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What's left of the leftward bias in scene viewing? Lateral asymmetries in information processing during early search guidance

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ABSTRACT

Understanding how early scene viewing is guided can reveal fundamental brain mechanisms for quickly making sense of our surroundings. Viewing is often initiated from the left side. Across two experiments, we focused on search initiation for lateralised targets within real-world scenes, investigating the role of the cerebral hemispheres in guiding the first saccade. We aimed to disentangle hemispheric contribution from the effects of reading habits and distinguish between an overall dominance of the right hemisphere for visuospatial processing and finer hemispheric specialisation for the type of target template representation (from pictorial versus verbal cues), spatial scale (global versus local), and timescale (short versus longer). We replicated the tendency to initiate search leftward in both experiments. However, we found no evidence supporting a significant impact of left-to-right reading habits, either as a purely motor or attentional bias to the left. A general visuospatial dominance of the right hemisphere could not account for the results either. In Experiment 1, we found a greater probability of directing the first saccade toward targets in the left visual field but only after a verbal target cue, with no lateral differences after a pictorial cue. This suggested a contribution of the right hemisphere specialisation in perceptually simulating words' referents. Lengthening the Inter-Stimulus Interval between the cue and the scene (from 100 to 900 ms) resulted in reduced first saccade gain in the left visual field, suggesting a decreased ability of the the right hemisphere to use the target template to guide gaze close to the target object, which primarily depends on local information processing. Experiment 2, using visual versus auditory verbal cues, replicated and extended the findings for both first saccade direction and gain. Overall, our study shows that the multidetermined functional specialisation of the cerebral hemispheres is a key driver of early scene search and must be incorporated into theories and models to advance understanding of the mechanisms that guide viewing behaviour.

1. Introduction

Cerebral structures and connectivity have evolved to optimise adaptation (see Bullmore & Sporns, 2012), including efficient search for information in complex visual settings. However, little research has focused on how brain organisation supports real-world search behaviour. As a key characteristic of the brain's organisation, the two cerebral hemispheres function as integrated and complementary processors, preferentially, and more efficiently, handling different information sources and tasks (see Hellige, 1993; Rogers et al., 2013). Each hemisphere, therefore, likely plays a distinct role in visual search. Functional hemispheric specialisation emerges in behavioural tasks as lateral performance differences: better left visual field performance indicates right-hemisphere dominance, while better right visual field performance indicates left-hemisphere dominance. This specialisation extends beyond the broad asymmetry that the left hemisphere preferentially handles verbal processes and the right hemisphere preferentially handles visuospatial processes (see Hellige, 1993) in 95–99 % of right-handers (with 20–30 % of left-handers showing reversed or mixed patterns, e.g., Flöel et al., 2005). While relevant for understanding task guidance, this broad dimension does not capture the complex asymmetries characterising hemispheric functions, where both hemispheres possess both verbal and visuospatial abilities (e.g., Corballis, 2003; Hugdahl, 2005; Hugdahl & Westerhausen, 2010; Spencer & Banich, 2005). Therefore, it does not seem to adequately explain the subtle and flexible lateral differences in behaviour, including search behaviour.

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1.1. Using eye movements within real-world scenes to study hemispheric specialisation

Real-world scenes are static images of everyday environments, maintaining their key properties like figure/ground organisation and semantic and spatial structure. However, controlled manipulations can be made for detailed process analysis, making these stimuli ideal for examining hemispheric engagement in visual search. Functional hemispheric specialisation likely guides early, quick decisions when initiating search, especially during the first fixation, before extensive integration across hemispheres occurs as time passes and gaze shifts. Analysing early eye guidance within scenes is more informative than relying solely on overall accuracy and response time at trial end. Eye movements reflect moment-to-moment attentional deployment and information selection, and each hemisphere directs gaze toward the contralateral hemispace (e.g., Bruce & Goldberg, 1984; Leigh & Zee, 2015; Sparks & Pollack, 1977). Therefore, lateral orienting of gaze is likely to depend on the balance of activation between hemispheres (e.g., Kinsbourne, 1974; Reuter-Lorenz et al., 1990). Leftward saccades may indicate higher right hemisphere involvement, while rightward saccades may indicate higher left hemisphere involvement in current processing. Studying eye movements toward lateralised targets within scenes offers a more ecologically valid approach for studying neurologically intact individuals than the classic divided-visual-field paradigm. This classic paradigm, unlike normal viewing conditions, presents only one or a few objects without a shared background, lateralised in the right or left visual field, for short durations (usually less than 200 ms), preventing viewers from remapping information by moving their gaze (Bourne, 2006; Dimond & Beaumont, 1972).

1.2. The leftward preference in early inspection of real-world visual scenes: reading bias versus hemispheric specialisation

Some studies have examined lateral asymmetries in real-world scene processing using eye movements. They report a slight but consistent preference for initial saccades to the left half of scenes, whether inspected for a memory task (Dickinson & Intraub, 2009), a sentence-verification task (Foulsham et al., 2013; Foulsham et al., 2018), or without any specific aim (free viewing: e.g., Hartmann et al., 2019; Ossandón et al., 2014). However, Nuthmann and colleagues specifically considered these asymmetries during scene search. Nuthmann and Matthias (2014) compared search with either memorisation or aesthetic preference judgement tasks, showing an initial leftward oculomotor preference in all tasks, lasting for several fixations up to 1.5 s. It emerged regardless of target location, although reduced for right-lateralised targets, or image peculiarities, persisting when the scenes were mirror-reversed (see also Dickinson & Intraub, 2009). Recently, Nuthmann and Clark (2023) replicated this leftward preference in scene search even for right-lateralised targets, persisting up to 1 s. The leftward preference in initial image inspection appears not to be specific to scenes, also occurring when viewing fractals (e.g., Foulsham et al., 2018).

This leftward preference has often been linked to left-to-right reading habits in Western cultures (see Kazandjian & Chokron, 2008), which may generate a default motor bias (i.e. a priori, before visual processing). If so, this leftward motor bias may be an additional bias in viewing (as suggested by Nuthmann & Clark, 2023) that operates alongside other image-content-independent biases that have been found previously, such as the tendencies to look at the centre of the scene (Tatler, 2007), to make more horizontal than vertical saccades (Foulsham et al., 2008) and to launch saccades that continue in the direction of the previous saccade (Smith & Henderson, 2009). If reading habits play a key role in initial eye guidance in scene search through the operation of a default motor bias to initially saccade leftward that is independent of image content, this should result in first saccades to the left of the scene that are not only more frequent but also, because there is no or minimal involvement of visual information in their planning (e.g., Carpenter, 1981, 2012; Clarke, Stainer, Tatler, & Hunt, 2017; Tatler & Vincent, 2009), less accurate and of shorter latency (e.g., Carpenter, 2012). Greater accuracy with longer latencies should accompany the less frequent rightward saccades, resulting from inhibiting the motor bias due to detecting features related to the target object in the right half of the scene (Nuthmann & Clark, 2023); indeed, inhibiting a prepotent response leads to prolonged saccade latencies (Hallett, 1978).

Previous work, however, has suggested that this bias arising from reading habits is not the sole determinant of early preferential inspection of the left half of the visual world. Nicholls and Roberts (2002) found a leftward bias in luminance judgement tasks in both left-to-right and right-to-left (Hebrew) readers. Afsari et al. (2016) tested bilingual (right-handed) readers, who had a native reading direction (first language) but could also read in the opposite direction (second language). They presented participants a with left-to-right or right-to-left text prime which followed by free viewing of real-world scenes or fractal images. They found that native left-to-right readers exhibited a leftward bias regardless of the reading direction of the prime, while native right-to-left readers showed a mild rightward bias only after reading right-to-left primes. Afsari et al. (2018) found that native right-to-left readers had more variable horizontal spatial biases than native left-to-right readers during free viewing of both scenes and fractal images. Taken together, these findings suggest that the reduced strength and the greater flexibility of the bias in native right-to-left readers may be the result of factors pushing in opposite directions: reading habits, on the one hand, and functional hemispheric specialisation, on the other hand. In this explanation, and in most other studies on the leftward bias in scenes that considered the role of the cerebral hemispheres (e.g., Dickinson & Intraub, 2009; Foulsham et al., 2013; Foulsham et al., 2018; Hartmann et al., 2019; Nuthmann & Matthias, 2014), hemispheric specialisation is understood in terms of broad right-hemisphere dominance for visuospatial attention (e.g., Corbetta & Shulman, 2011; Kim et al., 1999; Shulman et al., 2010; but see Vogel et al., 2003) and visuospatial information processing (e.g., Asanowicz et al., 2013; Gainotti, 2014; Shulman et al., 2010; Voyer et al., 2012), which would result in a left-visual-field prioritisation. This dominance should emerge in early scene viewing, favouring the left side of space when judging physical properties, known as "pseudoneglect" (see Brooks et al., 2014). For example, in the line bisection task, there is a systematic error to the left of the veridical centre (Jewell & McCourt, 2000). Foulsham et al. (2013, 2018) reported leftward biases in both scene viewing and line bisection, although these biases were not correlated. Ossandón et al. (2014) found a first saccade leftward bias only in right-handed individuals during scene free viewing, which may suggest a key role of the right-hemisphere visuospatial dominance. However, Foulsham et al. (2018) found no relationship between the first saccade leftward bias and handedness, and (see above) most left-handers have the same lateral functional organisation as right-handers (Flöel et al., 2005).

If the right-hemisphere visuospatial dominance is crucial in early scene search (Nuthmann & Matthias, 2014; Ossandón et al., 2014), with a preferential allocation of attention to the left half of the scene (left visual field) even before the first saccade (covert attention), we would expect shorter latency leftward (than rightward) first saccades (Foulsham et al., 2018; Ossandón et al., 2014; Reddi et al., 2003) and a greater proportion of leftward (than rightward) first saccades. This is because the lateralisation of visuospatial attention at cortical level should propagate throughout the saccade generation network through descending pathways to the superior colliculus, which launches the saccade (Leigh & Zee, 2015). Crucially, these first saccades should be influenced by the visual content of the scene, particularly by the presence of the target object in the left half of the scene, resulting in greater search initiation accuracy in that visual field. However, the leftward preference in search initiation may arise not solely from this overall right-hemisphere advantage in detecting and saccading to (left-side) targets, but also, and perhaps mainly, from finer hemispheric functional specialisations in information processing, involving more specific underlying perceptual and cognitive mechanisms. This would result in a more flexible lateral first saccade preference, closely linked to specific search conditions not only in terms of the target placement within the scene, but also of the type of prior information about the target (provided by the target cue) and the time available to process it. Previous research has, indeed, demonstrated hemispheric specialisation in information processing for these aspects, which we will discuss in the following sections. Therefore, understanding the mechanisms behind the leftward preference in scene viewing requires manipulating these factors. However, no existing work that investigated this preference has examined them.

1.3. Hemispheric contributions to target template guidance in scene search

Most real-world scene search studies, lacking consideration of hemispheric specialisation, have found improved search performance using a specific target template from a pictorial cue compared to an abstract target template from a name cue (e.g., Bravo & Farid, 2009; Castelhano & Heaven, 2010; Malcolm & Henderson, 2009; Schmidt & Zelinsky, 2009, 2011; Spotorno et al., 2014, 2015; Vickery et al., 2005). While usually explained as reflecting the precision of target representation, this enhancement may be influenced by the cue format (pictorial versus verbal). If so, this may lead to lateralised differences related to the right-hemisphere dominance for visual, pictorial representations, and the left-hemisphere dominance for verbal representations (see Gainotti, 2014; Hellige, 1993). The format of the target cue may, thus, induce a transient asymmetry in hemispheric activation (Kinsbourne, 1974; Reuter-Lorenz et al., 1990) that may influence the direction of the first eye movement in search. Activation of a right-lateralised representational network by pictures could increase the likelihood of the right hemisphere taking control of eye movements, leading to more frequent saccades toward the left (contralateral) visual field. Conversely, activation of a left-lateralised network by words could increase the likelihood of the left hemisphere taking control of eye movements, resulting in more frequent saccades toward the right (contralateral) visual field. Therefore, during search, a pictorial cue could lead to more frequent first saccades toward the left visual field, while a verbal cue could result in the same effect toward the right visual field. However, previous research exclusively using verbal target cues has revealed an early leftward bias in scene search (Nuthmann & Clark, 2023; Nuthmann & Matthias, 2014). Hence, it is more plausible to expect a modulation of this bias based on the visual-verbal dimension, with pictorial cues potentially inducing more frequent leftward first saccades compared to verbal cues. Critically, hemispheric specialisation for processing the format of the cue might influence scene information matching with the target representation, leading to more accurate initiation for left targets with a pictorial cue and for right targets with a verbal cue.

