Moving Attention: Social and Nonsocial Attentional Orienting and Consequences of Shifts for Perception

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Declaration

This thesis contains no material which has been accepted for the award of any other degree or diploma in any university. To the best of my knowledge, it contains no material previously published or written by another person, except where due reference is made in the text.

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Abstract

Our visual environment is incredibly complex. This complexity underscores the importance of visual spatial attention as a triaging mechanism for selecting the locations in our environment that are to receive preferential processing. Attentional resources are constantly deployed via shifts of attention across space, or *attentional orienting*; this orienting response occurs when someone we are speaking with averts their gaze, when a visually salient event occurs, and during countless other everyday events. In studying attentional orienting, two equally important lines of investigation are the factors that affect responsiveness to attentional cues, and how shifting attention alters perception of stimuli at the attended location. The aim of this thesis was to examine outstanding, yet important, questions about these two important aspects of attentional orienting, using the spatial cueing paradigm to manipulate visual spatial attention.

The first part of this thesis examined factors that may affect responsiveness to attentional cues, with a specific focus on the orienting response triggered by social cues (e.g., gaze direction), and, at times, nonsocial cues (e.g., arrows). The first study in this section showed that orienting in response to gaze direction remains intact across levels of social anxiety, an individual-differences variable known to be associated with a range of attentional biases. The next study showed that a nonsocial motion signal equivalent in magnitude to a pupil shift is insufficient to elicit orienting, indicating that the social information contained in a dynamic gaze cue—which involves a pupil shift—is important for eliciting an orienting response. The final study in this section examined the efficiency of orienting by arrow cues, dynamic gaze cues, and static gaze cues, and found that while orienting by both types of gaze cues consistently survived a working memory load and therefore appears to be highly efficient, orienting by arrows was sometimes eliminated by a working memory load and therefore appears to be limited in its efficiency. Taken together, these findings speak to the robustness of the gaze-cueing effect, the importance of the social nature of the cue in generating the effect, and the remarkable efficiency of social orienting.

The second part of this thesis examined two outstanding issues regarding the perceptual consequences of attentional orienting. In view of some research indicating that involuntary attentional shifts can harm temporal resolution (i.e., the ability to perceive fine temporal detail), the first study in this section examined whether the effect is a true attentional effect, or the outcome of perceptual conflict between the cue and target. The study found evidence to support the latter account, indicating that there is no true effect of involuntary attentional shifts on temporal resolution. The final study of this thesis examined the effects of attention on naturalistic ensemble processing, which involves the visual system pooling local detail to construct a global percept of a scene. The study found no effects of attentional shifts on this process, indicating that naturalistic ensemble processing is remarkably efficient. Together, these results clarify existing ambiguities concerning the effects of attention on important aspects of perception.

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Chapter 1

Introduction

Thesis Rationale and Aims

It is almost impossible to imagine what our experience of the world would be like without attention: so critical is this mechanism for allowing us to selectively process the most relevant aspects of our visual environment. While there are different ways of allocating attention, one of which is resizing the scope of what we are attending to, a particularly useful form of attentional allocation is orienting—or shifting—our attentional resources from one location to another. This method of allocating attentional resources allows for the ongoing prioritisation of different elements of our environment as they become relevant. Consider a tourist standing in the middle of a crowded plaza. This tourist might shift their attention from one pedestrian to another, then from a particular pedestrian to a colourful billboard, and finally from that billboard to a food stall advertising a local delicacy. It is the aim of this thesis to address outstanding, yet critical, questions regarding the factors that affect responsivity to stimuli that can elicit such shifts of attention, as well as the perceptual consequences of these shifts.

As indicated by this aim, there are two important issues to consider when studying attentional orienting: the factors influencing how responsive we are to attentional cues, and the consequences of attentional shifts for our experience of the world. Concerning the first issue, a particularly important attentional cue is gaze direction: Attending to where someone else is looking can be extremely informative regarding important events occurring in the environment, as well as the gazer’s goals and intentions (Baron-Cohen, 1995). However, several factors may influence the capacity of such cues to guide attention, including individual differences, the specific characteristics of the gaze cue, and the demands placed on the individual while they are perceiving this information. Investigating the potential influence of these factors is critical in delineating the conditions under which individuals are responsive to important attentional cues of this kind.

Just as important as considering the factors that influence responsiveness to attentional cues is the question of what consequences attentional shifts have for perception. A large body of research has shown that attentional shifts can affect many aspects of *visual* perception specifically; for instance, numerous studies have shown that attention can enhance our ability to perceive fine spatial detail (e.g., Yeshurun & Carrasco, 1998, 1999), as well as our sensitivity to contrast (i.e., our ability to distinguish an object from its background; e.g., Carrasco et al., 2000). Such studies have been critical in shaping our understanding of how attention affects our experience of the visual world.

The first part of this thesis investigates factors that may influence responsiveness to attentional cues, with a particular focus on gaze cues. Specific aims were to examine whether responsiveness to gaze cues varies as a function of social anxiety measured in a nonclinical sample; to test whether a motion signal similar in magnitude to that in a dynamic gaze cue—that is, a cue containing a visible pupil shift—is sufficient to elicit attentional orienting; and to assess the efficiency of both nonsocial (i.e., arrow) and social (i.e., gaze) cues by seeing whether shifts of attention ordinarily elicited by such stimuli persist under secondary task demands. Together, these studies aim to further our understanding of the conditions under which different attentional cues can elicit shifts of attention.

The second part of this thesis focuses on two outstanding questions regarding the effects of attention on visual perception. The first aim was to test an alternative explanation for previous findings showing detrimental effects of attentional shifts on temporal resolution (e.g., Yeshurun & Levy, 2003): our ability to perceive fine temporal detail. The second aim was to address the controversial issue of whether attention modulates perception of naturalistic ensemble stimuli (i.e., collections of elements that the visual system summarises to form a single percept), given mixed evidence from previous studies. Together, the chapters in this section aim to add clarity to two key debates in the area of attention and visual perception.

Thesis Structure

Including the current chapter (Chapter 1), this thesis consists of ten chapters. In Chapter 2, I provide a general overview of attention, with a specific focus on the orienting of visual spatial attention and the factors that determine where it is guided. In Chapter 3, I then describe the characteristics of the spatial cueing paradigm (also known as the Posner cueing paradigm), the most commonly used method of manipulating shifts of attention and assessing their consequences, and the paradigm used in each empirical chapter of this thesis. In Chapter 3, I also discuss social orienting (i.e., orienting in response to gaze cues), since this process is either the sole or partial focus of Chapters 4, 5, and 6, which address the factors affecting responsiveness to attentional cues.

Chapter 4 examines the potential effect of social anxiety on the attentional response to gaze cues by seeing whether the magnitude of this response varies as a function of social anxiety, as measured in a nonclinical sample. Chapter 5 then assesses whether a motion signal that is similar in magnitude to that in a dynamic gaze cue, yet contains no social information, is sufficient to elicit an attentional shift. Chapter 6 goes on to examine the efficiency of orienting by a symbolic cue (an arrow), as well as different types of gaze cues (dynamic and static).

Chapters 7, 8, and 9 address the perceptual consequences of attentional shifts. In Chapter 7, I outline existing research on attention and visual perception for the purposes of contextualising the final two empirical chapters of this thesis. Following this overview, Chapter 8 examines an alternative account of purportedly attentional effects on temporal resolution: the spatiotemporal-confusion account. Chapter 9 goes on to examine the effects of attentional orienting on the processing of a global motion stimulus, a naturalistic ensemble.

Finally, in Chapter 10, I summarise the empirical findings of this thesis and discuss how they have advanced our understanding of both the factors that influence responsiveness to attentional cues and the perceptual consequences of attentional orienting. Throughout Chapter 10, I indicate directions for future research.

Thesis Format and Publication Details

Chapters 4, 8, and 9 were prepared as manuscripts for publication. Apart from stylistic changes made to ensure consistency across the thesis (e.g., the change from American spelling to Australian spelling in Chapter 9), the text in Chapters 4 and 9 is identical to that in the published versions of the manuscripts. For Chapter 8, which is currently under review, alterations from the submitted version of the manuscript were made following suggestions from reviewers. The publication status of each manuscript is indicated below.

