (around 300 ms). Trials were grouped based on the target location (left vs. right) and the distractor status (congruent distractors, incongruent distractors, no distractors), thus giving 6 trial groups. The ERP responses from P7 and P8 electrodes were calculated for each trial group, thus giving 12 ERP responses. Each ERP response had its own corresponding behavioural responses (accuracy and reaction time) from the same trials. Correlation analyses were performed between each ERP response and

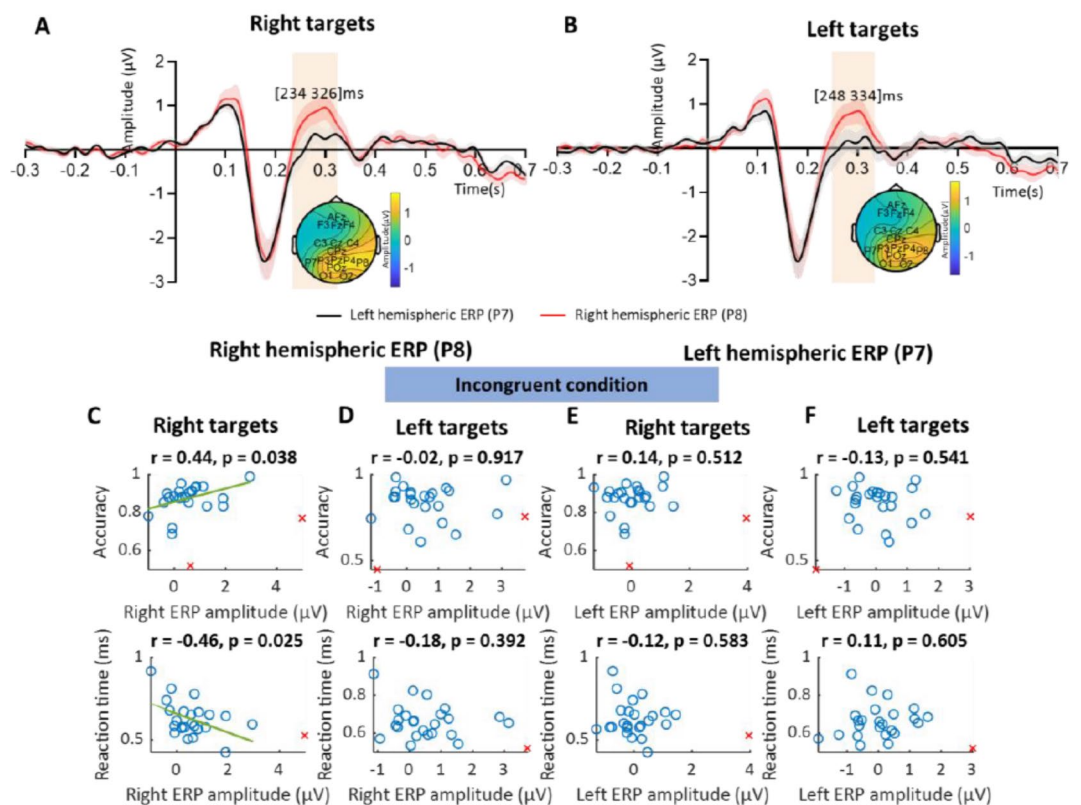


Fig. 3. The left and right hemispheric ERP responses and the correlation to behaviour. The ERP is shown for the left parietal electrode (P7, black line), the right parietal electrode (P8, red line), separately for left targets (A) and right targets (B) using incongruent distractor trials. The topography for the left targets and right targets is shown separately. The time window during which left and right electrodes showed a significant difference is marked in yellow. Time 0 marks the stimulus onset. For the right hemispheric ERP component, a significant correlation was found between the behaviour and the ERP component amplitude with trials having a right target (C) but not with trials having a left target (D). The upper panel is with accuracy data, the lower panel is with reaction time data. For the left hemispheric ERP component, the correlation was neither significant with behaviour with trials having a right target (E) or trials having a left target, either (F). This suggests that only for the right hemispheric ERP component, the processing of the left distractor was relevant to the performance in the right visual field. The direction of correlation hints a suppression related process.

its corresponding behavioural responses (separately for accuracy and reaction time), thus giving a total of 24 correlation results.