Besides the verbal versus visuospatial axis of hemispheric specialisation concerning the format of target cue, it is also important to specifically consider the necessity generating a representation of the target prior to search, and the asymmetric hemispheric contributions in this regard. Enactive theories of knowledge propose that linguistic information is processed by representing (i.e., simulating) perceptual and motor properties of words' referents (see Barsalou et al., 2008). The cerebral hemispheres may differ in this perceptual simulation competence, with the right hemisphere also possibly being dominant in representing typical object locations indicated by words (Zwaan & Yaxley, 2003), potentially reinforced by its role in activating long-term memory of spatial object-scene associations learned from life experience (Demiral et al., 2012). Evidence is varied regarding shape representation (Lincoln et al., 2007, 2008; Norman & Peleg, 2023; Zwaan & Yaxley, 2004), but overall, the right hemisphere appears crucial in linking language to visuospatial information (Huang et al., 2010; Shibahara & Lucero-Wagoner, 2001; Vandenbulke et al., 2006; Wang et al., 2003) and specific visual object representations within the same category (Koutstaal et al., 2001; Marsolek & Burgund, 2008; Stevens et al., 2012). If this competence influences the first saccade, we may expect more accurate search initiation toward the left visual field than the right following a verbal cue (Nuthmann & Clark, 2023; Nuthmann & Matthias, 2014). However, both hemispheres may equally direct the eyes toward target candidates when cued by a specific picture, which bypasses the need for extracting abstract information, and provides strong search guidance from the first saccade in the scene (e.g., Spotorno et al., 2014, 2015).

1.4. The time course of hemispheric contributions to search

The influence of target cue type in scene search appears modulated by target cue-scene delay (but see Malcolm & Henderson, 2009): the pictorial cue advantage is mainly found with short delays (e.g., up to 200 ms: Vickery et al., 2005; Wolfe et al., 2004), while differences between cues diminish with longer delays. This pattern likely depends on working memory consolidation rather than encoding difficulties (Schmidt & Zelinsky, 2011). Therefore, while most prior research varied Stimulus-Onset Asynchrony, including cue presentation time, the Inter-Stimulus Interval (ISI), from cue offset to scene onset, seems critical. The different impact of ISI duration may in part stem from differences in pictorial and verbal information processing nature and time course, possibly influenced by the cerebral hemispheres' asymmetrical involvement. A short ISI may enhance the contribution of the right hemisphere to processing of pictorial cues, potentially through its dominance in fast-acting attentional mechanisms (Corbetta & Shulman, 2002; Shulman et al., 2010; Thiebaut de Schotten et al., 2011). Conversely, a longer ISI may facilitate efficient processing of word cues in the left hemisphere through verbal and analytical strategies, which may require more time to be deployed effectively (see Gainotti, 2014; Hellige, 1993). For instance, it has been shown that the involvement of the left hemisphere follows that of the right when activating semantic object knowledge from visually presented words (e.g., Assaf et al., 2009), although evidence for this has been mixed (e.g., Koivisto, 1997). Previous work has also shown that the right hemisphere performed better at matching information across a short (100-ms) interval in a visual change detection task, which requires working-memory comparison of the original and modified scenes, whereas lengthening the ISI to 900 ms improved change detection performance of the left hemisphere (Spotorno & Faure, 2011).

In the present study, for the first time in the literature, we manipulated the ISI duration (short: 100 ms, versus long: 900 ms, as in Spotorno & Faure, 2011) to explore how hemispheric differences related to the timescale of information processing influence scene search. These differences may specifically influence template guidance. We, thus, hypothesised increased first saccade accuracy in the left than in the right visual field with a short ISI following a pictorial cue and increased first saccade accuracy in the right than in the left visual field with a long ISI following a verbal cue. Note that lengthening the ISI provides more opportunities for interhemispheric communication about the target template (see Banich, 1998). However, since the target cue is presented at the centre of the screen and, thus, processed by both hemispheres (see Bourne, 2006), the influence of the ISI duration on initial scene search for a lateralised target object should genuinely reflect differences in the nature of the target template representation formed in each hemisphere and how it is influenced by the time course of processing the target cue information.

1.5. Hemispheric competencies for global versus local processing in scene search

To our knowledge, the only previous work that investigated finer specialisations of the cerebral hemispheres in real-world scene inspection by analysing lateral preferences in eye-movement behaviour is the study conducted by Ossandón et al. (2014). They examined free viewing, focusing on the role of hemispheric specialisation in global and low spatial frequencies processing (right hemisphere) and local and high frequencies processing (left hemisphere) (e.g., Brederoo et al., 2017; Chokron et al., 2000; Fink et al., 1996; Ivry & Robertson, 1998; Mills et al., 2017; Peyrin et al., 2003). They found no difference in the early leftward preference between low-pass and high-pass filtered scenes, suggesting that any cerebral lateralisation concerning image content resolution is not fundamentally involved. However, hemispheric specialisations for global and local processing and for low and high spatial frequencies, while related, are not completely overlapping, with more robust evidence reported for the global versus local asymmetry than for the low versus high spatial frequencies asymmetry (see Brederoo et al., 2019).

Moreover, a right-hemisphere specialisation for global processing and a left-hemisphere specialisation for local, fine-grained analysis has often been suggested in visual search studies that used simple object arrays instead of real-world scenes (but see Arguin et al., 1990; Lane et al., 2011) and analysed performance accuracy and/or response time. For example, Poynter and Roberts (2012) found greater efficiency of the right hemisphere in feature search, based on a pop-out property and parallel processing across the visual field, and greater efficiency of the left hemisphere in conjunction search, requiring serial inspection and binding of multiple local properties. Similarly, Efron et al. (1990); Efron & Yund, 1996; Yund et al., 1990) reported a right-visual-field advantage for discriminating between gratings, while Donelly and Wilkinson (1998) observed a linear relationship between display size and error rate in search for right-lateralised targets but not for left-lateralised targets. Polich et al. (1990) found an advantage for right-lateralised targets in feature search requiring serial inspection and individual item analysis, and an advantage for left-lateralised targets in pop-out conditions.

No study has yet focused on early lateral eye-movement preferences within unfiltered (and thus more akin to everyday viewing conditions) real-world scenes to investigate hemispheric specialisation for global versus local processing. We argue that this specialisation can be explored using different oculomotor measures reflecting either more global or local processes during search initiation, while being indicative of saccade accuracy linked to processing target information within the scene. Therefore, to examine more global processes, we analysed whether the direction of the first saccade was broadly toward the target (a 45-degree sector of the scene containing the target, see Spotorno et al., 2014). This measure reflects the fact that information processing at the target location may result in saccades that are launched in the general direction of, but not directly onto, the target object (Carpenter, 1988; Spotorno et al., 2015; Zelinsky et al., 1997). For example, in Zelinsky et al. (1997) up to three saccades were used to bring the eye to the target, and the location of the target influenced the direction of the second saccade even though it did not land on the target. To examine more local processes, we analysed the gain of the first saccade directed toward the target, computed as the ratio between the amplitude of the first saccade and the initial retinal eccentricity of the target's centre (e.g., Miller et al., 1981; Spotorno et al., 2014; Straube & Deubel, 1995), such that a gain of 1 indicates a saccade of correct amplitude to reach the target, gains less than 1 indicate saccades that undershoot the target and gains of more than 1 indicate saccades that overshoot the target. This measure, therefore, reflects the extent to which local information about the distance to the target has been encoded and used for programming the saccade. We expected any right-hemisphere contribution to search due to its global processing dominance to emerge as a higher probability of first saccading toward left-lateralised than right-lateralised targets, while left-hemisphere dominance in local processing would likely result in initiating saccades with gain closer to 1 toward right-lateralised targets than toward left-lateralised targets.

1.6. The present study

In this study, across two experiments, we examined the lateral asymmetries in eye guidance during real-world scene search, focusing on search initiation, i.e., on the first saccade in the scene, to infer hemispheric specialisation in the task. We analysed first saccade latency and – as measures of search initiation accuracy – direction and gain of the first saccade. We used a lateralised target object in the left or right visual field (i.e., in the left or right half of each scene), whose information was thus initially processed by the contralateral hemisphere. In Experiment 1, we also manipulated the type of target cue (its format: precise image – providing a specific, pictorial template, or its name at the basic category level – providing an abstract, verbal template) and the delay (ISI: short/100 ms or longer/900 ms) between target cue and scene presentation. These target visual field, cue type and ISI manipulations, together with the use of both relatively broader (saccade direction) and more precise (saccade gain) measures of initiation accuracy, allowed us to test several competing possible accounts of lateral first saccade asymmetries in scene search, investigating the underlying perceptual and cognitive mechanisms. The different potential underlying mechanisms that we evaluated in Experiment 1 are summarised in Table 1, along with the predictions that arise from each potential mechanism. In Experiment 2, we followed up the findings of Experiment 1 in two ways. First, we considered a different mechanism through which left-to-right reading habits might influence initial lateral

Table 1

The six potential mechanisms that might underlie lateral differences in search initiation that were tested in Experiment 1. Mechanisms are grouped into three categories (reading habits, general hemispheric specialisation, and finer hemispheric specialisation). For each mechanisms the predictions derived from prior studies are included. LVF = left visual field (i.e., target information within the scene initially directed to the right hemisphere), RVF = right visual field (i.e., target information within the scene initially directed to the left hemisphere).

Reading habits

Mechanism: ***A priori* motor bias to saccade leftward**
Predictions:
- Shorter first saccade latency toward the LVF than RVF
- Fewer saccades toward targets when saccading into LVF than RVF

General hemispheric specialisation

Mechanism: **General right hemisphere dominance for visuospatial information processing**
Predictions:
- Shorter first saccade latency toward the LVF than RVF
- Better first saccade accuracy for targets in the LVF than RVF

Finer hemispheric specialisation

Mechanism: **Different competencies of the hemispheres for processing pictorial and verbal information**
Predictions:
- Better first saccade accuracy for targets in the LVF than RVF following pictorial cues
- Better first saccade accuracy for targets in the RVF than LVF following verbal cues

Mechanism: **Different competencies of the hemispheres for perceptual simulation of the target template from verbal cues**
Predictions:
- Better first saccade accuracy for targets in the LVF than RVF following verbal cues
- No difference in first saccade accuracy for targets in the LVF and RVF following a pictorial cue

Mechanism: **Different competencies of the hemispheres for global vs local processing**
Predictions:
- More saccades directed toward targets in the LVF than in the RVF
- Gain closer to 1 for targets in the RVF than in the LVF

Mechanism: **Different involvement and proficiency of the cerebral hemispheres over time, depending on cue format**
Predictions:
- Better first saccade accuracy for targets in the LVF than in the RVF following pictorial cues at a short (100-ms ISI) timescale
- Better first saccade accuracy for targets in the RVF than in the LVF following verbal cues at a longer (900-ms ISI) timescale

viewing preferences. Specifically, we examined whether the need to read the verbal cue in Experiment 1 might have promoted an attentional bias to the left visual field during search initiation. We tested this by comparing verbal cues presented visually as words on the screen (as in Experiment 1) with auditory verbal cues, which should not promote any biases that arise from reading a word. Experiment 2 also served to test whether any laterality effects would replicate with a different set of scenes and targets, thereby assessing the robustness of findings from Experiment 1.

2. Experiment 1

2.1. Method

2.1.1. Participants

Because we had eight versions of the experiment to counterbalance all factors (see Procedure below), we aimed to recruit three or more participants per version. We recruited four participants per version (32 in total), but four datasets were not usable due to being unable to achieve good quality eye tracking data across the experiment. This resulted in twenty-eight native English-speaking participants (15 males, aged 20–30), all with solely left-to-right reading habits, and a minimum of three participants per experiment version. With no appropriate prior work to base a power analysis on, this sample size reflected what we used in other similar search tasks with young adults, similar scenes and repeated-measure design (Spotorno et al., 2014, 2015). All participants reported normal or corrected-to-normal visual acuity, normal colour vision and no history of neurological disease. According to the Edinburgh Handedness Inventory (EHI; Oldfield, 1971), all were right-handed (laterality quotient: $M = 88.8$, $SD = 16.4$, range = 45.5–100). Participants took part on a voluntary basis and received no money or course credits. They all gave informed consent. The study was approved by the local ethics committee and was in accordance with The Code of Ethics of the World Medical Association (Declaration of Helsinki).

2.1.2. Apparatus

Experimental sessions were carried out on a Dell Optiplex755 computer running OS Windows XP. Stimuli were shown on a ViewSonic G90f-4 19-in. CRT monitor, with a resolution of 800 × 600 pixels, and a refresh rate of 75 Hz. Viewing was binocular, but only the dominant eye was tracked with an EyeLink 1000 (SR Research, Canada), at a sampling rate of 1000 Hz. A chin and forehead rest stabilised the eyes 63.5 cm away from the display. A response pad was used for manual responses. Stimulus presentation and response recording were controlled by Experiment Builder (SR Research, Canada).

2.1.3. Materials

Seventy-two full-colour photographs (800 × 600 pixels, 31.8 × 23.8°) of real-world scenes (outdoor and indoor, natural and man-made), plus four for practice, were used. Scenes were taken from the SUN database (Xiao et al., 2010) or from Google Images. All image manipulations were made using Adobe Photoshop CS5 (Adobe, San Jose, CA). Several unique objects were placed, widely distributed, into the scenes and one object included in the left or right visual field (LVF or RVF) was selected as the target object. Objects added into the scenes were taken from the Hemera Images database (Hemera Technologies, Gatineau, Canada), the MIT Object Categories database (Konkle et al., 2010) or Google Images. Scenes were flipped horizontally, creating two versions of each, one with the target in the LVF and the other with the target in the RVF.