Chapter 4: Published

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Candidate Contributions to Empirical Chapters

- Louisa Talipski proposed the project presented in each empirical chapter, with contributions from A/Prof Mark Edwards and A/Prof Stephanie Goodhew.
- Louisa Talipski designed the experiments, with contributions from A/Prof Mark Edwards and A/Prof Stephanie Goodhew. Coauthors Dr Amy Dawel and Emily Bell assisted with the design of the experiment presented in Chapter 4.
- Louisa Talipski programmed all experiments.
- Louisa Talipski collected the data for all experiments other than the experiment reported in Chapter 4, data for which was collected by coauthor Emily Bell; Experiment 5 in Chapter 6, data for which was collected by a research assistant, and Experiment 6 in Chapter 6, data for which was collected by undergraduate students.
- Louisa Talipski analysed the data for all experiments, with advice from A/Prof Mark Edwards, A/Prof Stephanie Goodhew, and, for Chapter 4, Dr Amy Dawel.
- Louisa Talipski drafted each empirical chapter, implementing changes suggested by A/Prof Mark Edwards, A/Prof Stephanie Goodhew, and, for Chapter 4, Dr Amy Dawel.

Chapter 2

Visual Spatial Attention

Chapter Overview

The purpose of this chapter is to provide a conceptual overview of visual spatial attention that is necessary for contextualising the empirical chapters of this thesis. I begin by describing the main functions and types of attention, before describing how the distribution of *visual spatial attention* can be modified through attentional-breadth resizing or a shift of the attentional locus across space, the latter being the focus of subsequent chapters. I conclude this chapter by discussing the factors that determine where attentional shifts are directed at any given moment.

Visual Spatial Attention

What Is Attention?

The concept of attention has intuitive appeal, as William James succinctly expressed when he wrote that “everyone knows what attention is” (James, 1890, p. 403). It seems true that most individuals know what it means to “pay attention” to an event or object, to experience a “lapse of attention,” and for an aspect of our environment to “grab our attention”. While the precise definition of attention has been a continuous source of debate among scholars, there appears to be some consensus regarding its main functions: Attention is a mechanism that selects a subset of the information we are confronted with at any given moment, and modulates processing of this selected fragment of information (Carrasco, 2011; Chun et al., 2011). In other words, stimuli in the environment compete for attentional resources, and processing of the stimuli that are ultimately selected by attention is modulated via the application of these attentional resources. The necessity of attention comes about from the brain’s limited processing capacity (Lennie, 2003)—there is simply too much information in the environment for us to be able to process it in its entirety, which underscores the need for a mechanism that can flexibly prioritise different aspects of the environment on an ongoing basis.

Countless studies have demonstrated the power of attentional selection. Early experiments on dichotic listening, where different auditory information is presented to each ear and individuals attend only to the information presented to one ear, showed that much of the information presented in the “unattended” stream was not reportable, having effectively been filtered out by attention (Broadbent, 1958; Cherry, 1953; Moray, 1959). Research on inattentional blindness shows that even a directly fixated, salient stimulus (e.g., a gorilla) can go unnoticed if an attentionally demanding task is performed at the time of its appearance (e.g., Mack & Rock, 1998; Simons & Chabris, 1999). Demonstrations of attention as a selective mechanism can also be found outside the behavioural domain; for instance, neurophysiological evidence from single-cell recordings shows that when two stimuli are presented within the receptive field of a neuron, the response of the neuron is driven primarily by the attended stimulus (e.g., Moran & Desimone, 1985), consistent with the notion that stimuli compete for selection (Desimone & Duncan, 1995). While unattended information does appear to undergo some level of processing—for example, observers can notice their own names being spoken in an unattended auditory stream (the “cocktail party effect”; Cherry, 1953; Moray, 1959)—these examples serve to demonstrate how effectively attention can select a fragment of information for preferential processing.

Examples of the *modulatory* functions of attention are just as ubiquitous: Attention, among other effects, speeds detection of stimuli (e.g., Posner et al., 1978), enhances different aspects of perception, such as contrast sensitivity and spatial resolution (e.g., Carrasco et al., 2000; Yeshurun & Carrasco, 1999), and even alters the appearance of stimuli (e.g., Carrasco et al., 2004). Correspondingly, a large body of evidence from neuroimaging, electrophysiology, and neurophysiology shows attention-related modulations of neural processes related to perception (e.g., Hopfinger & Mangun, 1998; Kastner et al., 1999; McAdams & Maunsell, 1999). These effects of attention on perception will be discussed more fully in Chapter 7 of this thesis.

While selection of information and modulation of processing appear to be defining functions of attention, attention is not unitary—that is, there are different *types* of attention. A useful “taxonomy” of attention was proposed by Chun et al. (2011). At the highest level of this taxonomy, a distinction is made between internal attention and external attention: Internal attention involves the selection and modulation of information represented in the mind (e.g., thoughts and emotions), while external attention involves the selection and modulation of information received by one of the five senses (i.e., vision, touch, taste, smell, and hearing). External attention can be deployed over space, over time, or to a modality itself; evidence for these modes of allocation comes from studies showing that individuals are generally quicker to respond to a stimulus when they know at which location in space (e.g., Posner et al., 1978), at which point in time (e.g., Coull & Nobre, 1998), or in which modality (e.g., Spence & Driver, 1997) that stimulus will appear.

When considering the deployment of attention over space, it is important to distinguish between spatial, feature-based, and object-based attention (Carrasco, 2011). Spatial attention involves the allocation of attentional resources over a region of space; for instance, an individual might attend to the left-hand side of visual space when they are driving down a highway, in anticipation of an upcoming exit sign. Feature-based attention involves the selection of a particular feature (e.g., a specific colour, orientation, or direction of motion); for example, if an individual is searching for their friend on a busy street and knows that their friend is likely to be wearing their favourite red coat, their attention might be directed to red stimuli. Object-based attention involves the selection of an entire object—for instance, a meal sitting on a waiter’s tray. Importantly, spatial-, feature-, and object-based attention interact. For example, one study found that when an object in a scene was cued (thereby eliciting object-based attention), processing of objects that were not cued, yet were perceptually or semantically (i.e., featurally) identical to the cued object, was facilitated; this effect extended to the surrounding regions of the uncued object, demonstrating an additional interaction with spatial attention (Kravitz & Behrmann, 2011). Therefore, while it is useful to distinguish between different types of attention, the aspects of our visual environment that ultimately receive preferential processing are determined by interactions between them.

This thesis is concerned with the deployment of attention to different regions of visual space—that is, *visual spatial attention.* Visual spatial attention is one of the most commonly studied forms of attention, and is regularly deployed to constrain the spatial region over which our limited processing resources are distributed. It is also known to be associated with a range of behavioural consequences (discussed further in Chapter 7 of this thesis). Importantly, the allocation of visual spatial attention is dynamic: It can be achieved through *resizing* to capture different amounts of visual information, or *orienting* (i.e., shifting) to select entirely different aspects of the visual environment.

Allocating Visual Spatial Attention: Resizing versus Orienting the Attentional Spotlight

Visual spatial attention is commonly thought of as a “spotlight” that encompasses a portion of the visual environment, and which can be moved around to select different spatial locations for preferential processing (Posner et al., 1980; Figure 1). An extension to the spotlight model acknowledges the capacity for this attentional spotlight to be resized—that is, expanded or contracted—akin to the zoom lens of a camera (Eriksen & St. James, 1986; Eriksen & Yeh, 1985). A broad distribution of attention allows for the gist of a scene (e.g., the rolling hills of a meadow) to be captured, while a relatively narrow distribution of attention allows for the processing of smaller aspects of a scene (e.g., a single blade of grass). This resizing comes with a perceptual trade-off: Broadening the spotlight allows for a relatively large amount of information to be attended at the expense of a detailed representation of that information, while contracting the spotlight means that less information is attended, but this information can be represented at a higher resolution (Balz & Hock, 1997; Castiello & Umiltà, 1990; Eriksen & St. James, 1986; Eriksen & Yeh, 1985; Lawrence, Edwards, &

Goodhew, 2020). While the spotlight and zoom-lens metaphors may be imperfect—because, for instance, attention can be allocated to noncontiguous locations (e.g., Müller et al., 2003)—they elegantly convey the selective nature of visual spatial attention; furthermore, a range of perceptual consequences are known to accompany resizing of the attentional spotlight (for reviews, see Goodhew, 2020; Lawrence, Edwards, Talipski, & Goodhew, 2020).