The correlation analyses showed that only the right hemispheric ERP response was positively correlated with the accuracy for right targets (i.e. when the incongruent distractor was on the left side and contralateral to the ERP) ($r=0.44$, $p=0.038$, Fig. 3C, upper panel; the p-value was not corrected for multiple comparisons). The correlation was also significant when the reaction time was used as a behavioural index ($r = -0.46$, $p=0.025$, Fig. 3C, lower panel; the p-value was not corrected for multiple comparisons). No correlation was found between the behaviour of left targets and the right hemispheric ERP component amplitude (i.e. when the contralateral stimulus was a target) (Fig. 3D). These results indicated that the right ERP might reflect a suppression process, with a higher amplitude leading to a stronger suppression of the contralateral distractor and accordingly an increased behavioural performance. For the left hemispheric ERP response, no correlation was found with either accuracy or reaction time either for right targets (Fig. 3E) or for left targets (Fig. 3F).

The results did not show any other significant correlation between the ERP and behaviour when distractor was congruent as the target (Fig. 4A-D) or when no distractor (Fig. 4E-H) was present. These findings support the idea that the right hemispheric ERP marked suppression of the visual input only when it was actively distracting.

To further confirm whether a higher right hemispheric ERP amplitude is associated with better behavioural performance when the contralateral stimulus is a distractor (right target condition), we conducted a within-participant analysis using the half-split method. Outliers identified in the previous between-participant correlation analysis were excluded. For each participant, trials with a right target and an incongruent distractor were classified into a low ERP group (50%) and a high ERP group (50%). We calculated the average accuracy for both the low and high ERP groups for each participant, resulting in 23 values in the high ERP group and 23 values in low the ERP group. A t-test was then performed to check whether the accuracy difference between the