Target cues were either the identical picture of the target object or its name (font: Times New Roman, colour: black, font size: 30, no capital lettering). Verbal cues varied in length from three to 14 letters ($M = 7.29$, $SD = 3.50$) and comprised one (58 cues), two (13 cues) or three (1 cue, “hot air balloon”) words. When more than one word was presented, if any two consecutive words together totalled 10 or more letters, they were placed one below the other, to minimise lateralised presentation of any words and facilitate reading. The verbal cues subtended a range of 1.26–5.68° in width and 0.54–3.79° in height. For the size of pictorial cues, which is the same as the size of the target objects, please see 2.1.5. Two versions of each pictorial cue were created, to counterbalance the orientation of the target object within each version (original and mirrored) of the scene.

2.1.4. Procedure

The experiment was conducted individually in a quiet, dimly illuminated room. It began after a randomised nine-point calibration and validation procedure, performed to ensure that data accurately reflected gaze position. Recalibrations were performed during the task if necessary. A single-point calibration check was conducted before each trial, while the participant fixated a central, small black dot. When the check was deemed successful, the experimenter started the trial sequence. This began with a 200-ms black central fixation cross, followed by a 250-ms picture or word cueing the target presented at the centre on the screen. The cue was followed by a black central fixation cross lasting 100 ms, in half of the trials, or 900 ms, in the other half of the trials, according to the ISI condition. The scene then appeared, and participants searched for the target object, responding as soon as it was located by pressing with both index fingers, at the same time, two buttons (one on the right and one on the left side) on the response pad, to avoid the predominant involvement of one hemisphere in planning and executing the manual response. We used a white background during the single-point calibration check and all the trial sequence, excluding the scene presentation, which was full screen. The experiment had a 2 (Cue Type) x 2 (ISI) x 2 (Target Visual Field) repeated-measure design. Half of the scenes were cued with the picture of the target object, the other half with the name of the target object (Fig. 1).

Each participant saw half of the scenes with the target in the LVF and the other half with the target in the RVF. The scenes were presented in a random order, and each was displayed only once during the experiment. All the experimental factors were counterbalanced between participants. The experiment overall consisted of 72 experimental trials (nine per condition), plus four as practice, and lasted for approximately 30 min.

2.1.5. ROI definition and data analysis

For each target object, a ROI was defined as the smallest fitting rectangle that encompassed the target. The first saccade in each trial was scored as being directed toward a specific target ROI if its angular direction (from the saccade’s starting position near the centre of the screen) was within 22.5° of the angular direction to the centre of the ROI, and landing on the target when its landing point was at least within 0.5° from the ROI’s boundary (as in Spotorno et al., 2014, 2015). The target object ROIs subtended a range of 1.03–12.69° in width and 1.34–8.60° in height and had a mean size of 12.71 deg^2 ($SD = 13.05$), occupying on average 1.68 % of the scene ($SD = 1.72$) The eccentricity of the target object ROIs from the centre of the scene, along the horizontal axis, was between 4.97° and 14.1° ($M = 9.94$, $SD = 2.23$) considering the centre of the target ROI and between 3.17° and 12.9° ($M = 8.22$, $SD = 2.45$) considering the nearest edge of the ROI. Along the vertical axis, target ROI centres varied from 9.84° below the midline to 9.71° above the midline ($M = 0.14°$ below the midline, $SD = 6.45°$).

Raw data were parsed into saccades and fixations using the SR Research algorithm with default parameter settings (velocity of the eye position signal greater than 30°/s and acceleration above $8000°/s^2$). Subsequent analyses of saccades and fixations were conducted using routines written in Matlab (MathWorks, Inc., Natick, MA, USA) and R (R Core Team, 2024). See Supplementary Materials to access the data in the Open Science Framework repository, the list of variables included in the dataset and the analysis code. We discarded, from all analyses, 16 trials with high mean calibration error and 70 trials when the single-point calibration check at the start of the trial indicated an error in excess of

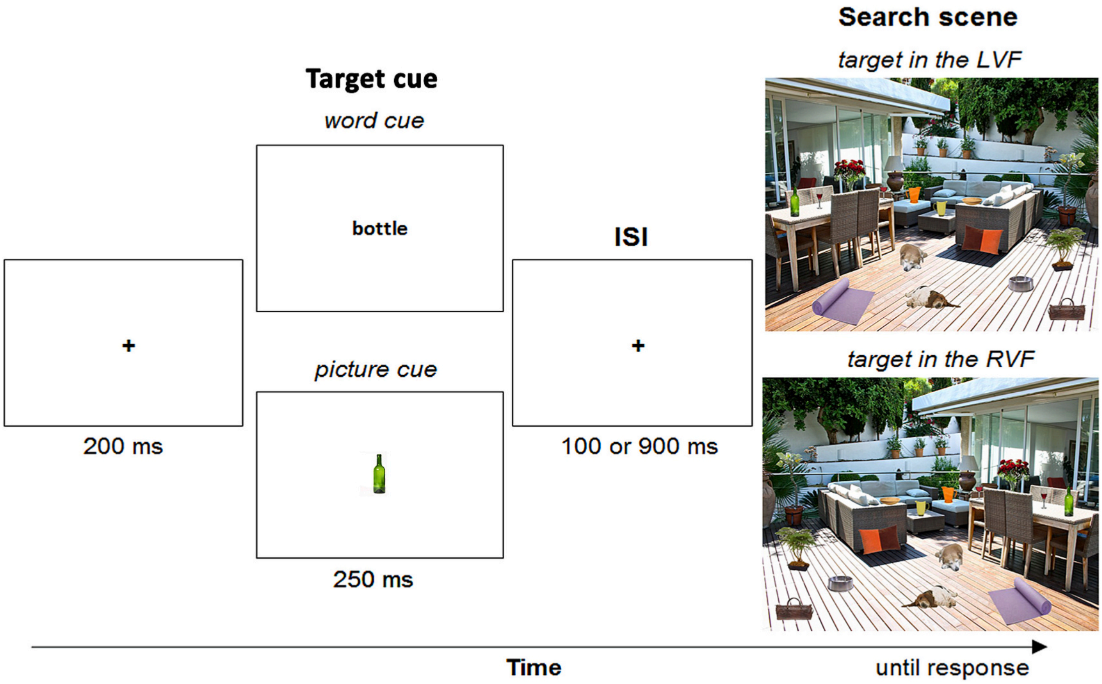

Fig. 1. Experiment 1. Examples of trials. The figure shows the two types of target cue (verbal and pictorial) and the two mirror-reversed images of a scene, used to present the object once in the left visual field (LVF; top picture) and once in the right visual field (RVF; bottom picture). Each participant was presented with only one version of each scene The trial started with a single-point calibration screen, here not depicted (refer to the online article to see this figure in colour).

1°. In total, we removed 4.29 % of the overall data (trials) as result of these exclusions. The average calibration error of the remaining trials was 0.36° (*SD* = 0.09°, min = 0.21°, max = 0.56°) for the mean error across all nine calibration points and 0.71° (*SD* = 0.19°, min = 0.43°, max = 1.20°) for the maximum calibration error on any one of the nine points. The single-point calibration check at the start of the trial indicated an average error of 0.46° (*SD* = 0.22°, min = 0.02°, max = 1.00°). Further trials were excluded if participants did not maintain fixation within a radius of 1.5° from the screen's centre when the scene appeared (9.34 % of the remaining data).

Our hypotheses centre around the initiation of search (the timing and targeting of the first saccade after scene onset), thus our analyses focus on this phase of search (Malcolm & Henderson, 2009; Spotorno et al., 2014, 2015). As measures of the spatial targeting of the first saccade, we first considered whether the end point of this saccade was within the target's ROI. However, we expected that this would not often be the case because initial saccades toward a target detected in the periphery tend to fall short and are followed by a corrective saccade to bring the eye to bear upon the target (e.g., Carpenter, 1988), and that observers may make several saccades to bring the eyes to a target when searching simple arrays of objects (e.g., Zelinsky et al., 1997) or more complex photographic scenes (e.g., Spotorno et al., 2015). Thus, saccades that do not directly land on the target may also have been programmed based upon information extracted from it, so as broader measures of spatial targeting we considered the direction and amplitude gain of the first saccade (see Spotorno et al., 2014, 2015, for prior use of these measures in scene search). The gain of the first saccade is the ratio between the amplitude of the first saccade and the initial retinal eccentricity of the centre of the target's ROI (e.g., Miller et al., 1981; Spotorno et al., 2014; Straube & Deubel, 1995), with values less than 1 indicating first saccades that undershoot the target and values greater than 1 indicating first saccades that overshoot the target. In the Supplementary Materials, we also provide an analysis of the scene scanning phase of search (the period between the first saccade in viewing and the first fixation on the target object) because Nuthmann and colleagues (Nuthmann & Clark, 2023; Nuthmann & Matthias, 2014) found a leftward preference in search that persisted beyond the first saccade.

Inspection of the distribution of first saccade latencies revealed a subpopulation of infrequent but very fast first saccades (8.29 % of the remaining data after the previous exclusions), with latencies up to 100 ms (see Fig. 2), which – given the short time available before they are launched – are likely not guided by scene and target information processing. These trials were removed from subsequent analyses.

Moreover, to include only initial saccades that are likely to reflect explorative behaviour directed toward one visual field (see also Foulsham et al., 2013; Foulsham et al., 2018; Nuthmann & Clark, 2023), we

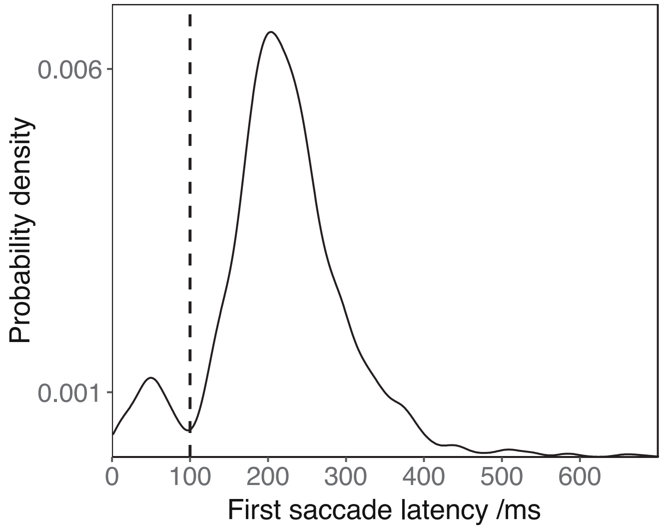

Fig. 2. Experiment 1. Density plot of first saccade latency. The figure shows a clear bimodal distribution of first saccade latencies in our data, which defined two subpopulations of initial saccades. The first subpopulation included the (infrequent) saccades with latencies up to 100 ms (as indicated by the dashed line). The second, major subpopulation included most of the initial saccades, with latencies greater than 100 ms, and was used in the analyses reported here.

removed trials with initial saccades with amplitude less than 1° (a further 1.82 % of the data), considered characteristic of fixational saccades, made while attempting to fixate (see Martinez-Conde et al., 2009). Overall, 21.9 % of the raw data was removed from search initiation analysis because of all the exclusions described above.

With the exception of a preliminary one-sample t-test to examine whether there was a lateral preference in first saccade direction, in the main population of first saccades, and a one-sample t-test to test whether first saccades were directed to the target more frequently than expected by chance, for all the other analyses we ran linear mixed models (LMMs) or generalised LMMs (GLMMs) for binomial data using the lmer() function of the lme4 package (Bates et al., 2015) in R. Participants and scenes were specified as random factors in the models. LMMs and GLMMs have many advantages over traditional ANOVA models, especially when the design is not fully balanced because of missing data (Baayen et al., 2008). They allow for the inclusion of each trial as a separate data point, which is a crucial feature, especially in experiments with a limited number of trials per condition for each participant (such as ours, with nine trials). They also enable the simultaneous estimation of between-subject and between-item variance, allowing control over the influence of individual differences as well as item peculiarities (in addition to the control implemented via counterbalancing). In these ways, they increase statistical power while reducing the risk of Type 1 error (Matuschek et al., 2017).

Predictors (fixed effects) entered in each model were all categorical with two levels and are detailed in the Results. All fixed effects were entered as sum-coded contrasts (deviation coding), in which each level of the predictor is compared to the grand mean. For each model, we attempted to include the full structure of the random factors, specifying intercepts and slopes for all the effects (as recommended by Barr et al., 2013) to account for the possibility of different influences of our fixed effects on different participants or different scenes. If models were singular, we ran a Principal Component Analysis using rePCA() from the lme4 package and removed all slopes that did not contribute along with any higher order interactions involving those slopes. If models failed to converge, we removed slopes corresponding to the highest order interaction within the scene (item) random effect structure, and then stepwise simplified the scene random effect structure until either the model converged or was an intercept-only structure for the scene random effect. Following this, any further simplification followed the same process of stepwise simplification but this time for the participant random effect structure. For each model, we report the t-values, or the z-values for binomial models, and the associated p-values, calculated using the lmerTest() function (Kuznetsova et al., 2017). These values are reported for all the effects of the single predictors (whether significant or not), all the significant interactions and any interaction that tended toward significance (p-value range 0.051–0.099); for all the other interactions, we report the greatest t-value or z-value and the lowest p-value. When an interaction was significant, we conducted pairwise comparisons for the effects of interest using the function emmeans() from the emmeans package (Lenth, 2024). Graphics were created using the ggplot2 package (Wickham, 2016). The structure of each LMM and GLMM used, after any necessary simplifications of the random effects due to singularity and convergence issues, is included in Supplementary Materials.