Figure 1

Movement of the Attentional Spotlight Across Space

Note. An individual observing this busy Tokyo scene may shift their locus of attention from the pink cap of the individual in front of them to the billboards on the left, and then to the sign of an eatery on the right. From *Busy street* [Photograph], by B. Fröberg, 2016, Flickr (https://www.flickr.com/photos/blondinrikard/26277584311). CC BY 2.0.

This thesis is concerned not with resizing the attentional spotlight, but with *orienting*—or *shifting*—the attentional spotlight across space (Figure 1). These shifts are critical for ongoing prioritisation of different aspects of the visual environment, and they can be executed either overtly or covertly—that is, with an accompanying eye movement, or without one (Posner, 1980). While we often attend to aspects of our environment simply by moving our eyes towards them (overt attention), there are situations in which it may be more appropriate or useful to attend to a stimulus without looking at it directly (covert attention). For instance, an individual mingling at a conference morning tea may be approached by someone they know they have seen before, but struggle to remember their name; in this instance, rather than looking directly at their nametag, a covert shift of attention could be deployed to make out the person’s name without causing offense. Beyond its utility in social situations, a further advantage of covert attention is that while eye movements can only be directed to one location at a time, covert attention can be distributed more broadly and to multiple locations (Carrasco, 2011). Some research has indicated a coupling between overt and covert orienting; for instance, there is evidence that it is impossible to covertly attend to one location while moving the eyes to another location (e.g., Hoffman & Subramaniam, 1995; but see Kowler et al., 1995; Smith & Schenk, 2012). Nevertheless, it becomes important to distinguish between these two forms of orienting when examining the effects of attention on perception, since in order to isolate the effects of attention on visual processes, controlling for the effects of eye movements to the target is imperative (see Chapters 7, 8, and 9 of this thesis, which examine the perceptual consequences of attentional orienting).

Factors Driving Attentional Selection

As discussed above, attention can be shifted across space to select different regions of the visual environment. But what factors determine where visual spatial attention is guided at any given moment? Traditionally, a distinction has been made between endogenous attention and exogenous attention. Endogenous attention (also referred to as voluntary, sustained, goal-driven, or top-down attention) is guided in accordance with goals; for example, an individual eagerly awaiting their coffee order might endogenously attend to the café’s barista. Exogenous attention (also referred to as involuntary, transient, stimulus-driven, or bottom-up attention) is guided automatically to a salient event in the environment—for example, the flashing lights of a police car. There are several key differences between endogenous attention and exogenous attention (for a review, see Chica et al., 2013). First, they differ in their time course, with endogenous attention taking longer to deploy than exogenous attention (Chakravarthi & VanRullen, 2011; Geweke et al., 2021; Keefe & Störmer, 2021; Müller & Rabbitt, 1989; Nakayama & Mackeben, 1989). Endogenous and exogenous attention have also been found to produce qualitatively distinct behavioural effects for some tasks, such as texture segmentation (e.g., Yeshurun et al., 2008). Finally, while there appears to be a large degree of overlap in the neural mechanisms subserving endogenous and exogenous attention (Corbetta et al., 2008; Peelen et al., 2004), some differences do exist; for instance, one region of the temporoparietal junction is associated with reorienting following endogenous, but not exogenous, attentional allocation (Dugué et al., 2018).

Although the distinction between endogenous and exogenous attention is widely accepted, it requires two qualifications. First, while they exert largely independent effects (e.g., Berger et al., 2005), endogenous and exogenous attention can interact. In a classic demonstration of this interaction, Folk et al. (1992) showed that an exogenous cue will fail to capture attention if it does not possess properties consistent with the goals of the participant (i.e., their “attentional control setting”); for example, if a target is defined by an abrupt onset, then abrupt onsets will capture attention in an exogenous fashion, but such attentional capture will fail to occur if the target is instead defined by colour. This shows that whether attention is exogenously allocated to a stimulus depends on endogenous attention, to the extent that endogenous attention involves the adoption of top-down control settings.

Second, in an influential paper, Awh et al. (2012) posited selection history as a third driver of attentional allocation, supplanting the decades-old dichotomy between endogenous and exogenous attention with a “trichotomy”. Selection history refers to lingering biases in selection that come as the result of past experience; for example, attention may be biased towards stimuli that have been previously rewarded (Failing & Theeuwes, 2018), or more readily allocated to targets presented in familiar stimulus configurations relative to unfamiliar configurations (“contextual cueing”; Chun & Jiang, 1998). Selection history cannot be fully subsumed by either the “endogenous attention” or the “exogenous attention” label, because while these biases in selection are learned—and therefore “top-down” in the sense that they stem from factors internal to the observer—they can be incompatible with current goals (Awh et al., 2012). Therefore, while the distinction between endogenous attention and exogenous attention is a common one and captures a key difference in the factors that drive attentional selection, it does not encapsulate all types of selection. Overall, Awh et al. argued that the three main drivers of attentional selection are current goals (which they view as one element of endogenous attentional allocation—see below for a note on terminology), physical salience (which they equate with exogenous attentional allocation), and selection history.

Altogether, current goals, physical salience, and selection history feed into a “priority map” of attention (Bisley & Goldberg, 2010; Fecteau & Munoz, 2006; Itti & Koch, 2001) that determines the ultimate target of selection—that is, the selected stimulus is the one that receives the most weight from the combined inputs of these three drivers of selection. To provide an illustrative example, a parent in a park might have the *current goal* of ensuring that their child is playing safely on the playground, and thus their child is “upweighted” in the priority map on this basis. However, they have recently taken up running, and as a result of their exposure to stimuli associated with the sport, a nearby group of runners is upweighted on the basis of *selection history*. One runner in particular is wearing a neon green shirt that stands out amongst the other runners’ grey shirts, and therefore this *physical salience* leads to an upweighting of this particular runner in the priority map. Considering the relative weighting of each aspect of this scene, the ultimate target of selection might be—despite the parent’s caregiving duties—the runner in the neon green shirt, as they have been upweighted on the basis of both selection history and physical salience. Therefore, each driver of selection contributes to determining which aspect of the visual environment is selected.

Before concluding this chapter, a note on terminology should be made. There has been some debate about what is meant by “endogenous,” or “top-down,” forms of selection. Awh et al. (2012) view endogenous attention as including any form of selection driven by the observer’s goals (see also Gaspelin & Luck, 2018; Sisk et al., 2018). This is why Awh et al. prefer to use the term “current goals” instead of “endogenous,” or “top-down,” attention; they argue that since endogenous attention encompasses selection driven by any kind of goal, the term does not distinguish between selection on the basis of current goals and selection on the basis of more implicit goals that come as the product of past experience (i.e., selection history). Other authors (e.g., Theeuwes, 2018) prefer to reserve the terms “endogenous” and “top-down” for referring to selection based specifically on current goals. Given the way endogenous and exogenous attention were defined earlier in this chapter, as well as how the terms have traditionally been used in the orienting literature, I adopt the latter use of the term “endogenous” when referring to endogenous attention in this thesis.

Summary

Our limited-capacity processing resources mean that it is simply impossible for us to process all elements of our visual environment to their full extent. Therefore, attention is key in prioritising certain aspects of the environment for preferential processing. Visual spatial attention allows us to prioritise certain regions of visual space, and is dynamically allocated through a resizing of the attentional spotlight or—as is the focus of this thesis—shifts of the attentional spotlight across space, which can be executed either overtly or covertly. Where attention is allocated at any given moment is dependent on current goals (endogenous attention), physical salience (exogenous attention), and selection history, which each feed into a priority map that determines the ultimate target of selection. In the next chapter, I will discuss how shifts of visual spatial attention can be studied using the spatial cueing paradigm (also known as the Posner cueing paradigm), and how this paradigm can be configured to study different forms of attentional orienting. In this chapter, I will also highlight the importance of considering the types of cues that elicit shifts of attention, with a particular focus on social cues. This discussion will be relevant to the subsequent empirical chapters of this thesis, which examine factors that may influence responsiveness to both social and nonsocial attentional cues.

Chapter 3

Spatial Cueing and Social Orienting

Chapter Overview

The purpose of this chapter is to explain how visual spatial attention is operationalised via the spatial cueing paradigm (also known as the Posner cueing paradigm), with a particular focus on the types of cues that can drive shifts of attention and therefore influence where attention is allocated at any given time. In the second half of this chapter, I focus on social cues—in particular, gaze cues—which have received considerable research attention over the last two decades. Each empirical chapter of this thesis utilises a variant of the spatial cueing paradigm to examine the factors affecting responsiveness to cues and the perceptual consequences of attentional shifts, and Chapters 4, 5, and 6 specifically address issues related to attentional orienting by social cues.