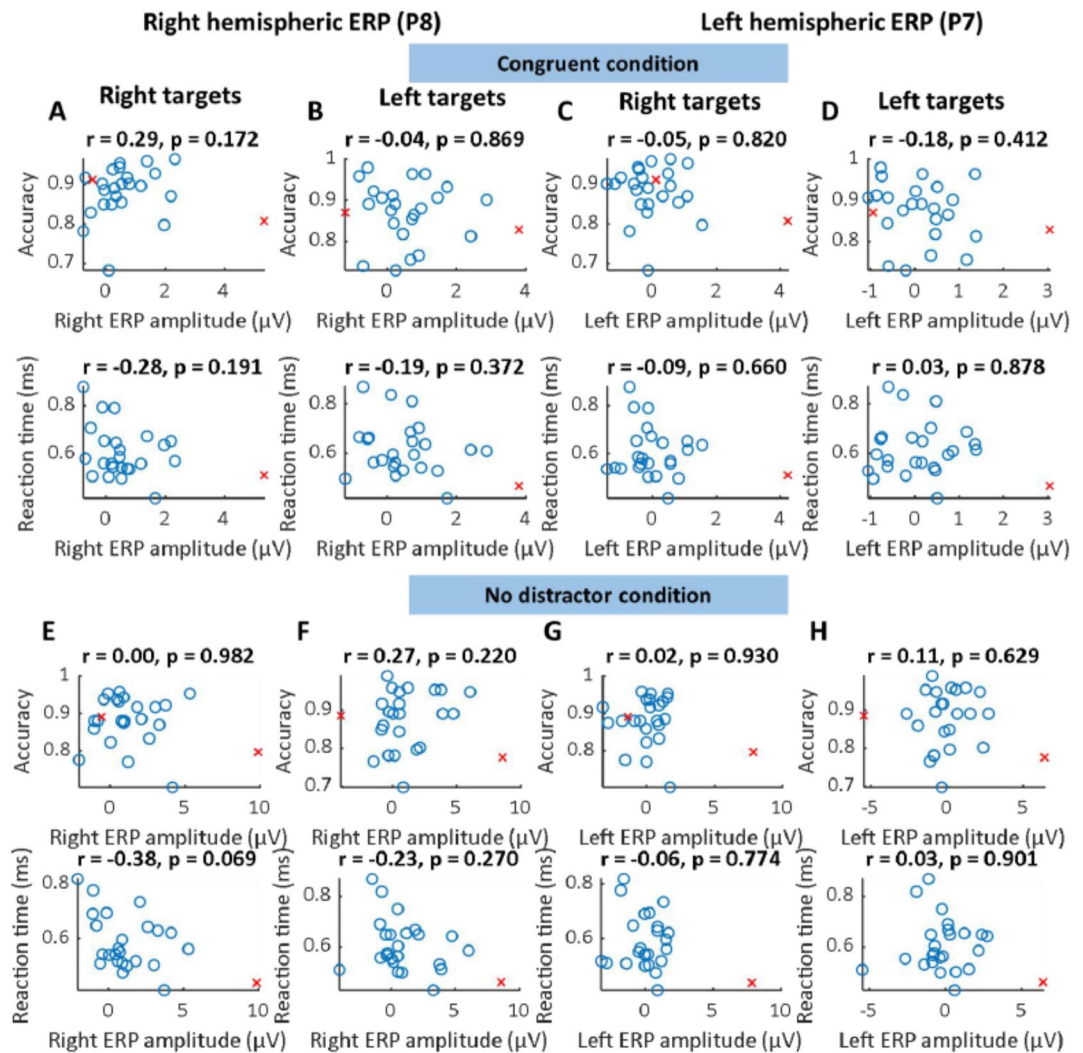


Fig. 4. The correlation between the ERP components and behavioural performance with trials having a congruent distractor (congruent condition, A, B, C, D) and the no distractor (E, F, G, H), for left and right targets conditions. No significant correlation was observed for either the right or left hemispheric ERP component and behavioural performance in those conditions.

two ERP groups was significant. A similar analysis was performed with the reaction time data. Results showed that a higher ERP amplitude was associated with a faster reaction time ($t(23)=2.65$, $p=0.014$), which was consistent with the between-participants correlation analysis. This correlation was not significant with trials that had a contralateral target towards the right hemispheric ERP component ($t(22)=1.00$, $p=0.327$). The within-participant analysis with accuracy did not show any significant result.

The right hemispheric ERP component was related to the right visual field advantage

The correlation analyses above suggested that the right hemispheric ERP component reflected a suppression process of the left distractor with trials had a right target and a left incongruent distractor. There was no evidence of a neural process reflecting increased processing of the right target. In the next step, we checked whether the distractor related process predicted the strength of the right visual field advantage, e.g. higher accuracy and faster reaction time for trials with a right target compared to trials with a left target only when the line orientation between the distractor and target was incongruent. The right visual field advantage was calculated separately for congruent trials, incongruent trials, and no distractor trials, using the accuracy difference between target locations (calculated as right targets – left targets) and the reaction time difference between target locations (calculated as left targets – right targets). The right hemispheric ERP component was based on trials with a right target and a left distractor, as this is the condition in which we found the right hemispheric ERP component reflected a functional suppression process. Since the right visual field advantage was only found in incongruent trials, a significant correlation between the right visual field advantage and the right hemispheric ERP component was only expected for incongruent trials.

As a result, the amplitude of the right hemispheric ERP correlated positively with the level of right visual field advantage for both accuracy ($r=0.46$, $p=0.024$, not corrected for multiple comparisons) and reaction time ($r=0.55$, $p=0.005$, not corrected for multiple comparisons), however only in trials with an incongruent distractor (Fig. 5A). The right hemispheric ERP correlated did not correlate with the right visual field advantage with trials having a congruent distractor (Fig. 5B) or did not have a distractor (Fig. 5C).