2.2. Results

We examined whether a general lateral preference in the direction of the first saccade was present. A one sample t-test (two-tailed, test value = 50 %) showed that significantly more saccades were directed to the LVF (57.9 %) than to the RVF, $t(27) = 4.18$, $p < .011$. The following LMMs/GLMMs analyse what factors modulated this leftward preference.

2.2.1. Is there an a priori motor bias to go left?

If the overall tendency to launch saccades toward the left visual field in the above analyses reflects a motor bias to saccade leftward at scene onset irrespective of the viewed content, we may expect that leftward first saccades were launched with shorter latency and had a lower probability of being directed toward the target than rightward first saccades. Indeed, rightward first saccades should reflect those trials on which such a motor bias has been suppressed, presumably because some evidence of the target in the RVF has been detected and both response suppression and visual information processing prolong saccade latencies (Carpenter, 1981; Hallett, 1978).

2.2.1.1. First saccade latency. We entered the First Saccade Visual Field (LVF, RVF), First Saccade Direction with respect to the Target (toward the target or not), Cue Type (pictorial, verbal), ISI (100, 900 ms) and all their interactions in the LMM (Model 1.1). First saccades with latencies greater than 2.5 standard deviations from the mean were excluded from these analyses (2.0 % of the dataset). There was no overall latency effect of whether the first saccade was directed leftward or rightward, $\beta = -2.53$, $SE = 1.61$, $t = -1.57$, $p = .128$, nor was there an effect of whether the cue was pictorial or verbal, $\beta = -2.13$, $SE = 1.67$, $t = -1.27$, $p = .212$. There was an effect of whether the saccade was directed toward the target, $\beta = -7.59$, $SE = 1.36$, $t = -5.60$, $p < .001$, with longer latency for saccades directed toward the target object ($M = 237$ ms, $SE = 2$) than for saccades directed elsewhere ($M = 220$ ms, $SE = 2$). The effect of ISI was also significant, $\beta = 6.36$, $SE = 2.14$, $t = 2.97$, $p = .006$, with longer first saccade latencies after a 100-ms ISI ($M = 233$ ms, $SE = 2$) than after a 900-ms ISI ($M = 221$ ms, $SE = 2$). There was a tendency toward an effect of the interaction between the ISI condition and whether the first saccade was directed leftward or rightward, but this failed to reach significance, $\beta = 2.32$, $SE = 1.26$, $t = 1.85$, $p = .065$. No other effects were significant in the model (all ts ≤ 1.56, all ps ≥ 0.128).

2.2.1.2. Probability of saccading toward the target object. The probability that the first saccade landed on the target was low ($M = 0.157$, $SE = 0.009$). This was expected as viewers usually undershoot targets with their first saccade (e.g., Carpenter, 1988) and take several saccades to reach the target (e.g., Spotorno et al., 2015; Zelinsky et al., 1997). The low prevalence of first saccades landing on the target meant that it was not appropriate to model this behaviour. However, the proportion of first saccades directed toward the target was considerably higher ($M = 0.439$, $SE = 0.013$) and, thus, this accuracy measure could be modelled appropriately. To test whether the first saccade was more likely to be toward the target than would be expected by chance, it was important to account for the fact that not all saccade directions are equally likely when viewing images: people make more horizontal than vertical saccades when viewing photographic scenes (Foulsham et al., 2008). To account for this oculomotor bias, for each trial, we simulated 10,000 saccades, sampled from an anisotropic Gaussian function with the parameters suggested by Clarke and Tatler (2014) to act as an image-content-independent baseline that incorporates typically observed differences in the directions in which saccades are launched. We then computed the proportion of these saccades that were directed toward the target location. We tested whether the difference between the observed and expected probability of saccading toward the target differed from zero using a one-sample t-test. First saccades were more likely to be directed toward the target than would be expected by chance, $t(27) = 15.35$, $p < .001$.

We then analysed the probability of first saccades being directed toward the target with First Saccade Visual Field, Cue Type, ISI and all their interactions as predictors in the GLMM (Model 1.2). It was not significantly influenced by whether that first saccade was launched into the LVF or RVF, $\beta = -0.077$, $SE = 0.061$, $z = -1.26$, $p = .209$, nor was it influenced by the ISI, $\beta = 0.072$, $SE = 0.060$, $z = 1.21$, $p = .227$. The type of cue did have a significant effect, $\beta = 0.332$, $SE = 0.061$, $z = 5.41$, $p < .001$, with a lower proportion of saccades toward the target object following a verbal cue ($M = 0.380$, $SE = 0.017$) than following a pictorial cue ($M = 0.499$, $SE = 0.018$). No interactions were significant (all zs ≤ 1.43, all ps ≥ 0.152).

2.2.2. *Online processing of scene information in search initiation*

The above models including the first saccade visual field do not support an a priori, generic leftward motor bias independent of any information processing. Indeed, we found no evidence that leftward first saccades were launched overall more quickly or had a lower probability of being directed toward the target than rightward saccades. Moreover, the longer latency for first saccades launched in the direction of the target may reflect online processing of scene information and consequent covert selection of the plausible target candidate.

2.2.2.1. First saccade direction with respect to the target object. The model for first saccade direction reported above (Model 1.2) also allows us to consider the possibility of a greater covert allocation of attention to the left visual field due to right-hemisphere visuospatial dominance. In this case we expected that leftward saccades would be more likely to be launched in the direction of the target than rightward saccades, but this was not the case. Thus, the results of this model do not support our predictions if lateral differences in search initiation arose from right-hemisphere visuospatial dominance in attention allocation.

While the above model (Model 1.2) provides an important test of the factors that influence saccade accuracy for leftward and rightward saccades, it does not explicitly take into account the location of the target in the scene and, therefore, to which hemisphere the target information is initially directed. Thus, it cannot directly capture some aspects of how online information processing by each hemisphere influences search initiation. Therefore, we analysed whether the placement of the target object in the left versus right half of the scene (LVF versus RVF) influenced the probability of launching the first saccade toward it. Indeed, effects of target placement would indicate that search initiation is guided by the functional specialisation of the cerebral hemispheres, as the lateralised target information is initially only received by the contralateral hemisphere. This approach of accounting for whether the target appears in the left or right visual field allows us to consider the possible contributions of finer hemispheric contributions to search initiation.

We first ran one-sample t-tests (two-tailed, test value = 50 %) to consider whether the overall tendency to initiate search with a leftward saccade persisted even when the target was in the RVF (as reported in Nuthmann & Matthias, 2014 and Nuthmann & Clark, 2023). We found that in this case participants were less likely to initiate search with a leftward than a rightward saccade (M = 43.2 % leftward), $t(27) = -2.73$, $p = .011$. This was true, however, only when the target was cued by a picture (M = 34.3 % leftward), $t(27) = -5.48$, $p < .001$; there was no lateral preference to initiate search when the target in the was in RVF and cued by a word (M = 52.3 % leftward), $t(27) < 1$, $p = .432$.

We then entered the Target Visual Field, Cue Type, ISI and all their interactions as predictors in a GLMM (Model 1.3) that modelled the probability of launching the first saccade in the direction of the target object. In this way, we could also examine whether the cue and the time available to process it before scene onset modulated any effect of the visual field containing the target. This would suggest that, besides a generic dominance of the right hemispheres in visuospatial processes, more subtle hemispheric asymmetries linked to the processing of the target cue and the time course are involved in guiding search initiation. The first saccade was more likely to be directed toward the target when this object was in the LVF than when it was in the RVF, $\beta = 0.253$, $SE = 0.063$, $z = 4.01$, $p < .001$, and this effect was qualified by an interaction between target visual field and cue type, $\beta = -0.156$, $SE = 0.063$, $z = -2.48$, $p = .013$ (Fig. 3). Pairwise comparisons showed that following a pictorial cue, the probability of saccading toward the target did not depend on the target visual field, $z = 1.15$, $p = .249$, while following a verbal cue, a higher proportion of initial saccades were launched toward the target when it was in the LVF ($M = 0.453$, $SE = 0.025$) than when it was in the RVF ($M = 0.304$, $SE = 0.023$), $z = 4.36$, $p < .001$. Moreover, initial saccades were more likely to be launched toward the target following a pictorial cue than following a verbal cue, independently of the visual field in which the target was placed (LVF: $\beta = 0.371$, $SE = 0.170$, $z = 2.19$, $p = .029$, pictorial cue: $M = 0.509$, $SE = 0.026$ versus verbal cue: $M = 0.453$, $SE = 0.025$; RVF: $\beta = 0.995$, $SE = 0.175$, $z = 5.70$, $p < .001$, pictorial cue: $M = 0.454$, $SE = 0.025$ versus verbal cue: $M = 0.304$, $SE = 0.023$). Overall, the pattern for this interaction seems to be driven by the relatively low probability of saccading toward a target in the RVF cued by a word. As expected from the previous model considering first saccade direction (Model 1.2), the probability of launching the first saccade toward the target was not influenced by the ISI, $\beta = 0.087$, $SE = 0.059$, $z = 1.48$, $p = .140$, but was influenced by the type of cue, $\beta = 0.342$, $SE = 0.059$, $z = 5.81$, $p < .001$ (see above). No other effects were significant (all zs ≤ 1.32, all ps ≥ 0.187).

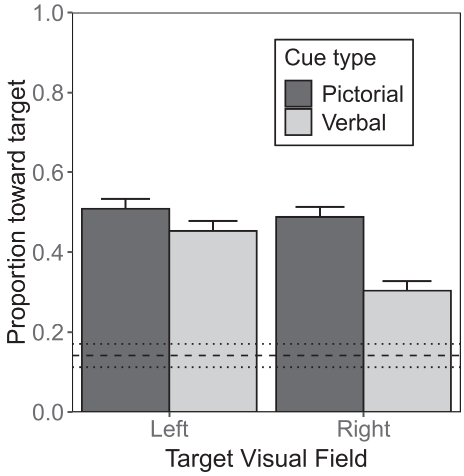

Fig. 3. Experiment 1. Proportion of first saccades directed toward the target object, as a function of the Target Visual Field and the Cue Type. The dashed line indicates chance level (0.141), computed by simulating 10,000 saccades on each trial using the baseline distribution suggested by Clarke and Tatler (2014), with dotted lines showing ±1 SD across scenes. Thus, this shows the chance of saccading toward the target given oculomotor biases when viewing images of natural scenes. Bars show condition means +1 SE.

2.2.2.2. First saccade gain with respect to the target object. While first saccade direction with respect to (the area that includes) the target reflects the effects of more global information processing on saccade accuracy, the gain of the first saccade directed toward the target reflects the effects of more local, finer-grained processing that is involved in getting gaze near the target (or even directly on it). This measure is the ratio between the amplitude of the first saccade and the initial retinal eccentricity of the centre of the target's ROI (e.g., Miller et al., 1981; Spotorno et al., 2014; Straube & Deubel, 1995). The influence of hemispheric specialisation, particularly the higher competence of the left hemisphere compared to the right in local processing (see Brederoo et al., 2019: Ivry & Robertson, 1998), may emerge in gain differences, with a gain closer to 1 when the target is in the LVF than when it is in the RVF. To examine this, Target Visual Field, Cue Type and ISI, and all their interactions were included as predictors in a LMM (Model 1.4) that examined gain when search was initiated toward the target object (43.9 % of the data included in the previous models). On average, first saccades undershot the target, with a mean gain of 0.720 ($SE = 0.009$), as would be expected given that first saccades tend to undershoot their targets (see Carpenter, 1988). Gain was higher following a pictorial cue ($M = 0.745$, $SE = 0.012$) than following a verbal cue ($M = 0.687$, $SE = 0.015$), $\beta = 0.024$, $SE = 0.007$, $t = 3.35$, $p < .001$. While there was no overall effect of target visual field, $\beta = -0.007$, $SE = 0.009$, $t = 0.753$, $p = .455$, the effect of ISI was significant, $\beta = 0.018$, $SE = 0.008$, $t = 2.19$,

$p = .038$, with higher gain following a short ISI ($M = 0.739$, $SE = 0.012$) than following a long ISI ($M = 0.695$, $SE = 0.015$), and was qualified by a significant interaction with the target visual field, $\beta = 0.018$, $SE = 0.007$, $t = 2.57$, $p = .011$ (Fig. 4). Pairwise comparisons showed that following a 100-ms ISI, targets in the LVF and RVF were saccaded to with equal gain, $t = 1.08$, $p = .282$, while following a 900-ms ISI, gain was higher for saccades directed toward targets in the RVF ($M = 0.734$, $SE = 0.022$) than for those in the LVF ($M = 0.663$, $SE = 0.020$), $t = -2.08$, $p = .039$. Moreover, when saccading toward targets in the LVF, gain was higher after a 100-ms ISI ($M = 0.741$, $SE = 0.016$) than after a 900-ms ISI ($M = 0.663$, $SE = 0.020$), $t = 3.50$, $p < .001$, while when saccading toward targets in the RVF, gain was not different after a 100-ms or 900-ms ISI, $t < 1$, $p = .966$. Overall, the pattern for this interaction seems to be driven by the relatively low saccade gain toward targets in the LVF after a 900-ms ISI. No other effects were significant (all $ts \leq 1$, all $ps \geq 0.516$).