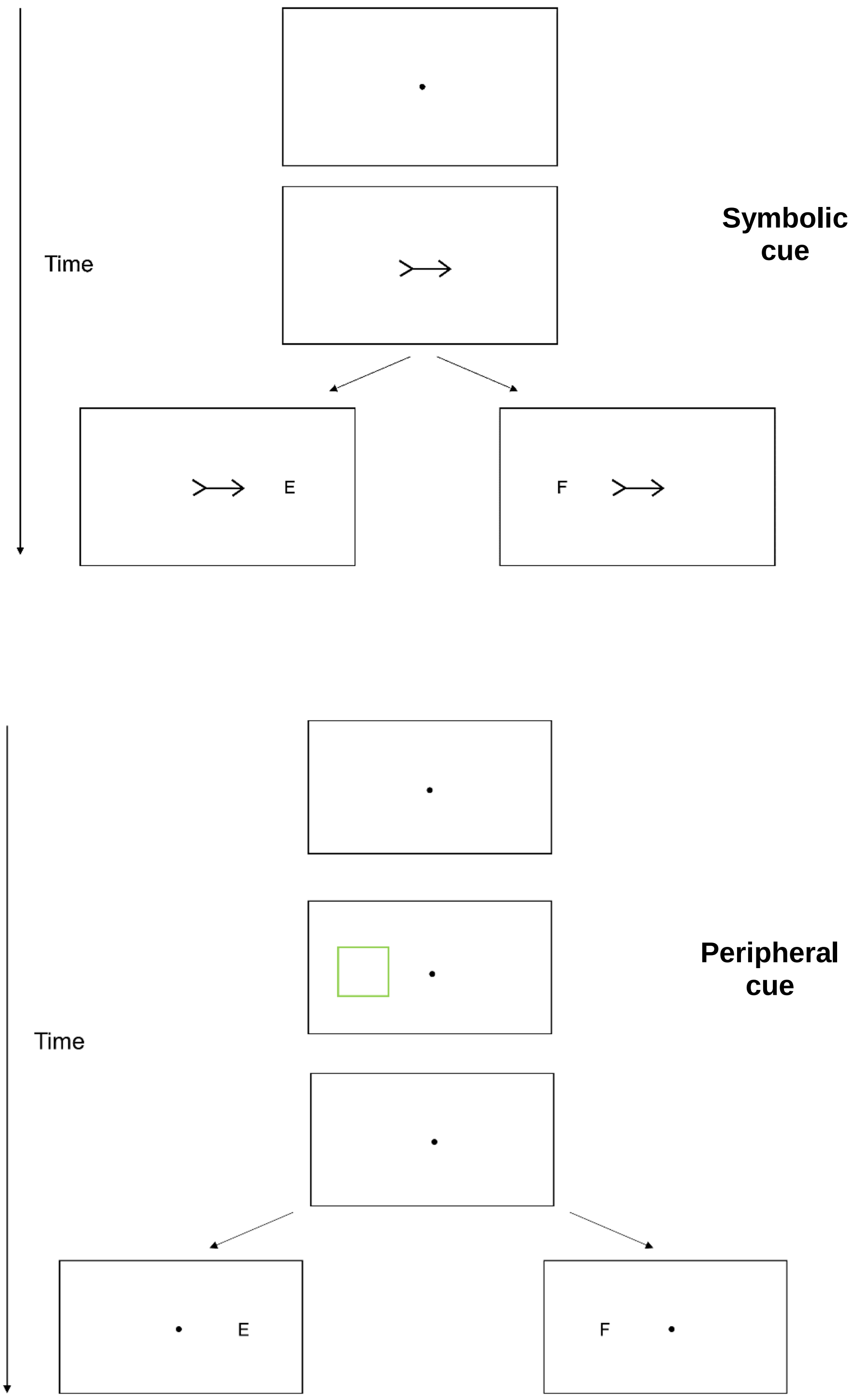
Manipulating Visual Spatial Attention: Spatial Cueing

Numerous methods have been used to investigate visual spatial attention. These include visual search (e.g., Kim & Cave, 1995; Treisman & Gelade, 1980); dual-task paradigms, where a secondary task is used to divert attentional resources away from a primary task to see how performance on the primary task is affected (e.g., Reddy et al., 2006); and manipulations of spatial uncertainty intended to alter the size of the observer’s attentional breadth (e.g., Huang et al., 2016), among others. By far the most common way of manipulating *shifts* of visual spatial attention, particularly for examining the factors driving these shifts and their perceptual consequences, is the spatial cueing paradigm. This paradigm was made famous by Michael Posner, but has its origins in the work of J. A. Leonard (Leonard, 1958; Posner, 1980; Posner, 2016; Posner et al., 1978; Posner et al., 1980).

In the spatial cueing paradigm, a visual cue—presented in either central or peripheral vision—is used to guide the observer's attention to a particular location (Figure 1). After some interval following the onset of this cue (typically termed the stimulus-onset asynchrony, or simply the cue-target interval), a target appears to which participants must respond. The task is typically to either detect the appearance of the stimulus as soon as it is perceived, or to make a judgment about the nature of the stimulus in a discrimination task (e.g., deciding which of two possible letters has been presented). Importantly, trials can be *valid*, meaning that the target appears at the location indicated by the cue, or *invalid*, meaning that the target appears at another location. The mean reaction time (RT) to detect or discriminate the target is computed for these two trial types. If mean RT is significantly faster on valid trials than on invalid trials, it is assumed that attention has been shifted to the location indicated by the cue—that is, it is assumed that participants are faster to respond to targets on valid trials because attention has been shifted to the target location on these trials, whereas they are slower to respond on invalid trials because the locus of attention was shifted elsewhere, having been "misguided" by the cue. This assumption is critical to the use of the spatial cueing paradigm as a means of manipulating visual spatial attention. Apart from RT, other dependent measures can be used to assess the effect of cueing on performance, such as accuracy, sensitivity, or psychophysical thresholds (see Chapter 7). The difference between the mean value for valid trials and that for invalid trials—if significant—is referred to as a *cueing effect*.

Figure 1

Symbolic and Peripheral Cueing



Note. This figure shows examples of trials in a spatial cueing procedure with a symbolic cue (top panel) and a peripheral cue (bottom panel). Trials can be either valid or invalid (both are shown here), depending on whether the target appears at the location indicated by the cue or at the opposite location, and the task in this example is to indicate whether the letter “E” or “F” has been presented. See text for further detail.

Sometimes neutral cues are used instead of or in addition to invalid cues. Unlike invalid cues, which guide attention to another possible target location (one where the target does not appear), neutral cues do not indicate any particular target location; for instance, a neutral cue may consist of a bar presented at each of the possible target locations. When all three trial types are used—valid, invalid, and neutral—neutral cues allow for the costs and benefits of attentional orienting to be quantified. For example, assuming that RTs are slower on invalid trials relative to neutral trials, as well as faster on valid trials relative to neutral trials, the difference in mean RT between invalid and neutral trials quantifies the *cost* of attention being oriented to a nontarget location, while the difference in mean RT between valid and neutral trials quantifies the *benefit* of attention being oriented to the target location (Wright et al., 1995). In this way, a neutral cue can be used as a “baseline” for assessing the costs and benefits of attentional shifts.

However, caution must be exercised when using neutral cues and when interpreting the results of studies that have used these cues. This is because performance on a task can be influenced not only by where the target appears relative to the location indicated by the cue, but also how alerting the cue is by virtue of its physical properties; when neutral cues are not physically identical to the cues presented on valid or invalid trials, it is unclear to what extent cueing effects are purely quantifying the consequences of shifting attention (Jonides & Mack, 1984). For example, if neutral trials involve a cue being presented at every possible target location, these trials might be more alerting to the observer than valid trials on which only a single cue is presented; such alerting might unduly speed responding or improve accuracy on neutral trials, resulting in a potentially diminished cueing effect. Furthermore, because neutral cues do not indicate any particular target location, it is unclear how attention is being distributed on these trials and whether it is equivalent to how attention is being distributed on valid and invalid trials. For instance, if neutral trials involve a cue being presented at each possible target location, attention might be distributed more broadly on these trials than on valid trials, where only one cue is presented; this would be problematic for isolating the perceptual consequences of attentional shifts because it is known that changes in attentional *breadth* themselves modulate perception (e.g., Lawrence, Edwards, & Goodhew, 2020). For these reasons, the empirical chapters of this thesis focus on comparisons between valid and invalid trial types.