Discussion

In the current study, a right visual field advantage in visual orientation discrimination was replicated during natural movement (walking and standing). Combining behavioural and neural data, we could further demonstrate that the right visual field advantage was related to the processing of distracting input from the left visual field independent of stimulus eccentricity. Behaviourally, our data showed that the right visual field advantage was only found when the line orientation was incongruent between targets and distractors, i.e. the information of the distractor was detrimental to the processing of the target. The improved performance might be based on a stronger suppression of distracting input from the left side or an improved processing of the

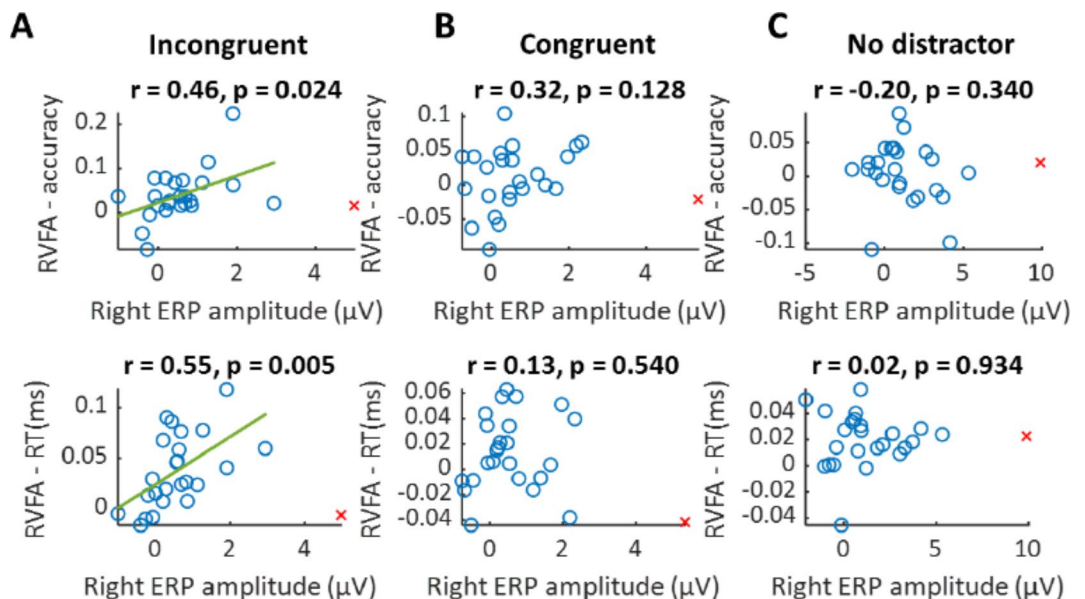


Fig. 5. The right hemispheric ERP was related to the right visual field advantage. For the right hemispheric ERP component, the amplitude was positively correlated with the level of right visual field advantage (abbreviated as RVFA in figures) when the target appeared on the right visual field (A). The upper panel is the right visual field advantage calculated with accuracy (right targets – left targets), and the lower panel is the right visual field advantage calculated with reaction time (RT, left targets – right targets). A higher RVFA value indicates a higher right visual field advantage. The correlation between the ERP components and RVFA with trials having a congruent distractor (B) and the no distractor condition (C) did not reveal any significant correlation. Those results suggest that only for the right hemispheric ERP component, the processing of the left distractor was relevant to right visual field advantage.

right target input. Neural data showed that the right visual field advantage was paralleled by a strong stimulus induced modulation of neural activity in the right hemisphere, that is, ipsilateral to the target and contralateral to distracting input. A significant correlation between this right hemispheric ERP component and behavioural measures (accuracy and reaction time) was further found for trials in which the target was presented on the right and an incongruent distractor was presented on the left. The direction of correlation suggests that the ERP component marks suppression of the distracting input because increased processing of the distractor unlikely leads to improved target discrimination. The right hemispheric ERP component further predicted the strength of the right visual field advantage. These findings suggest an important role of biased suppression of left distracting input in the right visual field advantage.