2.3. Discussion

This experiment aimed to understand the asymmetric contributions of the cerebral hemispheres to early eye guidance in real-world scene search, distinguishing these from left-to-right reading habits that promote a leftward bias (Kazandjian & Chokron, 2008). We focused on the first saccade within the scene to examine hemispheric involvement relative to the (contralateral) target before any spatial remapping. This study uniquely combined the lateralisation of the target, type of target cue (verbal or pictorial), and ISI duration (short or long) while examining both the direction and gain of the first saccade. This allowed us to explore various aspects of hemispheric functional specialisation concerning the format of target information and the temporal and spatial scales of information processing.

2.3.1. The first saccade in real-world scene search is not driven by an a priori motor bias

Despite equal probabilities of target placement in the left or right visual field (i.e. in the left or right half of the scene), we found a preference for starting search toward the left visual field. However, we found no evidence supporting an a priori motor bias as a key explanation for these findings; instead, several results suggested that the leftward preference was based on attention and information processing mechanisms. Notably, when the target was in the right visual field, the initial lateral preference reversed (i.e. there was a higher likelihood to launch the first saccade toward the right) following a pictorial cue, while no preference emerged following a verbal cue. This differs from the findings of Nuthmann and Matthias (2014) and Nuthmann and Clark (2023), who only used verbal cues and reported a leftward preference. Leftward first saccades were not overall faster than rightward first saccades, contrary to what would be expected with no, or very limited, information processing involved in first leftward saccades (e.g., Carpenter, 2012), and somewhat at odds with previous studies showing that shorter saccade latency predicted (Foulsham et al., 2018) or correlated with (Ossandón et al., 2014) the leftward bias. Moreover, the longer latencies we found for saccades directed toward the target are likely to reflect information processing involving matching the target template to scene information.

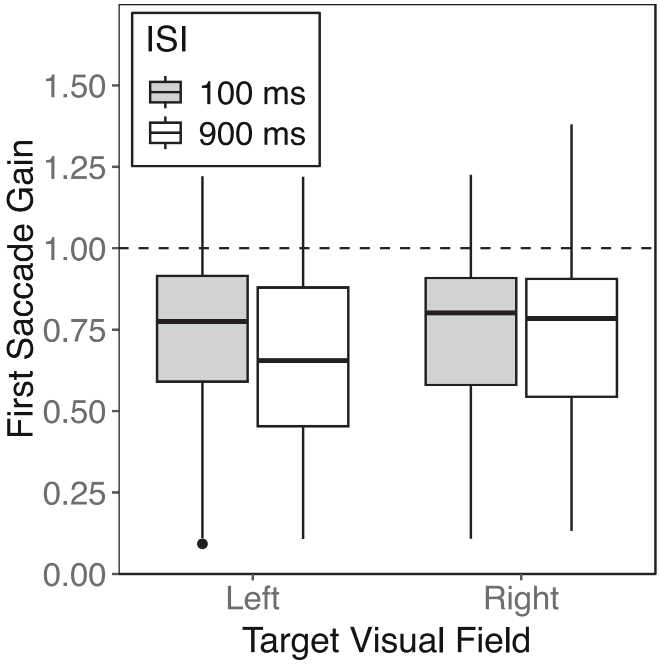

Fig. 4. Experiment 1. Gain of first saccades launched toward the target object, as a function of Target Visual Field and ISI. The box represents the interquartile range (IQR), the line inside the box indicates the median, and the whiskers extend to the minimum and maximum values (excluding outliers). The individual point below the whisker represents a trial outlier.

Participants initiated search toward the target with a probability greater than chance. The lateralised location of the target and how the target was cued were key factors influencing this probability, not whether participants initially saccaded leftward or rightward. We found a greater proportion of first saccades directed toward targets placed in the left visual field than toward targets placed in the right visual field following a verbal cue, while there was no difference between targets in either visual field following a pictorial cue. If the leftward lateral preference in scene search was driven by an a priori leftward motor bias, this would have, on the contrary, resulted in a lower proportion of first saccades being directed toward the target for leftward saccades than for rightward saccades, as rightward first saccades would likely arise from the suppression of the motor bias following detection of template-matching information within the right visual field.

2.3.2. The first saccade in real-world scene search is not driven by a general right hemisphere dominance for visuospatial information processing

Our results are better explained by hemispheric functional specialisation. If the overall right hemisphere dominance for visuospatial processes (see Corbetta & Shulman, 2011;Gainotti, 2014; Hellige, 1993) gave rise to leftward search initiation through greater covert (i.e. before saccading) attention in the left visual field, we would expect to find more first saccades into the left visual field than into the right, with shorter latencies (e.g., Foulsham et al., 2018; Ossandón et al., 2014; Reddi et al., 2003) and better accuracy. We did not find evidence supporting these predictions. Indeed, the gain of the first saccade was closer to 1 when saccading toward targets in the right visual field rather than toward targets in the left visual field. We did find a higher probability of directing the first saccade toward the target when it was in the left visual field than when it was in the right visual field, but (see 2.3.1) this was modulated by the type of cue and found only following a verbal cue. These results for first saccade accuracy cannot be explained by a general right hemisphere dominance for visuospatial processing. Moreover, we argue that the pattern for saccade direction is unlikely to have arisen from differences in task difficulty between the two types of cues, where the strong signal from target-relevant visual features with a pictorial cue would mask any initiation benefit from greater covert attention in the left visual field. Indeed, while we found that a pictorial cue, compared to a verbal cue, enhanced search initiation, with a higher probability of directing the first saccade toward the target and first saccade gain closer to 1 (see also Spotorno et al., 2014, 2015), the probability of directing the first saccade toward the target was far from ceiling level even with a pictorial cue, suggesting room for improvement from greater covert attention.

2.3.3. Finer hemispheric specialisation: hemispheric competencies for perceptual simulation explain the findings better than hemispheric competencies for pictorial and verbal processing

Our findings suggest that search initiation is guided by finer hemispheric functional specialisation in attention and information processing. However, contrary to one of our hypotheses, search initiation was not influenced by the traditional axis of specialisation related to information format: pictorial for the right hemisphere and verbal for the left (Gainotti, 2014; Hellige, 1993). Indeed, this should have resulted in (1) more frequent leftward initiation with pictorial cues and (2) more accurate initiation toward the left visual field with pictorial cues and toward the right visual field with verbal cues. However, the preferential rightward initiation with targets on the right after pictorial cues and the higher probability of saccading toward targets on the left after verbal cues contradict these predictions. Instead, they support our hypothesis regarding the impact of functional asymmetries in perceptual simulation, where the right hemisphere has a greater ability to generate perceptually-based representations from verbal stimuli (Gainotti, 2014), predicting object appearance and placement (Demiral et al., 2012; Lincoln et al., 2008; Norman & Peleg, 2023; Shibahara & Lucero-Wagoner, 2001; Vandenbulke et al., 2006; Wang et al., 2003; Zwaan & Yaxley, 2003). Previous work has highlighted the importance of reliable predictions during search initiation, particularly with abstract target templates generated from verbal cues, to guide visual search by narrowing feature and location selection (Eckstein et al., 2006; Spotorno et al., 2014, 2015; Wolfe et al., 2004; Wolfe et al., 2011).

2.3.4. Finer hemispheric specialisation: hemispheric competencies for global and local processing

When examining saccade probability, we considered whether the first saccade was directed toward a rather broad region (a 45° sector) containing the target object. Saccading to the target did not require a precise local representation but could be based on an oculomotor response to target-relevant features in a large scene region processed during the initial glance (Spotorno et al., 2014, 2015; Torralba et al., 2006). Thus, the left visual field advantage in this measure aligns with the right hemisphere's specialisation for global processing (see Brederoo et al., 2019; Ivry & Robertson, 1998), which may indeed emerge in early scene viewing (Mills et al., 2017; Peyrin et al., 2006). First saccade gain, measuring the proportion of the distance covered from the gaze start to the target centre (Miller et al., 1981; Spotorno et al., 2014; Straube & Deubel, 1995), reflects more local attentional and processing abilities. The better (closer to 1) gain for targets in the right visual field compared to targets in the left visual field is in line with the expected benefit due to the specialisation of the left hemisphere in local processing (see Brederoo et al., 2019; Ivry & Robertson, 1998). However, the lateral difference in gain depended on the ISI and the pattern of results suggested a disadvantage of the right hemisphere in this measure (which is also consistent with the lower competence of this hemisphere in local processing), depending on the timescale, rather than an advantage of the left hemisphere. We discuss this pattern in more detail in the following section.

2.3.5. Finer hemispheric specialisation: the time course of hemispheric involvement and proficiency in search initiation

We hypothesised that hemispheric involvement and proficiency over time would influence search initiation, varying with cue type. Specifically, we anticipated better initiation accuracy in the left visual field with a pictorial cue in the short (100-ms) ISI condition and better accuracy in the right visual field with a verbal cue in the long (900-ms) ISI condition. This was based on the hemispheric specialisation for pictorial (right hemisphere) and verbal (left hemisphere) information, with the right hemisphere processing better over shorter timescales and the left hemisphere over longer ones (Hellige, 1993). However, our results did not support this hypothesis. The probability of directing the first saccade toward the target did not depend on the ISI. We did find a lateral difference in first saccade gain toward the target dependent on the ISI, but this was not modulated by cue type. Overall, our gain result aligns with previous evidence on the temporal dynamics of hemispheric specialisation in attention and visual processing which, however, do not specifically affect processing of pictorial or verbal information. Indeed, the better (closer to 1) gain for targets in the right visual field than in the left appeared only with the long ISI, while with the short ISI we found no lateral differences. Crucially, the pattern was due to a lower gain in the left visual field with the long ISI compared to the short ISI, while gain in the right visual field was not influenced by the ISI. This suggests that increasing the delay between the offset of the target cue and the onset of the scene specifically disadvantages the right hemisphere, decreasing its ability to utilise target template information (arising from either a pictorial or verbal cue) to guide gaze near the target object. In other words, a target representation generated and retained over a longer timescale seems less suitable for the right hemisphere than for the left hemisphere. This is consistent with previous finding showing that the right hemisphere engages earlier than the left hemisphere in attentional processes (Corbetta & Shulman, 2002; Shulman et al., 2010; Thiebaut de Schotten et al., 2011) and object concept retrieval (Assaf et al., 2009), and shows decreased proficiency in matching object and scene representations over longer intervals (Spotorno & Faure, 2011). Moreover, saccadic gain being reduced (in the left visual field) or no different (in the right visual field) with a long ISI compared to a short ISI undermines the idea of suppression of an a priori motor bias, as such suppression would require more time for effective implementation and, therefore, should result in greater gain with the long ISI (Hill et al., 2010; Kuhn & Kingstone, 2009).

2.3.6. Conclusions from Experiment 1

Experiment 1 aimed to (1) distinguish between the extent to which the tendency to initiate search to the left reflects an a priori motor bias, driven by left-to-right reading habits or cerebral hemispheric specialisation, and, if there is a key contribution of the cerebral hemispheres to search initiation, (2) study whether this crucially depends on an overall visuospatial dominance of the right hemisphere or finer hemispheric specialisation in attention and information processing. Our argument that the findings from Experiment 1 reflect finer functional hemispheric specialisation relied on two key pieces of evidence arising from our analyses of the accuracy of the first saccade: (1) the finding that a greater proportion of first saccades was directed toward left-visual-field targets than right-visual-field targets, but only with a verbal cue, and (2) the finding that gain was closer to 1 when saccading toward right-visual-field targets than left-visual-field targets, but only for a longer ISI. The first of these key pieces of evidence was used to argue for the explanation involving finer hemispheric specialisation and against the idea of any relevant contribution of a leftward bias induced by reading habits. However, this argument only holds if we assume that the leftward bias from reading habits is merely a motor bias to saccade leftward after scene onset. An alternative interpretation of the bias related to reading habits might be that it is not only a motor bias but also an attentional bias (e.g., Bickel, 2024; Dickinson & Intraub, 2009; Eviatar, 1995; Rinaldi et al., 2014), promoting greater attention to the left visual field. If this is the case, then while the bias itself is information-independent (i.e., it exists independently of the content of the scene), the saccades influenced by it may instead be affected by information processing within the left visual field, following a covert, leftward shift of attention. According to this reasoning, our result regarding the lateral asymmetry in first saccade direction could alternatively be explained by an attentional bias related to reading habits after reading a verbal cue, even though the presentation time of the cue was not long enough to make eye movements during it. We, therefore, conducted a second experiment to test the potential reading-related attentional bias as an explanation for the lateralised differences in first saccade direction, and to test the robustness of the lateralised differences in first saccade gain found in Experiment 1.

3. Experiment 2

The first aim of this experiment was to determine whether a covert attentional bias toward the left visual field, driven by reading habits, could explain the finding from Experiment 1 that first saccades were more frequently directed toward targets in the left visual field than targets in the right visual field, but only following a verbal cue. To investigate this, we compared visual verbal cues, which may enhance the influence of reading habits during early inspection of the following scene, with auditory verbal cues, which do not involve reading and, therefore, should not promote such a bias. If the finding for first saccade direction observed in Experiment 1 was due to an attentional bias from reading words before the scenes appeared, we would expect to replicate this result mainly or solely with visual verbal cues in Experiment 2. Conversely, if the finding was related to a right hemisphere specialisation in perceptual simulation of word referents, as we argued in Experiment 1, we should replicate the left visual field advantage with either type of cue. Moreover, a leftward attentional bias from reading habits could result in a higher likelihood of the first saccade being directed toward the target following a visual verbal cue when examining either whether the saccade was directed toward the left or right visual field or whether the target object was in the left or right visual field. In Experiment 2, we tested both possibilities. Additionally, analysing the probability of directing the first saccade toward the target as a function of the whether the left or right visual field is saccaded to allowed us to distinguish between an attentional and motor bias from reading habits. A purely motor bias should lead to a lower proportion of first saccades toward the target when the left visual field is saccaded to, especially with a visual verbal cue if reading habits influence search initiation.