Several features of the spatial cueing paradigm make it an effective and versatile way of manipulating visual spatial attention. First, by changing the type of cue used to elicit attentional orienting, the stimuli that drive attentional shifts and their relative importance can be examined. For example, whether or not a particular type of cue is capable of eliciting an attentional shift can be determined by seeing whether it produces a cueing effect, or the magnitudes of cueing effects can be compared to see which types of cues are more effective at eliciting shifts of attention than others. Second, simply by changing the nature of the target, as well as the dependent measure used to assess performance (e.g., accuracy instead of RT), the spatial cueing paradigm allows for the effects of attention on a variety of tasks and perceptual processes to be investigated. A third strength of the spatial cueing paradigm is its simplicity—all that differs between valid and invalid trials is where the target appears in relation to the cue, so any performance differences between these conditions is likely to indicate an effect of attention (cf. dual-task paradigms, where the increased working memory load imposed by the demand to complete another task may complicate comparisons to a single-task condition; Pashler, 1994). This simplicity has also allowed researchers to separately examine the neural mechanisms driving attentional shifts and those involved in processing the target, because when the spatial cueing paradigm is used, the activity provoked by the stimulus generating the shift (the cue) can be readily decoupled from that of the target (e.g., Corbetta et al., 2002). Therefore, the spatial cueing paradigm is an ideal technique for studying attentional orienting.

Investigating Endogenous and Exogenous Attention with Spatial Cueing

As discussed in the previous section, the spatial cueing paradigm involves the use of a cue to elicit an attentional shift. What factors should be considered when deciding on the features of this cue? The answer to this question depends on whether endogenous or exogenous attention is of interest, because the two attentional systems possess different properties and are therefore responsive to different types of cues. More specifically, whether endogenous or exogenous attention is being investigated determines the visual properties of the cue, whether the cue is predictive or nonpredictive of the target location, and the temporal parameters of the cueing procedure (i.e., the interval between the cue and the target).

Traditionally, endogenous attention has been manipulated using a centrally presented symbolic cue that is predictive with respect to the target location (Posner, 1980; see top panel of Figure 1). The most common symbolic cue used to manipulate endogenous attention is an arrow cue, which points to one of the possible target locations and is predictive of the target location at a rate higher than chance. Posner et al. (1978), for instance, used a centrally presented, left- or right-pointing arrow cue that correctly indicated the target location on 80% of trials and misdirected attention on 20% of trials (i.e., 80% of the trials were valid and 20% were invalid), finding that RTs to detect a target were faster on valid trials than on invalid trials (and therefore that a shift of attention had occurred). The reasoning behind the use of such a cue to elicit *endogenous* orienting is that because the cue does not appear at a possible target location, individuals must voluntarily orient their attentional resources to the location indicated by the arrow following interpretation of the cue; the informativeness of the cue with respect to the target location provides an incentive for participants to deploy their attentional resources in this way (Jonides, 1981; Posner, 1980). Consistent with the need for the cue to be interpreted, the cue-target interval must be relatively long to allow for the voluntary allocation of attention—approximately 300 ms (e.g., Cheal & Lyon, 1991; Müller & Rabbitt, 1989). The cueing effects elicited via such a procedure are reduced or eliminated under secondary task demands (e.g., a working memory load), when individuals are instructed to ignore the arrow cue, and when observers know that the arrow cue will be presented infrequently (Jonides, 1981); these findings are consistent with the voluntary nature of endogenous attention.

One problem with using arrows to manipulate endogenous attention is that they are ubiquitous in our environment, and therefore their high degree of familiarity could mean that the shifts of attention they produce are not entirely volitional. In support of this idea, many more recent studies have shown that arrow cues produce cueing effects even when they are nonpredictive of the target location (and therefore when there is no incentive to volitionally attend to the indicated direction), with these effects emerging as soon as 100 ms following the onset of the cue (e.g., Hommel et al., 2001; Ristic et al., 2002; Tipples, 2002)—findings consistent with the features of exogenous (i.e., involuntary) attention. Furthermore, predictive arrow cues have been found to produce larger cueing effects than the sum of those produced by nonpredictive arrow cues and predictive (nonarrow) symbolic cues (i.e., ones that have been arbitrarily associated with possible target locations; Ristic & Kingstone, 2006). This has been taken as evidence that orienting by predictive arrow cues may reflect an interaction between exogenous and endogenous orienting (Ristic & Kingstone, 2006). For these reasons, in order to isolate endogenous orienting, it is preferable to use a symbolic cue that does not have an intrinsic association with a particular location—for instance, a numerical or colour cue where particular numbers and colours indicate with high likelihood that the target will appear at a certain location (e.g., where “yellow” means the target is more likely to appear on the left, and “blue” means the target is more likely to appear on the right; Bonato et al., 2016; Olk et al., 2008).[1,2]

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[1] Note that after repeated exposure to such a cue, orienting can begin to occur even when the cue is later made nonpredictive of the target location (e.g., Dodd & Wilson, 2009).

[2] When a numerical cue is used, care must be taken to ensure that the pairing of numbers and locations is purely arbitrary; some research has shown that numerical cues can produce shifts of attention even when they are nonpredictive (e.g., lower numbers elicit shifts of attention to left-hand-side locations and larger numbers elicit shifts of attention to right-hand-side locations, consistent with the mapping of numbers on a number line; Fischer et al., 2003; but see Colling et al., 2020).

Exogenous attention is typically manipulated via a salient, peripherally presented cue that is nonpredictive with respect to the target location, such as the sudden onset of a bar or the brightening of a placeholder. Unlike the types of cues used to elicit endogenous attention, an exogenous cue appears at the same location as, or in close proximity to, one of the possible target locations (Posner, 1980; see bottom panel of Figure 1). It is the salience of the stimulus, as defined by both its physical characteristics and the context in which it appears (e.g., the sudden onset of a bar in an otherwise stationary display; the brightening of a placeholder where the luminance of other placeholders remains constant), that provokes a shift of attention to its location. Attentional orienting in response to an exogenous cue may reflect an evolutionarily adaptive response to attend to salient events, which could represent a threat in the environment (Chica et al., 2013); this may explain why cueing effects emerge even when the cue provides no information about the likely location of the target.

Exogenous orienting has a shorter time course than endogenous orienting, with cueing effects emerging approximately 100 ms following the onset of the cue and decaying quickly thereafter (e.g., Nakayama & Mackeben, 1989). Interestingly, at intervals of longer than approximately 300 ms, responses to the target are slower on valid trials than on invalid trials; this phenomenon is termed inhibition of return, and may reflect an adaptive search (or “foraging”) strategy that prevents attention from being reoriented to where a target has previously failed to appear, instead encouraging attentional orienting to novel locations (Posner & Cohen, 1984; Posner et al., 1985). In contrast to endogenous spatial cueing, the cueing effects elicited by an exogenous cue are impervious to secondary task demands, persist even when participants are instructed to ignore the cue, and emerge in spite of individuals knowing that the cue appears only rarely (Jonides, 1981). These findings are consistent with the involuntary nature of exogenous attention.

It should be noted that other types of cues have been used that do not map neatly onto the “endogenous attention” and “exogenous attention” categories. For example, some researchers use a salient peripheral cue that is 100% predictive, and compare performance on “cued” trials (where the target appears at the location indicated by the cue) against performance on “neutral” trials (e.g., where the cue appears at a location that is not a possible target location; e.g., Yeshurun & Carrasco, 1999; Yeshurun & Levy, 2003). Although it is likely that the attentional orienting elicited by such a cue is largely involuntary, it cannot be called exogenous attention because these shifts might not be solely driven by the attention-capturing properties of the cue—the predictive nature of the cue means that there might be a volitional element to this type of orienting. In support of this, the cueing effects produced by predictive peripheral cues endure over longer cue-target intervals than those produced by nonpredictive cues, indicating that attention is endogenously maintained at the target location (Müller & Findlay, 1988). For this reason, it is best to use the term “transient attention” when describing the attentional shifts produced by such cues, reserving the term “exogenous attention” for those shifts elicited by nonpredictive peripheral cues (Carrasco, 2011). Interestingly, some authors have also used predictive peripheral cues with a long cue-target interval to manipulate *endogenous* attention (e.g., Prinzmetal et al., 2005), but it is likely that such shifts of attention have an involuntary component given the salience of the peripheral cue.