The distractor influences the behaviourally measured right visual field bias

The behavioural data showed that the level of right visual field advantage was influenced by the distractor manipulation. We found that the congruency of the distractor significantly modulated the level of right visual field advantage. A right visual field advantage in accuracy was only observed if the information provided by the distractor was incongruent with that from the target. If the distractor provided convergent information to the one from the target, no right visual field advantage was found. These results provide evidence for the influence of distracting input on the right visual field advantage. Interestingly, considering reaction time data, the right visual field advantage was also observed in the no distractor condition. This seems reasonable; as participant could still see the natural environment via the AR glasses, the background which was specifically clear in the visual field without extra AR input, might particularly serve as a distractor. A recent study provided evidence that background (e.g. such as a natural scene) can indeed serve as distractor³⁶. However, as background stimuli were not a task-relevant distractors, the background in no distractor condition may not bias the detection rate but only the speed of responses. In general, the important role of distractors when choosing between two competing stimuli has been described in both human and animal studies^{37–43}. Overall, our study highlights the influence of the distractor on the visual field bias in real world settings.

However, the behavioural results could not clarify whether the right visual field advantage during distractor presence was based on increased suppression of the left distractor, or a left distractor driven enhancement of right target processing, or a combination of both. Accordingly, we aimed to differentiate between target enhancement and distractor suppression by analysing the neural responses contra and ipsilateral to target and distractor input.

Distractor suppression influences the right visual field bias

Our two sets of correlational analyses showed a significant relationship between the right hemispheric ERP component and behavioral performance in trials with a left incongruent distractor, as well as between the right hemispheric ERP component and the right visual field advantage in those same trials. However, as noted in the Methods section, multiple comparison corrections were not applied for the consideration of statistical sensitivity. Therefore, these results should be interpreted with caution. Given the contralateral processing in the visual cortex, the observed correlation of the right hemispheric ERP component and the behavioural performance (in trials which had a left incongruent distractor) may show that it is more likely increased suppression of the left side distractor, that drives the right ERP amplitude. This right hemispheric ERP component therefore might be similar to the well-documented Pd component which was shown to reflect suppression of irrelevant and potentially distracting stimuli^{27,28,44–47}. The Pd component was normally considered as positivity contralateral to the distractor when a target is presented in the midline. In contrast, in the current experiment, both the target and distractor in the ‘with distractor’ condition were presented in the lateral positions. Accordingly, our described ERP component might not be related to Pd albeit the function seems similar. Another possibility is that our right hemispheric ERP component is a sub-component of the N2pc component, which can be elicited when both target and non-target stimulus are presented in lateral position^{21,28,48}. In our naturalistic set-up it might be the case that the suppression-related processing was more prominent and functional to the right visual field advantage. It should be noted that in many previous experiments contain lateral distractor and target which inducing the ‘N2pc’ component, left and right targets conditions were averaged under a higher experimental manipulation. This approach is reasonable as the left and right target differences were not of primary interest. However, this prevents us from further inspecting whether there is more evidence showing that the lateralized ERP component can indeed be driven by one hemisphere. In the few previous studies that have examined the ERP component separately for left and right targets, two studies consistently showed a pattern that the amplitude of the ERP component recorded from the right electrode was higher than that recorded from the left electrode^{49,50}. Taking together the findings from the current study, we would like to suggest that also future studies analyse the target location separately to better understand not only the visual field bias but also identify lateralised processes. In the current study, the bias in right hemispheric activity was independent of the target location, which indicates that there might be a bias by default. Given that our experiment also controlled for handedness, the Simon effect is unlikely to cause bias. However, our data further suggest this bias is only behaviourally relevant and observed as visual field bias when distracting visual stimuli are presented on the left side.