The second aim of Experiment 2 was to assess the robustness of the finding that, with a longer ISI, gain was closer to 1 for first saccades directed toward targets in the right visual field compared to targets in the left visual field. The ISI manipulation in Experiment 1 tested the possibility of different time courses of hemispheric functional specialisation for processing pictorial versus verbal information. Our hypothesis was based on previous research that linked the pictorial cue advantage in search to working memory consolidation (Schmidt & Zelinsky, 2011). Thus, we manipulated the ISI between the cue and the scene, using durations from Spotorno and Faure (2011) who, in a change detection task, showed a right-hemisphere advantage with a short (100-ms) ISI and a relative left-hemisphere facilitation with a longer (900-ms) ISI. However, the expected interactions between target visual field, cue type and ISI were not found in Experiment 1. The lateral difference in saccadic gain was interpreted in the context of previous evidence on the temporal dynamics of hemispheric specialisation in attention and visual processing independently of whether the cue is verbal or pictorial. In Experiment 1, the ISI manipulation was specific to our unsupported hypothesis about the modulation of the target cue influence. However, hemispheric functional asymmetries may occur throughout cue processing, starting during presentation, not only post-disappearance. In Experiment 2, we did not manipulate the ISI but focused on providing similar encoding and consolidation conditions that led to the lateral difference for first saccade gain in Experiment 1.

Auditory cues provide different encoding and consolidation opportunities and timescales than visual word cues. The entirety of a verbal label is shown on the screen at once and can be encoded quickly (Faure & Blanc-Garin, 1994; Hoyau et al., 2016; Potter & Faulconer, 1975), whereas auditory verbal cues take longer to present due to their sequential nature. An auditory verbal cue takes longer to present due to its sequential nature, making the brief 250-ms cue duration in Experiment 1 unfeasible for Experiment 2. However, encoding and consolidation of a verbal auditory stimulus begin soon after onset, with semantic processing effects evident at 100–200 ms post-onset (e.g., Chen & Spence, 2018; Kutas & Federmeier, 2011). Moreover, sufficient processing to influence eye-movement behaviour is shown at 200 ms post-onset based on phonological features and 400 ms based on semantic features (e.g., Allopenna et al., 1998). The concurrent processing of auditory cues during their presentation necessitates creating comparable Stimulus Onset Asynchrony (SOA) conditions, including cue duration, to those in Experiment 1 where lateral differences in saccadic gain emerged. Thus, we selected a 400-ms ISI in Experiment 2, making the SOA similar to the 900-ms ISI condition in Experiment 1 (see 3.1.4 for details). If the findings from Experiment 1 regarding first saccade gain robustly reflect hemispheric functional differences, Experiment 2 should replicate the same pattern of gain being closer to 1 for targets in the right visual field, irrespective of whether the verbal cue is visual or auditory.

Experiment 2 also examined lateral differences in search initiation with a larger sample and a different set of scene images and target objects, adding further control over any influence of our experimental materials and ensuring that our findings were not specific to the images used.

3.1. Method

3.1.1. Participants

Given that we were following up effects found in Experiment 1 for verbal cues, where guidance was less strongly toward the target object for the first saccade, we anticipated smaller effects and so sought to recruit a larger sample of participants. With again eight versions of the experiment for full counterbalancing, we aimed for a minimum of four participants per version. We tested five per version and were able to collect good quality eye-tracking data from all of these recruited participants. Therefore, our sample comprised 40 native English-speaking participants (17 males, age: $M = 23.3$, $SD = 4.6$, range = 18–30), all with solely left-to-right reading habits. All participants reported normal or corrected-to-normal visual acuity, normal colour vision and no history of neurological disease. According to the Edinburgh Handedness Inventory (EHI) (Oldfield, 1971), 34 were right-handed (laterality quotient >40) and six were ambidextrous (laterality quotient comprised between 40 and − 40). Participants took part on a voluntary basis and received course credits for their participation. They all gave informed consent. The study was approved by the local ethics committee and was in accordance with The Code of Ethics of the World Medical Association (Declaration of Helsinki).

3.1.2. Apparatus

Experimental sessions were carried out on an Asus SilverStone computer running OS Windows 7 Professional. Visual stimuli were shown on a BenQXL2420Z screen, 53.2 × 30 cm, with a resolution of 1920 × 1080 pixels, and a refresh rate of 120 Hz, while auditory stimuli were presented via two speakers, one on either side of the screen, adjusted to the same volume for each participant. Viewing was binocular, but only the dominant eye was tracked with an EyeLink 1000 (SR Research, Canada), at a sampling rate of 1000 Hz. A chin and forehead rest stabilised the eyes 72 cm away from the display. A computer keyboard was used for manual responses. Stimulus presentation and response recording were controlled by Experiment Builder (SR Research, Canada).

3.1.3. Materials

Sixty-four full-colour photographs (1440 × 1080 pixels, 30.4 × 22.8°) of real-world scenes (outdoor and indoor, natural and manmade), plus four for practice, were used. Scenes were taken from the SUN database (Xiao et al., 2010) or from Google Images. All image manipulations were made using Adobe Photoshop CS5 (Adobe, San Jose, CA). Fourteen unique objects were taken from the Hemera Images database (Hemera Technologies, Gatineau, Canada), the MIT Object Categories database (Konkle et al., 2010) or Google Images and were placed, widely distributed, into each scene. To better control the influence of specific scene/target object pairings, two objects included in the left or right half of each scene were selected as the potential targets. The assignment of which object served as the target was counterbalanced between participants (note: the practice scenes had only one possible target object). Two versions of each scene, original and mirrored, were created to counterbalance the visual field (left or right) that each potential target object appeared in across the experiment.

Target cues were the name of the target object, presented either in written format (font: Times New Roman, colour: black, font size: 54, no capital lettering) or spoken format recorded by a male native English speaker with Received Pronunciation and then edited using Audacity for precise start and end timing. The cues varied in length from three to 17 letters ($M = 7.42$, $SD = 3.36$) and comprised one (92 cues), two (35 cues) or three (one cue, "hot air balloon") words. The written word(s) subtended a range of 1.94–5.97° in width and 0.57–2.47° in height, and were displayed on a white background as in Experiment 1. To provide participants with both visual and auditory stimuli in each trial during the cue presentation, we also created a visual noise configuration consisting of nine hashtag symbols (i.e. *#########*, in black, matching the font and font size of the written word cues) for trials with auditory target cues, and an auditory stimulus of pink noise for trials with visual target cues.

3.1.4. Procedure

The experiment was conducted individually in a quiet, dimly illuminated room. Calibrations and validations of eye-movement recording before starting the experiment and the single-point calibration check before each trial were performed as in Experiment 1. We used a white background during the single-point calibration check and all the trial sequence. The trial started with a verbal target cue, presented either auditorily or visually. Auditory cues were presented simultaneously to both ears for of an average 655 ms (SD = 188 ms, range = 316–1175 ms), while the string of hashtag was presented in the centre of the screen for the same duration. Visual cues were presented for a similar duration to the average auditory cue (700 ms) in the centre of the screen, while auditory pink noise was presented for the same duration. To create similar SOA conditions compared to those in Experiment 1 with longer SOA, a 400-ms ISI with the presentation of a black central fixation cross, followed either an auditory or visual cue; this created an average SOA of 1055 ms for auditory cues and a SOA of 1100 ms of visual cues (the SOA was 1150 ms in Experiment 1 with the longer ISI). The scene then appeared, and participants searched for the target object, responding as soon as it was located by pressing the spacebar on the computer keyboard with both index fingers simultaneously. As in Experiment 1, a simultaneous response with both hands was required to avoid the predominant involvement of one hemisphere in planning and executing the action. Moreover, to minimise any stimulus/response spatial compatibility effect, we asked participants to position both index fingers in front of them, on the midsagittal plan. The experiment had a 2 (Cue Type) x 2 (Target Visual Field) repeated-measure design. Half of the targets were cued with a visual cue while the other half were cued with an auditory cue, and half of the targets were presented in the left visual field (LVF) while the other half were presented in the right visual field (RVF). All experimental factors were counterbalanced between participants, as were the specific target object cued within the scene and the orientation of the scene presented. The scenes were presented in a random order. Each participant saw only one occurrence of each scene, thus the experiment overall consisted of 64 experimental trials (16 per condition), plus four as practice, and lasted for approximately 30 min.

3.1.5. ROI definition and data analysis

As in Experiment 1, a ROI was defined for each target object as the smallest fitting rectangle that encompassed the target. The first saccade in each trial was scored as being directed toward a specific target ROI if its angular direction (from the saccade's starting position near the centre of the screen) was within 22.5° of the angular direction to the centre of the ROI, and landing on the target when its landing point was at least within 0.5° from the ROI's boundary. The target object ROIs subtended a range of 0.97–8.07° in width and 1.07–8.07° in height and had a mean size of 12.91 deg^2 ($SD = 9.23$), occupying on average 1.86 % of the scene ($SD = 1.33$). The eccentricity of the target object ROIs from the centre of the scene, along the horizontal axis, was between 4.81° and 12.3° (M = 9.15, SD = 1.56) considering the centre of the target ROI and between 2.54° and 11.1° (M = 7.29, SD = 1.84) considering the nearest edge of the ROI. Along the vertical axis, target ROI centres varied from 9.47° below the midline to 9.53° above the midline (M = 0.75° below the midline, SD = 5.84°).

We used the same data analysis techniques and procedures as in Experiment 1, focusing on search initiation, with the exception that only measures of saccade accuracy for search initiation were included, as this experiment aimed to replicate the key results for first saccade accuracy found in Experiment 1, and extend our understanding of the contribution of the cerebral hemispheres to search initiation. See Supplementary Materials to access the data in the Open Science Framework repository, the list of variables included in the dataset and the analysis code. In Experiment 2, the presence or absence of an effect of the interaction between the visual field and the type of target cue is key for our theoretical interpretation of the findings. Evidence of an attentional bias promoted by reading the visual verbal label will be provided if this interaction is significant in the models below. However, it is also important for our interpretation to evaluate the strength of evidence of an absence of this interaction if it is not significant in the models, because this provides evidence that our findings cannot be explained by an attentional bias promoted by reading the visual verbal label. Therefore, if no significant effect of this interaction is found in the models below, we calculate Bayes Factor to assess the strength of evidence for the absence of the interaction (i.e. BF_{01}). This was calculated from the Bayesian Information Criterion (BIC) of models with and without the interaction included as a fixed effect, where $BF_{01} = \exp.(-0.5[BIC(Model\ with\ interaction) - BIC(Model\ without\ interaction)])$.

We employed the same eye-movement data quality criteria for calibration as in Experiment 1 and no trials needed to be removed. The average calibration error was 0.23° (SD = 0.06°, min = 0.12°, max = 0.40°) for the mean error across all nine calibration points and 0.42° (SD = 0.10°, min = 0.24°, max = 0.79°) for the maximum calibration error on any one of the nine points. The single-point calibration check at the start of the trial indicated an average error of 0.29° (SD = 0.13°, min = 0.01°, max = 0.96°). We excluded trials in which participants did not maintain fixation within a radius of 1.5° from the screen's centre when the scene appeared (13.1 % of the overall data). As in Experiment 1, we

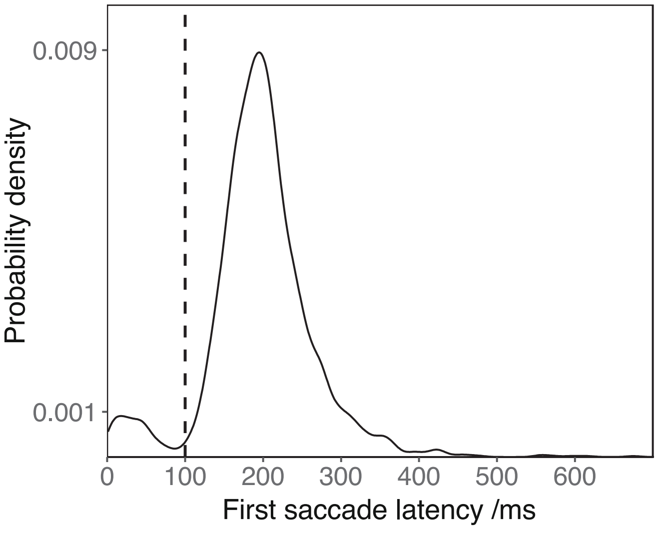

Fig. 5. Experiment 2. Density plot of first saccade latency. As in Experiment 1, there is a distinct subpopulation of very short latency saccades. For consistency with Experiment 1, saccades with latencies up to 100 ms (as indicated by the dashed line) were removed from subsequent analyses.

excluded the subpopulation of very fast first saccades (9.40 % of the remaining data) with latencies up to 100 ms (Fig. 5) and longer latency first saccades with an amplitude up to 1° (a further 0.58 % of the data). Overall, 18.8 % of the raw data was removed from search initiation analysis because of all the exclusions described above. The structure of each LMM and GLMM used, after any necessary simplification due to singularity and convergence issues, is reported in Supplementary Materials, where we also provide an analysis of the scene scanning phase of search.