As discussed earlier, there are also centrally presented, symbolic cues that elicit shifts of attention despite being nonpredictive, with the typical example of this being an arrow cue (e.g., Hommel et al., 2001). Shifts elicited by these types of cues might reflect an interaction between endogenous and exogenous attention because the cues must be interpreted for the attentional shift to occur (they do not appear directly at the location of the target), but these shifts occur even when there is no advantage to be gained from executing them (and thus they occur involuntarily). Conceptual cues—centrally presented words that have a metaphorical association with a particular location (e.g., “God” with “up” and “devil” with “down”), and therefore elicit a shift of attention to that location even when nonpredictive (e.g., Chasteen et al., 2010)—also fall into this category.

Considering the variety of cues that can be used in a spatial cueing procedure, one question that arises is whether different cueing paradigms simply represent different ways of “triggering” the deployment of a unitary attentional resource, or whether these different cueing configurations are deploying different types of attention altogether. For instance, when a nonpredictive peripheral cue is used to elicit a shift of attention, is it more appropriate to say that *exogenous attention* has been shifted, or that a shift of attention has been *exogenously triggered*—with the latter statement implying that the same attentional resource is being deployed regardless of whether an endogenous or exogenous cueing paradigm is used? On balance, there appears to be more evidence for the paradigms deploying different attentional systems. A particularly powerful piece of evidence for this is that the perceptual consequences of attention often depend on whether an endogenous cueing paradigm or an exogenous cueing paradigm is used (e.g., Jigo et al., 2021), with such differences being difficult to explain if each paradigm is deploying the same attentional resource. Therefore, in this thesis, I take the view that the abovementioned cueing procedures are manipulating different forms of attention rather than a single attentional resource.

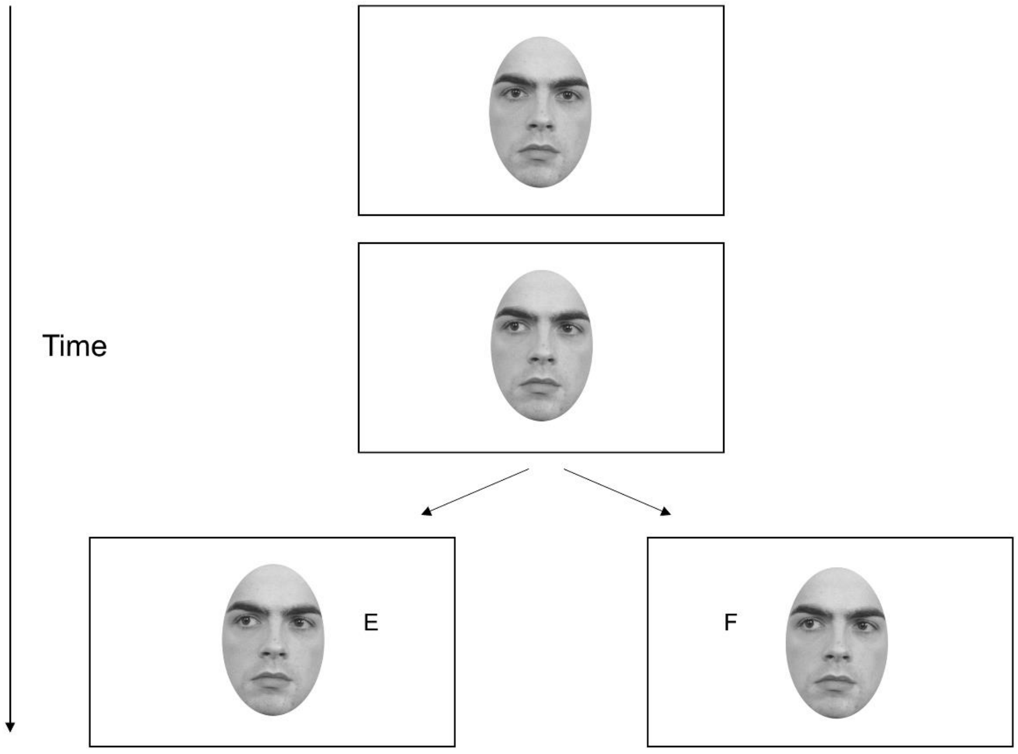
To summarise, spatial cueing is a method of deploying attentional resources over space with a cue that either correctly indicates the location of a subsequently appearing target, or directs attention to another location. This paradigm provides an elegant way of examining how responsive we are to particular attentional cues, as well as the perceptual consequences of visual spatial attention. Endogenous attention is best manipulated via a predictive, centrally presented, and symbolic cue with a relatively long cue-target interval, and exogenous attention is best manipulated via a nonpredictive peripheral cue with a relatively short cue-target interval. Certain cues, such as arrows, cannot be said to solely elicit either endogenous or exogenous attention despite being traditionally used to manipulate the former; this is because while such cues do require interpretation, their ubiquity means they produce shifts of attention even when they are nonpredictive of the target location. However, arrows are not the only example of a centrally presented cue that produces a seemingly involuntary shift of attention. Another such cue—one which has received a considerable degree of research attention by virtue of its social relevance—is gaze direction.

Social Orienting: Gaze Cues

Over two decades ago, researchers found that similar to nonpredictive arrow cues, centrally presented, nonpredictive *gaze* cues were capable of eliciting shifts of attention (Driver et al., 1999; Friesen & Kingstone, 1998; Hietanen, 1999; Langton & Bruce, 1999). That is, numerous studies have shown that when a picture of a face with averted gaze is presented (either a photograph or a schematic, and either with gaze already averted, or with direct gaze followed closely by a pupil shift), responses to a subsequently appearing target are faster when the target appears at the gazed-at location than when it appears at another location (Figure 2). This effect is commonly referred to as social orienting, or the *gaze-cueing effect* (GCE). The GCE emerges relatively early, at approximately 100 ms following cue onset; however, compared with nonpredictive peripheral cues, this facilitative effect decays less rapidly, and inhibition of return occurs only at very long cue-target intervals (e.g., 2,400 ms; Frischen, Smilek, et al., 2007; Frischen & Tipper, 2004). The fact that the GCE occurs in spite of the cue being nonpredictive and even with a short cue-target interval has been taken as evidence that this orienting response is involuntary, and this in itself has been attributed to the importance of eye gaze in processes such as social communication, detecting threats in the environment, and understanding others’ mental states (Baron-Cohen, 1995). The importance of eye gaze is further reflected in evidence that even infants exhibit an orienting response to eye gaze (Farroni et al., 2004), and that humans have dedicated neural networks for their processing (Carlin & Calder, 2013). In view of the social importance of eye gaze, recent research has focused on uncovering the variables that modulate the GCE (see Dalmaso et al., 2020, for a review), as well as determining whether the attentional response produced by gaze cues differs from that produced by nonsocial (yet highly familiar) cues, like arrows. In the remainder of this chapter, I provide an overview of some of this research in order to contextualise the first three empirical chapters of this thesis.

Figure 2

Gaze-Cueing Procedure



Note. This figure shows examples of both valid and invalid trials in a gaze-cueing procedure. In this example, the task for the participant is to determine whether the letter “E” or “F” has been presented. See text for further detail.

Before proceeding with this overview, it should be noted that gaze cues are not the only “social” cues that elicit shifts of attention despite being nonpredictive. Other social cues with a directional component, such as biological motion (i.e., point-light walkers moving either left or right; Shi et al., 2010), head orientation (Visser & Roberts, 2018), pointing gestures (Ariga & Watanabe, 2009), and implied body action (e.g., a static image of an individual running in a particular direction; Gervais et al., 2010) also produce cueing effects. Indeed, processing of these directional social cues may have a common neural basis in the superior temporal sulcus, leading some to propose the existence of a visual pathway specifically devoted to social perception (Pitcher & Ungerleider, 2021). However, given that gaze cues have by far been the most commonly studied social cue, the remainder of this thesis will focus on gaze cues as an exemplar of social orienting.