Is the influences of the left distractor based on an attentional bias?

It is well established that the attentional processing includes both the processing of relevant information (target enhancement) and the suppression of irrelevant information (distractor suppression)^{21,30,51,52}. Our findings of the left distractor suppression might be an expression of an attentional bias towards the right side. Although the current study only provides evidence that suppression plays a relevant role in the visual field bias, this does not necessarily mean that improved right target enhancement does not exist or is irrelevant. The reason why we did not find a neural marker for enhanced processing of the target input from the right visual field, might be due to the specific task used in the current study. In the singleton-search paradigm, the distractor was usually designed

to be more salient than the target and the neural stimuli and was assumed to capture attention initially^{27,47,53,54}. In a modified task, with the reduced number of neutral stimuli that we adapted from a previous study⁵⁵, both the neutral stimuli and distractors act as distractor¹⁶. We are unable to further clarify if it is true that the distractors had a stronger salience than the targets in the current task. However, the observed decline in behavioural performance in the presence of a distractor implies the necessity to process the distractor. This processing demand might be a contributing factor to the significant influence of suppression on the bias in the visual field.

A right hemispheric lateralisation of the attentional system has been described in the human brain⁵⁶. In the current study, a significantly higher right hemispheric ERP amplitude was found independent of the target location, which was in line with many studies showing that the attentional network is located in the right cerebral hemisphere⁵⁷. However, as we did not find a general correlation between the right hemispheric ERP component and behaviour for both the left target condition and right target condition, the visual field bias may not be driven by this rather general brain lateralisation.

The right visual field bias is independent of eccentricity

Contrary to our hypothesis, eccentricity did not affect the right visual field advantage. Notably, we did find that the general behavioural performance decreased with the increase of eccentricity, however, the neural component was independent of eccentricity. The influence of eccentricity on visual processing is well-established. Many studies have indicated a better behavioural performance when targets were presented at the fovea compared to the periphery^{58–62}. However, whether a foveal advantage is related to an increased distractor suppression or target identification is under debate. Chen and Treisman¹⁹ have shown a behaviourally stronger interference from incompatible distractors at peripheral locations compared to a central location. Unfortunately, no neural evidence was provided. Our findings are in line with the idea of a better visual processing at the fovea compared to the periphery and show no evidence that the suppression related perceptual bias is affected by eccentricity.

Future directions

While the right visual field advantage is a replicable and stable behavioural finding, which, as we showed, was based on suppression of visual input from the left hemifield, we do not know what is the origin of this advantage. Innate processes based on cortical asymmetries or learned traits could have led to the visual spatial bias. One idea we would like to voice is a possible influence of the reading direction. Reading is a highly trained process. There is evidence that the reading direction influences visual processing. For example, it was found that the target search performance was better in the right visual field for left-to-right readers whereas it was superior in the left visual field for right-to-left readers. No bias was found in bilinguals⁶³. Also, detection performance was found to be better in the right visual field for participants with a reading habit from left-to-right, whereas the pattern was eliminated for participants with reading difficulties due to developmental dyslexia⁶⁴. Based on those findings, it is interesting to see whether the right visual field advantage is influenced by the preferred reading direction and persists outside the visual domain.

Conclusion

To summarize, a right visual field advantage in visual orientation discrimination was replicated during natural movement (walking and standing). The behavioural and neural evidence demonstrate that the right visual field advantage was related to a biased suppression of left distracting input during natural body states.

Data availability

The data and materials for data analysis of this experiment are available in Figshare (DOI: 10.6084/m9.figshare.20156744).

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Author contributions

XC developed the experiment, collected the data, analysed the data, and wrote the initial manuscript. LC developed the experiment, supervised the data collection and analyses, and revised the manuscript. BH led the project, provided suggestions of analyses and revised the manuscript. All authors read and approved the final manuscript.

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Declarations

Competing interests

The authors declare no competing interests.

Additional information

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