3.2. Results

We examined whether a general lateral preference in the direction of the first saccade was present. A one sample *t*-test (two-tailed, test value = 50 %) showed that significantly more saccades were directed to the LVF (62.3 %) than to the RVF, $t(39) = 4.96$, $p < .001$. The following LMMs/GLMMs analyse what factors modulated this leftward preference.

Overall, as in Experiment 1, the probability that the first saccade landed within the target ROI was low ($M = 0.125$, $SE = 0.007$) and so this behaviour was not modelled. We found that the probability that the first saccade was directed toward the target was higher than chance (overall $M = 0.285$, $SE = 0.009$), $t(39) = 11.64$, $p < .001$, with chance calculated, as in Experiment 1, from the baseline suggested by Clarke and Tatler (2014) in order to account for biases in the directions in which saccades are initiated.

We first modelled whether the probability of directing the first saccade toward the target depended on the visual field into which the saccade was launched and whether there was any influence of the type of target cue. These two factors and their interaction were entered as predictors in the GLMM (Model 2.1). No effect was significant: the proportion of first saccades directed toward the target was not influenced by whether the first saccade was launched into the LVF or RVF, $\beta = 0.090$, $SE = 0.063$, $z = 1.43$, $p = .152$, cue type, $\beta = 0.004$, $SE = 0.058$, $z < 1$, $p = .950$, or their interaction, $\beta = -0.011$, $SE = 0.059$, $z < 1$, $p = .847$. There was very strong evidence for the absence of an effect of the interaction ($BF_{01} = 44.9$).

To examine the role of target location in lateral asymmetries of search initiation, we first ran one-sample *t*-tests (test value = 50 %) to analyse whether the overall tendency to initiate search with a leftward saccade persisted even when the target was in the RVF. We found that this was the case (58.6 % leftward first saccades overall, $t(39) = -2.92$, $p = .006$); however, the effect was significant only when the cue was visual (59.9 % leftward, $t(39) = 3.36$, $p = .002$), while it showed a strong tendency toward significance, $t(39) = 2.01$, $p = .052$) with an auditory cue (57.2 % leftward).

To consider the possibility that the tendency to saccade more frequently to targets placed the left visual field following a verbal cue in Experiment 1 arose from an attentional bias promoted by reading a word (the visual verbal cue) on the screen, we modelled the probability of directing the first saccade toward the target as a function of the Target Visual Field, Cue Type and their interaction, which were entered as predictors in the GLMM (Model 2.2). A greater proportion of first saccades was directed toward the target when it was in the LVF ($M = 0.36$, $SE = 0.015$) than when it was in the RVF ($M = 0.21$, $SE = 0.013$), $\beta = 0.450$, $SE = 0.085$, $z = 5.32$, $p < .001$ (Fig. 6). The effects of the cue type, $\beta = -0.015$, $SE = 0.054$, $z < 1$, $p = .779$, and the interaction between the target visual field and the cue type, $\beta = -0.011$, $SE = 0.057$, $z < 1$, $p = .844$, were not significant. There was very strong evidence for the absence of an effect of the interaction ($BF_{01} = 57.5$).

To test the replicability of the laterality difference in first saccade gain found in Experiment 1, we entered Target Visual Field, Target Cue and their interaction as predictors in the LMM (Model 2.3) for saccades launched in the direction of the target (28.5 % of the data included in Model 2.1. and Model 2.2). On average, and as expected (see also Experiment 1; Carpenter, 1988; Spotorno et al., 2015; Zelinsky et al., 1997), first saccades undershot the target, with a mean gain of 0.697 (*SE*

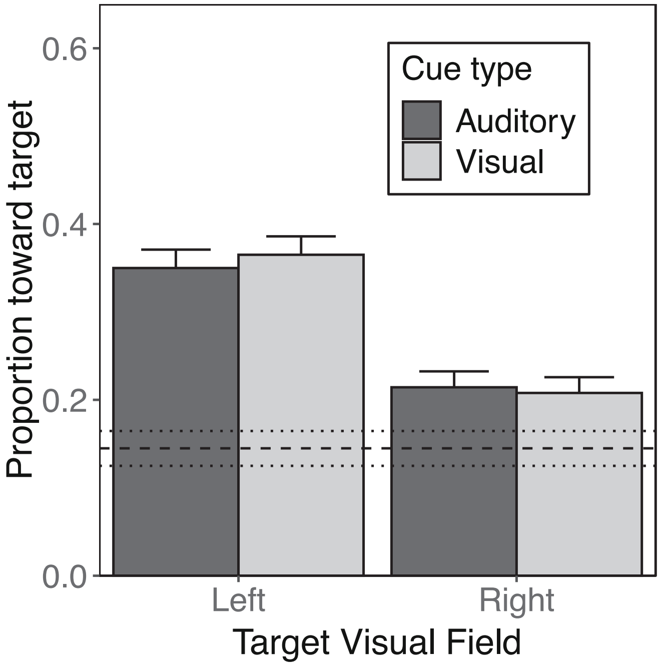

Fig. 6. Experiment 2. Proportion of first saccades directed toward the target object, as a function of the Target Visual Field and the Cue Type. The dashed line indicates chance level (0.145), computed by simulating 10,000 saccades on each trial using the baseline distribution suggested by Clarke and Tatler (2014), with dotted lines showing ±1 SD across scenes. Thus, this shows the chance of saccading toward the target given oculomotor biases when viewing images of natural scenes. Bars show condition means +1 SE. Note that the interaction between Target Visual Field and Cue Type in Experiment 2 was not significant, but it is shown for comparisons purposes with Experiment 1.

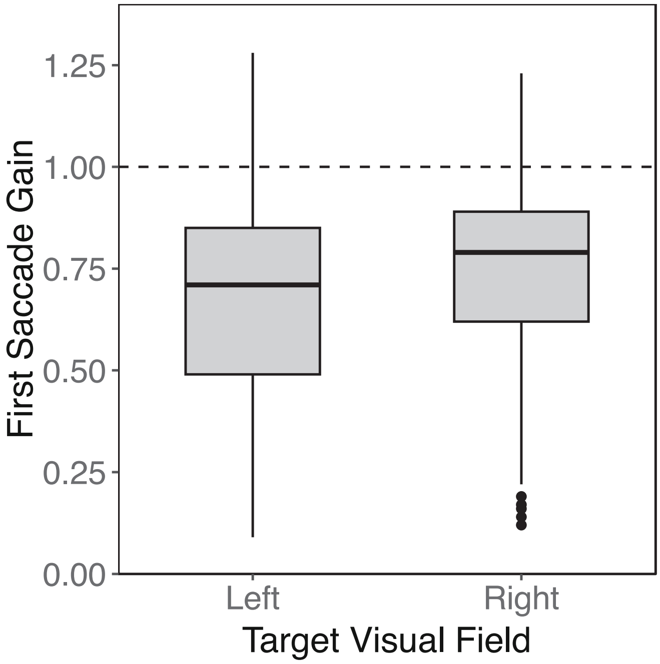

Fig. 7. Experiment 2. Gain of first saccades launched toward the target object, as a function of Target Visual Field and ISI. The box represents the interquartile range (IQR), the line inside the box indicates the median, and the whiskers extend to the minimum and maximum values (excluding outliers). The individual points below the whisker represent trial outliers.

$= 0.009$). Gain was higher when the target was in the RVF ($M = 0.741$, $SE = 0.015$) than when it was in the LVF ($M = 0.672$, $SE = 0.0.12$), $\beta = -0.023$, $SE = 0.010$, $t = -2.21$, $p = .035$ (Fig. 7). The effects of the cue type, $\beta = -0.011$, $SE = 0.008$, $t = -1.28$, $p = .200$, and the interaction between the target visual field and the cue type, $\beta = 0.002$, $SE = 0.008$, $t < 1$, $p = .853$, were not significant. There was extreme evidence for the absence of an effect of the interaction ($BF_{01} = 1148.3$).

3.3. Discussion

The aims of Experiment 2 were to replicate key findings from Experiment 1 regarding first saccade accuracy (direction and gain) and to assess whether first saccade direction was significantly influenced by an attentional bias from reading habits in the verbal cue condition of Experiment 1. To examine this, we compared visual verbal cues to auditory verbal cues.

The overall preference for initiating search to the left, observed in Experiment 1, was also found in Experiment 2. However, while in Experiment 1 search initiation was equally likely in either direction when the target object was in the right visual field and cued with a visual, verbal label, in Experiment 2 the leftward preference emerged under this condition (with also a strong trend toward significance for auditory, verbal cues), marking the only discrepancy between the experiments. This leftward initiation preference in Experiment 2 even with a right visual field target aligns with prior findings (Nuthmann & Clark, 2023; Nuthmann & Matthias, 2014) and might explain the numerically lower proportion of first saccades directed toward the target in Experiment 2 (0.28) compared to Experiment 1 with verbal cues (0.38). Nevertheless, the first saccade in Experiment 2 was guided by target object information, evidenced by the greater-than-chance probability of initiating search toward the target and average first saccade gain being closer to 1 (0.72) compared to Experiment 1 (0.69).

The three models of first saccade accuracy in Experiment 2 replicated findings from Experiment 1 for first saccade direction with a visual verbal template and gain, despite differences in scenes, target objects, and a larger participant sample. As in Experiment 1, the probability of initiating search toward the target depended on the target object's lateralised placement, suggesting that early differences in processing related to the object were the key drivers. A greater proportion of first saccades was directed toward the target when it was in the left visual field, regardless of whether the verbal cue was visual or auditory. This indicates that any triggering of reading habits from reading the verbal cue did not translate into a greater attentional leftward bias in early search. Moreover, these findings do not show any support for a merely motor leftward bias promoted by reading habits, as this should have led to fewer leftward saccades directed toward the target.

In Experiment 2, as in Experiment 1 with a long ISI, saccades toward targets in the right visual field had a gain closer to 1 than those toward targets in the left visual field, regardless of cue modality. This opposes the expectation of a leftward attentional bias from reading habits, which would have resulted in a gain closer to 1 in the left visual field, especially after reading the cue. Instead, the results suggest that the left hemisphere is more proficient than the right in guiding gaze closer to the target object, which requires finer local target information processing. This finding aligns with the local (left hemisphere) versus global (right hemisphere) specialisation related to spatial scale processing (see Brederoo et al., 2019; Ivry & Robertson, 1998). The time for processing the search cue before scene onset in Experiment 2 was comparable to the long ISI condition in Experiment 1 (around 1 s). This reinforces our interpretation of the gain results that a relatively extended timescale to generate and maintain the target template disadvantages the right compared to the left hemisphere, and this specifically impacts hemispheric differences in the ability to match the template with the local scene information. Therefore, this further corroborates the notion arising from the literature that the left hemisphere is better suited than the right for processing over longer timescales (e.g., Hellige, 1993; Spotorno & Faure, 2011).

The results from Experiment 2 show no evidence that reading the verbal cue promotes a leftward attentional bias that guides search initiation. Such a bias should have led to interactions between cue modality (visual or auditory) and target visual field, which were not found; indeed, we found strong evidence for their absence. This suggests that reading habits were not the key determinant first saccade accuracy. Moreover, even if hearing a word could trigger a reading-habit-based attentional bias due to it being a form of verbal cue, it is unlikely as an explanation for our findings given the first saccade gain results in both experiments. In summary, the replication of first saccade direction and gain effects in Experiment 2 supports the reliability of these effects. This strengthens our claims that search initiation is driven by functional asymmetries of the cerebral hemispheres rather than reading habits. It also strengthens our argument against the notion that search initiation is driven by a general right hemisphere dominance in the visuospatial domain, which should have led to better initiation accuracy in the left visual field for both first saccade direction and gain, independent of cue modality.

4. General discussion

Understanding guidance of real-world scene viewing from an early stage may reveal fundamental mechanisms of the brain proficiency in making sense of our surroundings quickly and from the limited information available initially (see Fabre-Thorpe, 2011). This early understanding is the foundation upon which subsequent viewing behaviour is shaped. A key characteristic of early scene viewing is that viewers show a lateral preference, usually starting by saccading into the left side, at least in Western cultures where the phenomenon has been mainly studied (e.g., Afsari et al., 2016; Afsari et al., 2018; Dickinson & Intraub, 2009; Foulsham et al., 2013; Foulsham et al., 2018; Hartmann et al., 2019; Nuthmann & Clark, 2023; Nuthmann & Matthias, 2014; Ossandón et al., 2014). Across two experiments, we examined the possible mechanisms underlying this preference and evaluated their impact on how viewers initiate search for a target object within a scene, a fundamental everyday task. To this purpose, in both experiments, we lateralised the target object in either left or right half of the scene, thus initially presenting it in the left or right visual field, thereby directing its information selectively to the contralateral cerebral hemisphere. We also manipulated the type of target cue (format: pictorial versus verbal, in Experiment 1; modality: visual versus auditory, in Experiment 2), and the time between the cue and the scene (Inter-Stimulus Interval, ISI: short / 100 ms versus longer / 900 ms, in Experiment 1). We analysed latency, direction and gain of the first saccade within the scene, which, due to target lateralisation, could be used to characterise the possible role of hemispheric contributions to search initiation.