Social Orienting: Emotional Modulation and Individual Differences

Given the communicative value of different emotional expressions, it seems plausible that the emotion expressed by a gaze cue could alter the magnitude of the GCE. Indeed, there appears to be some evidence that the GCE is larger when the gaze cue exhibits a fearful expression relative to when it exhibits a neutral expression (e.g., Bayless et al., 2011; Graham et al., 2010; Lassalle & Itier, 2013, 2015a; McCrackin & Itier, 2019; Putman et al., 2006), with similar enhanced GCEs having been observed for happy (e.g., McCrackin & Itier, 2018; McCrackin & Itier, 2019), angry (e.g., Holmes et al., 2006; Lassalle & Itier, 2013, 2015a), disgusted (e.g., Pecchinenda et al., 2008), and surprised (e.g., Bayless et al., 2011; Lassalle & Itier, 2013, 2015a; Neath et al., 2013) expressions. These effects may be due to the benefits of attending to the location gazed at by faces expressing these emotions. For instance, it would be advantageous to attend to where a fearful face is looking since this location might contain a threat (Fox et al., 2007), and similarly, it might be beneficial to attend to the location gazed at by a happy expression since this location may contain a potential reward (Chen, McCrackin, et al., 2021). While such explanations have face validity, it is important to note that the evidence for these emotional modulations is mixed, with some studies failing to find any modulation of the GCE by emotional expression (e.g., Coy et al., 2019). Whether or not these effects are observed may depend on variables such as task demands (i.e., the nature of the response required by the participant), the cue-target interval, and at what point in the trial sequence the gaze cue expresses the relevant emotion (e.g., Chen, McCrackin, et al., 2021; Lassalle & Itier, 2015a). Further research is required to assess the replicability of these emotional modulations, and if they are real effects, to delineate the conditions under which they occur.

There is also some evidence for modulations of the GCE by several individual-differences variables (see Dalmaso et al., 2020, for a review). For example, there is some evidence that females show larger GCEs than males (e.g., Bayliss et al., 2005; McCrackin & Itier, 2019); that there is a negative association between autistic-like traits and the GCE (e.g., Bayliss et al., 2005; Ristic et al., 2005); that the GCE declines with age (e.g., McKay et al., 2022; Neath et al., 2013); and that conservatives show smaller GCEs than liberals (Dodd et al., 2011). Apart from influencing the size of the GCE in its own right, some individual-differences variables may also affect the *emotional modulation* of the GCE; for instance, there is some evidence to suggest that trait anxiety modulates responding to fearful gaze cues, such that those scoring high on trait anxiety show an enhanced GCE for fearful faces relative to those low on trait anxiety (e.g., Fox et al., 2007; Holmes et al., 2006; Mathews et al., 2003). As with the emotional modulation of gaze cueing itself, however, the evidence for individual differences in the emotional modulation of the GCE is mixed; these findings may depend on such variables as the scale used to measure the individual difference under investigation and, again, the point in the gaze-cueing procedure at which the gaze cue expresses the relevant emotion (e.g., McCrackin & Itier, 2019).

Although many individual-differences variables have been studied in relation to gaze cueing, other variables that are potentially even more relevant have not received the same degree of research attention. One such variable is social anxiety, which is defined as an individual’s fear of situations in which they may be socially evaluated (American Psychiatric Association, 2013). Given the range of attentional biases exhibited by individuals high on social anxiety, such as a bias towards threatening stimuli (e.g., Mogg et al., 2004), and the fact that social anxiety reflects a sensitivity to social—especially socially threatening—information, it is possible that this variable modulates the GCE; moreover, any modulation may be specific to gaze cues expressing socially threatening emotions. This question is addressed in Chapter 4 of this thesis, which has the secondary goal of examining the replicability of the effects of other individual-differences variables on the GCE.

Automaticity of Social Orienting

Apart from investigating the emotional modulation of the GCE and individual differences in the effect, researchers have also been interested in determining the extent to which social orienting is an *automatic* response. This question is important because the answer may shed light on the consequences of gaze direction being a socially relevant cue—a common hypothesis being that social orienting may proceed automatically (or at least *more* automatically than cueing by nonsocial cues, like arrows) because of the social importance of attending to where others are looking (e.g., Ristic et al., 2007). However, it is important to acknowledge that automaticity is a multifaceted construct (Melnikoff & Bargh, 2018; Moors & De Houwer, 2006). For instance, in their review of the automaticity literature, Moors and De Houwer (2006) identified "(un)intentional, goal(independent), (un)controlled/(un)controllable, autonomous, purely stimulus driven, (un)conscious, (non)efficient, and fast (slow)" as being largely separable features of automaticity (p. 319).[3] It therefore may be more fruitful to investigate these dimensions individually and restrict conclusions about the automaticity of social orienting to the particular feature being investigated. It is also important to acknowledge that the modulation of the GCE by a number of different variables (e.g., some individual differences) means that its automaticity, however the concept is defined, is conditional on the presence or level of such variables (Bargh, 1989; Dalmaso et al., 2020). In this section, I outline some of the research on the *intentionality* and *efficiency* of social orienting—two of the most commonly studied components of automaticity in the gaze-cueing literature. The purpose of this overview is to contextualise Chapters 5 and 6 of this thesis, which either touch on or directly address the automaticity of social orienting along these two dimensions.

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[3] Moors and De Houwer (2006) group together the first five of these features under the general label of "goal-related features," given that these features overlap with one another.

Many researchers have sought to determine the extent to which social orienting is an *unintentional* process—that is, to what extent it occurs regardless of the absence of an intention to attend to where another is looking. A common view in this line of research is that because gaze-following behaviour has considerable social importance, and because it may have a biological basis, the GCE may occur even if an observer does not intend to follow someone else's gaze, or indeed, even if they have an intention that contradicts this one (e.g., Galfano et al., 2012). The mere existence of the GCE—that is, a cueing effect emerging even when the gaze cue is nonpredictive of the target location and when participants are instructed to ignore it (e.g., Driver et al., 1999; Friesen & Kingstone, 1998; Hietanen, 1999; Langton & Bruce, 1999)—can be taken as evidence that this orienting response is unintentional to some degree. However, following from this basic finding, different methods have been used to assess the extent of this unintentionality. For instance, Galfano et al. (2012) found that even when participants were informed via verbal instruction where a target would appear, task-irrelevant gaze and arrow cues still elicited shifts of attention to nontarget locations. This indicates that even when participants had intended to shift their attention to where they knew the target would appear, they unintentionally attended to the location indicated by the gaze and arrow cues. Another study found that a counterpredictive gaze cue (i.e., one that indicates, at an above-chance level, where the target will *not* appear) still elicited a shift of attention towards the gazed-at location at short cue-target intervals despite it being in the participant's best interest to attend to the *opposite* location (Friesen et al., 2004; see also Tipples, 2008). Furthermore, unlike in the Galfano et al. study, this pattern of results was not found for the arrow cue. Collectively, these studies suggest that the GCE occurs unintentionally—both when participants do not intend to follow another's gaze direction, and when they have an intention that incentivises the opposite behaviour.

What factors contribute to the unintentionality of the GCE? As mentioned previously, the social importance of interpreting another's gaze direction, as well as the presence of dedicated neural mechanisms for gaze processing (Carlin & Calder, 2013), are likely to be leading factors. However, in considering whether social orienting is unintentional, another potentially relevant variable is the physical nature of the gaze cue—specifically, whether it is dynamic or static. Dynamic gaze cues contain a pupil shift that signals the direction of gaze, while static gaze cues appear with gaze already averted. While dynamic and static gaze cues produce GCEs of an equivalent magnitude (Hietanen & Leppänen, 2003), one possibility is that the motion signal produced by the pupil shift in a dynamic gaze cue is sufficient to elicit a GCE. This possibility seems particularly likely when considering the finding that infants only exhibit gaze-following behaviour in response to faces with a visible pupil shift (Farroni et al., 2000). With respect to the intentionality of the GCE, this would mean that part of the seemingly unintentional response to gaze direction conveyed by dynamic gaze cues is a product of this motion signal, rather than the social information conveyed by averted gaze. However, it is currently unclear whether a pure motion signal, devoid of any social content yet similar in magnitude to that in a dynamic gaze cue, is capable of eliciting an attentional shift. Chapter 5 of this thesis seeks to address this very question by determining whether a pure motion signal absent of any social information can produce a cueing effect, and thereby uncover one possible contributor to the unintentionality of dynamic gaze cueing.