Previously, the initial leftward preference in scene viewing has been explained in terms of a bias related to left-to-right reading habits in Western cultures (see Kazandjian & Chokron, 2008) or a functional dominance of the right hemisphere in the visuospatial domain (see Gainotti, 2014; Hellige, 1993) that would lead to an attentional bias to the left (i.e., contralateral) side of space (Kinsbourne, 1974; Reuter-Lorenz et al., 1990). We evaluated evidence for these two explanations by examining different underlying mechanisms associated with each, and investigated whether, instead, finer functional specialisation of the cerebral hemispheres in information processing may better explain the early lateral preference.

4.1. A reading bias?

As possible mechanisms underlying an effect of reading habits on the first saccade in scene search, in Experiment 1 we considered the possibility of an a priori motor bias to saccade leftward when the scene appears, independently of its visual content. The findings did not support this possibility: there was a greater (and higher than chance) probability of saccading toward the target when it was placed in the left visual field than when it was placed in the right visual field. This pattern, replicated in Experiment 2, differs from that predicted by an a priori leftward motor bias, which would likely result in first saccades being directed toward the target no more often than expected by chance. Moreover, such a leftward motor bias, not requiring any evaluation of scene information, would likely result in quicker search initiation toward the left visual field. However, we did not find any difference in first saccade latency depending on whether it was launched leftward or rightward.

In Experiment 2, we evaluated the possibility that reading habits induce a bias that is not merely motor but attentional, with greater covert (i.e., before the execution of the saccade) attention to the left visual field (Bickel, 2024; Dickinson & Intraub, 2009; Eviatar, 1995; Rinaldi et al., 2014), and that reading an object name on the screen just before the scene appears may promote this bias in search initiation. Indeed, this explanation could have accounted for the findings for first saccade direction toward the target in Experiment 1, where we showed that the greater probability of saccading toward the target in the left visual field emerged only when the target was cued by its written name (with no differences following a pictorial cue). We did not find evidence to support this possibility in Experiment 2, where we compared presenting the target verbal cue visually versus auditorily: the lack of any modulation of the lateral effects of whether the verbal cue was read on the screen or listened to was against the predictions from this attentional reading-habit-induced bias account. Thus, across the two experiments, we found no evidence to support – and indeed in places evidence in opposition to – the possibility that motoric or attentional mechanisms related to the habitual reading direction are the primary factors responsible for the lateral differences in search initiation that we found in our study.

4.2. *A general visuospatial dominance of the right hemisphere?*

Our consideration of the role of hemispheric functional specialisation included two broad possibilities: whether lateral differences in search initiation could be explained by a general right-hemisphere dominance for visuospatial processing (see Corbetta & Shulman, 2011; Hellige, 1993), or by more nuanced, finer hemispheric specialisation (see Brederoo et al., 2019). A general right-hemisphere visuospatial dominance, leading to greater cover allocation of attention to the left visual field followed by a leftward saccade, would predict better first saccade accuracy and shorter first saccade latency toward the left than toward the right visual field (Foulsham et al., 2018; Ossandón et al., 2014; Reddi et al., 2003). These effects should not be modulated by the type of target cue, or the time available to process it. The findings from Experiment 1 argued against any general right hemisphere visuospatial dominance as a key explanation for search initiation because, although saccades were more likely to be directed toward the target in the left visual field than in the right visual field, this was only found following a verbal cue. Moreover, first saccade gain was better (closer to 1) in the right than in the left visual field, and this pattern depended on the ISI in Experiment 1. Finally, we found no differences in latency for leftward versus rightward first saccades.

4.3. *Finer hemispheric specialisation in information processing during search initiation*

While our findings strongly suggest that reading habits and general right hemisphere visuospatial dominance are insufficient explanations for the mechanisms underlying the first saccade in scene search, they are consistent with search initiation being influenced by mechanisms related to finer hemispheric functional specialisation. Within this category of explanation, we considered four possible mechanisms through which finer hemispheric specialisation might operate.

First, we considered the possible role of differences in the overall competencies of the hemispheres for processing pictorial and verbal information (see Gainotti, 2014; Hellige, 1993). This explanation predicted that in Experiment 1 we should have found better first saccade accuracy in the left than in the right visual field after pictorial cues and, vice-versa, better saccade accuracy in the right than in the left visual field after verbal cues. However, we did not find this. In both experiments, contrary to this prediction, we found that following verbal cues a greater proportion of saccades were directed toward the target when it was in the left visual field than in the right. Also, the absence of lateral differences after pictorial cues in Experiment 1 suggests that both hemispheres were similarly proficient in directing the first saccade toward the target when its template was precise. Finally, while first saccade gain was closer to 1 in the right than in the left visual field in both experiments, this effect was not influenced by the cue format in Experiment 1.

A second possible manifestation of finer hemispheric specialisation that we examined was whether this involved functional asymmetries in perceptual simulation processes, with the right hemisphere being more proficient at generating a more specific representation of the target template information after a verbal cue than the left hemisphere, including visual and spatial aspects (e.g., Demiral et al., 2012; Gainotti, 2014; Lincoln et al., 2008; Norman & Peleg, 2023; Shibahara & Lucero-Wagoner, 2001; Vandenbulke et al., 2006; Wang et al., 2003; Zwaan & Yaxley, 2003). This explanation predicted better accuracy of first saccades after a verbal cue when the target was in the left visual field than in the right. Verbal cues, indeed, only provided the basic category of the object without any specific information about its visual features, making perceptual simulation highly beneficial for the task. No lateral differences were expected after a pictorial cue, which in our study was the exact image of the target as it would appear in the scene, meaning that no perceptual simulation of its visual features was required. We found the predicted pattern of results for first saccade direction, with a verbal cue in both experiments and with a pictorial cue in Experiment 1 (where we did manipulate the cue format). However, functional hemispheric specialisation in perceptual simulation, with higher proficiency of the right hemisphere, could not explain the findings for first saccade gain: we did not find the predicted interaction between visual field and cue format in Experiment 1, where gain was closer to one in the right than left visual field regardless of whether the target cue was verbal or pictorial, and in Experiment 2, where cues were always verbal, we replicated the right visual field advantage.

A third possible way in which finer hemispheric specialisation might underpin lateral differences in search initiation is through hemispheric differences related to the spatial scale of processing, with the right hemisphere specialised for global processing and the left hemisphere specialised for local processing (see Brederoo et al., 2019; Ivry & Robertson, 1998). If this were the case, we predicted that a higher proportion of first saccades should be directed broadly toward the target when it was in the left visual field than in the right. Indeed, in our study (as in, e.g., Spotorno et al., 2014, 2015) first saccade direction was a measure of rather global processing, considering a 45-degree sector of the scene. We found evidence to support this possibility in both experiments, although in Experiment 1 this – as discussed above – was only the case following a verbal cue. A second prediction of this account was about first saccade gain, which reflects more local processing of the target's position. We predicted that gain should be better (closer to 1) in the right visual field than in the left. The results of both experiments aligned with this prediction, although only after a longer ISI (see below) in Experiment 1. Thus, the results for both first saccade direction and gain supported the possibility that differences in global and local information processing between the hemispheres contribute to lateral eye-movement asymmetries in search initiation.

Note that Ossandón et al. (2014) reached the opposite conclusion, suggesting that hemispheric specialisation for global versus local processing was not important in early eye-movement guidance in scenes. This apparent discrepancy between our findings and theirs may arise from the fact that those authors only considered whether this axis of specialisation could explain the lateral preference in early free viewing in terms of proportion of saccades directed leftward or rightward within the scene, without considering any targeting of specific objects. They also equated global versus local processing with low versus high spatial frequency (LSF versus HSF) processing, studying viewing of filtered scenes. However, previous work has demonstrated that global versus local processing does not solely rely on different specific frequency bands but includes different attentional mechanisms (Chokron et al., 2000), and that findings on functional specialisation for global versus local processing are more robust than those for low LSF versus HSF processing (Brederoo et al., 2019). The Double Filter by Frequency (DFF) theory (Ivry & Robertson, 1998) posits a first stage in which information is selected by each hemisphere based on its task relevance and a second stage in which the selected information is filtered asymmetrically based on the preference for certain frequency bands (LSF for the right hemisphere and HSF for the left hemisphere). Lateral effects in behaviour would emerge from both these stages of processing. We suggest that these mechanisms may explain the mixed results in the literature depending on whether asymmetries are examined in filtered or unfiltered scenes.

A fourth possibility that we considered in the domain of finer functional specialisation of the cerebral hemispheres in scene search is that effects may be time dependent. More specifically, in Experiment 1, we considered previous research suggesting that the left hemisphere preferentially adopts language-mediated and analytical processing strategies, which are more time-consuming (Carpenter, 1981; Hellige, 1993). In contrast, the right hemisphere would more quickly engage attention (Corbetta & Shulman, 2002; Shulman et al., 2010; Thiebaut de Schotten et al., 2011) and activate semantic knowledge about objects (Assaf et al., 2009), while being less proficient in comparing representations over longer timescales (Spotorno & Faure, 2011). We integrated this previous evidence with findings showing that the scene search advantage from a precise, pictorial target cue over a verbal cue arises mainly on a short timescale (Vickery et al., 2005; Wolfe et al., 2004). We argued that this effect might depend on time modulations of the cerebral hemispheric specialisation in processing pictorial and verbal information. Therefore, we predicted that saccade accuracy would be better in the left visual field than in the right at a short timescale (100-ms ISI) following a pictorial cue and, vice-versa, in the right visual field than in the left at a longer timescale (900-ms ISI) following a verbal cue. We did not find evidence supporting the role of cue format over different timescales, but we did find evidence of differential involvement and proficiency of the hemispheres over time, in line with the literature. Importantly, in this respect, first saccade gain was better (closer to 1) in the right visual field than in the left with a long ISI in Experiment 1, with no lateral differences found with a short ISI. The gain advantage in the right visual filed was replicated in Experiment 2 at a comparably long timescale. However, there was no evidence supporting differential recruitment of the hemispheres over time from our analyses of first saccade direction. Overall, therefore, we found some support for the notion that differences in the involvement and proficiency of the cerebral hemispheres over time would have influenced search initiation, but not in the manner that we initially predicted. The overall pattern of temporal modulation suggests that a longer timescale to generate and retain a target template representation is less suitable for the right hemisphere than for the left hemisphere in order to match this template with local scene information.

5. Conclusions

This study advances understanding of the mechanisms driving initial viewing behaviour during real-world scene search. By examining the lateral differences in the first saccade within the scene, it challenges previous explanations of the leftward preference in initial viewing behaviour being based exclusively on reading habits (in the form of an a priori motor bias or attentional bias) or broad dominance of the right hemisphere for visuospatial processing. It demonstrates that these factors are insufficient to account for the observed patterns and provides a nuanced perspective of search initiation, where information is processed in both the left and right visual fields, and the lateral differences favour one side depending on what measure related to the first saccade is examined.

Our findings show that finer aspects of hemispheric specialisation in information processing are crucial. The right hemisphere’s proficiency in generating specific perceptual simulations from verbal cues appears to play a key role in directing the first saccade toward the target, at least when prior, detailed visual information about the target is lacking. Hemispheric functional asymmetries in global versus local processing and time-dependent modulations of hemispheric involvement and proficiency also influence early search. More specifically, the greater competence of the left hemisphere in processing local, detailed information in the scene seems important for guiding the first saccade closer to the target. On the other hand, the greater competence of the right hemisphere in processing more global aspects seems beneficial for directing the first saccade toward the area of the scene that includes the target, but less effective in bringing gaze closer to the target object, especially when the target template representation is generated and maintained over a longer timescale.

It is important to note that we do not argue that cerebral hemispheric specialisation contributes exclusively to guiding the first saccade during scene search, or during scene viewing in general. We focused on the first saccade because this is the one where we can fully control the information each hemisphere receives, before the scene is remapped during eye movements. Moreover, as viewing progresses, information from prior fixations may be accumulated (e.g., Hollingworth & Henderson, 2002; Tatler et al., 2005) and contribute to each decision to move the eyes (Hollingworth, 2009). Furthermore, as viewing progresses, there are greater opportunities for the hemispheres to share information, leading to an integrated representation of the scene. While the methodological approach of this study was not designed to study hemispheric contributions beyond the first saccade, this does not imply that functional hemispheric specialisation is irrelevant for guiding subsequent scene understanding and viewing behaviour.

Our study shows that the functional asymmetries of the cerebral hemispheres should be understood as a complex and flexible pattern of relative dominance. It highlights the need for examining specialisation while avoiding oversimplifications in terms of general dominance, which impede progress in understanding how the cerebral hemispheres contribute to representing our surroundings and guiding behaviour. Ultimately, these nuanced hemispheric contributions must be integrated into theoretical models of scene viewing to explain how the brain functions.

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CRediT authorship contribution statement

Sara Spotorno: Writing – review & editing, Writing – original draft, Visualization, Supervision, Software, Resources, Project administration, Methodology, Formal analysis, Data curation, Conceptualization. **Benjamin W. Tatler:** Writing – review & editing, Writing – original draft, Visualization, Supervision, Software, Resources, Project administration, Methodology, Formal analysis, Data curation, Conceptualization.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.cognition.2024.106009.

Data availability

The data and the analysis code are available in an OSF repository. The link to the repository has been included in the Supplementary Materials (Appendix A).

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