Another aspect of automaticity that has been investigated in relation to gaze cueing is *efficiency*. A process is said to be efficient to the extent that it does not draw on top-down processing resources (Moors & De Houwer, 2006). Some researchers have suggested that because social orienting is so fundamental to daily functioning, and because humans have dedicated neural mechanisms for processing gaze direction, social orienting may require minimal contribution from top-down processing resources (e.g., Ristic et al., 2007). The efficiency of social orienting has typically been studied by examining whether the GCE persists under a concurrent working memory load, which requires the observer to retain information in working memory while they are completing a gaze-cueing task; the assumption underlying this method is that if “performance” on the main task (e.g., the magnitude of the GCE) is diminished under a working memory load, it can be said to rely on top-down processing resources (Moors & De Houwer, 2006). Using this approach, some studies have demonstrated that social orienting is unaffected by both a verbal (Hayward & Ristic, 2013; Law et al., 2010) and a visuospatial (Law et al., 2010) working memory load—that is, there are no changes in the magnitude of the GCE when the participant is required to hold verbal or visuospatial information in working memory. This has led to these studies concluding that social orienting is a highly efficient process in that it is unaffected by the depletion of cognitive resources.

While the presence of secondary task demands does not appear to affect the GCE, an outstanding research question concerns the efficiency of orienting by *nonsocial* cues, like arrows. For example, is it the case that while social orienting is an efficient process, orienting by arrow cues (overlearned, yet nonsocial symbols) *does* consume top-down processing resources? Indeed, some researchers have suggested that because arrows do not have the social relevance or dedicated neural circuitry possessed by gaze cues, this might be the case (e.g., Ristic et al., 2007). The efficiency of orienting by arrow cues is an important issue to consider because it could speak to the more fundamental question of whether social cues are unique in their limited reliance on top-down processing resources. Another outstanding question is whether the efficiency of social orienting depends on the nature of the gaze cue—that is, whether it is dynamic or static. As discussed earlier, the motion signal contained in dynamic gaze cues might contribute to the *unintentionality* of gaze following in response to these cues—it seems possible, then, that social orienting by dynamic gaze cues might be *efficient* (efficiency being another aspect of automaticity), while social orienting by static gaze cues is somewhat *inefficient*. In Chapter 6 of this thesis, I examine the efficiency of orienting by arrow cues, dynamic gaze cues, and static gaze cues.

Summary

The spatial cueing paradigm provides an elegant way of manipulating visual spatial attention, useful for examining both individuals' responsiveness to attention-guiding stimuli and the perceptual consequences of attentional shifts. Different types of attention can be examined by changing the nature of the cue—both its physical characteristics and its informativeness with respect to the target location—and the interval between the appearance of the cue and that of the target. While a large body of research has focused on orienting by nonsocial cues, many studies have also focused on orienting by social cues such as gaze direction. These studies have examined the variables that could modulate social orienting (e.g., the emotion expressed by the gaze cue; various individual-differences variables), and have attempted to determine the degree to which such orienting is an automatic process.

Despite the considerable body of research that has been devoted to examining both social and nonsocial attentional orienting, several important questions remain. The next three chapters of this thesis focus on addressing some of the outstanding issues regarding the factors influencing responsiveness to social and nonsocial cues. First, while a number of individual-differences variables have been investigated in relation to social orienting (e.g., trait anxiety; Fox et al., 2007), Chapter 4 examines whether social anxiety, a variable that is known to influence a range of attentional processes but has been relatively understudied in the gaze-cueing domain, modulates the GCE. Next, Chapter 5 examines whether the motion signal contained in a dynamic gaze cue is sufficient to elicit an attentional shift, even when it contains no social information. Finally, Chapter 6 examines the efficiency of cueing by arrows, dynamic gaze cues, and static gaze cues.

Chapter 4

Examining the Effects of Social Anxiety and Other Individual Differences on Gaze-Directed Attentional Shifts

Chapter Overview

Chapter 4 is the first of three studies in this thesis to examine factors that may influence responsiveness to attentional cues. Chapter 4 specifically examines whether levels of social anxiety, as measured in a nonclinical sample, affect orienting in response to gaze cues exhibiting different emotions; in doing so, this chapter considers whether a *characteristic of the observer* can affect responsiveness to social cues. Other individual-differences variables that have been claimed to modulate social orienting are controlled for and considered in their own right, and a nonsocial cue (i.e., an arrow) is also used to see whether any observed modulations by social anxiety are specific to the social nature of the gaze cue.

Abstract

Gaze direction is a powerful social cue, and there is considerable evidence that we preferentially direct our attentional resources to gaze-congruent locations. While a number of individual differences have been claimed to modulate gaze-cueing effects (e.g., trait anxiety), the modulation of gaze cueing for different emotional expressions of the cue has not been investigated in social anxiety, which is characterised by a range of attentional biases for stimuli perceived to be socially threatening (e.g., Mansell et al., 1999). Therefore, in this study, we examined whether social anxiety modulates gaze-cueing effects for angry, fearful, and neutral expressions, while controlling for other individual-differences variables that may modulate gaze cueing: trait anxiety, depression, and autistic-like traits. In a sample of 100 female participants, we obtained large and reliable gaze-cueing effects; however, these effects were not modulated by social anxiety, or by any of the other individual-differences variables. These findings attest to the social importance of gaze cueing, and also call into question the replicability of individual differences in the effect.

Introduction

Attention is a finite resource, and therefore must be deployed in a selective manner. To this end, humans—as highly social creatures—often rely on social cues to guide their attentional resources. One such cue is another individual’s gaze direction: Attending to where another is looking allows us to detect important events in the environment, assists us in understanding their goals and intentions (Baron-Cohen, 1995), and facilitates communication in social situations. The purpose of this study was to determine whether attention to gazed-at locations is modulated by social anxiety (SA), thus providing insight into how those with high levels of SA experience their social world. In the process of controlling for other individual-differences variables that have been found to modulate this process, we set another goal: to assess the replicability of these effects. This is important because previous studies that have demonstrated contextual modulations of gaze following have shown poor replicability (e.g., Coy et al., 2019; McCrackin & Itier, 2019).

In the lab, gaze following is operationalised by the *gaze-cueing procedure* (a variant of the Posner cueing paradigm; Posner et al., 1978; for a review, see Frischen, Bayliss, & Tipper, 2007).[1] In a typical gaze-cueing task, a photo or drawing of a face is presented in the centre of the screen, with the eyes averted either to the left or to the right. After a brief interval, a target appears either to the left-hand side or to the right-hand side of the stimulus, and participants must respond to this target via a keypress. It has consistently been shown that in such a task, reaction times (RTs) are faster to targets appearing at the gazed-at (or valid) location compared to the non-gazed-at (or invalid) location, even when the cue is nonpredictive of the target location (e.g., Friesen & Kingstone, 1998; Langton & Bruce, 1999). This finding is thought to reflect the strong social relevance of gaze direction: Gaze

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[1] Note that the term “gaze following”, in the manner we employ it, encapsulates both covert and overt attention to gazed-at locations, where the former occurs without eye movements and the latter is accompanied by them. We distinguish between these two forms of attentional orienting where necessary.

conveys such meaning in everyday life that even when participants are instructed to ignore a gaze cue in the lab, attention is shifted to the gazed-at location.

Several contextual variables appear to modulate this *gaze-cueing effect* (GCE; see Dalmaso et al., 2020, for a recent review). One is the emotional expression of the gaze cue, with some studies finding that fearful faces increase the magnitude of the GCE relative to neutral faces (e.g., Bayless et al., 2011; Graham et al., 2010; Lassalle & Itier, 2013, 2015a; McCrackin & Itier, 2019; Putman et al., 2006), and some finding similar enhancements of the GCE for happy (e.g., McCrackin & Itier, 2018; McCrackin & Itier, 2019), angry (e.g., Holmes et al., 2006; Lassalle & Itier, 2013, 2015a), and surprised (e.g., Bayless et al., 2011; Lassalle & Itier, 2013, 2015a; Neath et al., 2013) expressions. These modulations are thought to result from the enhanced social relevance of averted gaze when combined with such expressions; a fearful face gazing in a particular direction, for instance, could signal the appearance of an object or event urgently requiring attention (e.g., the appearance of a snake), and therefore it is particularly beneficial for attention to be shifted to the gazed-at location (Tipples, 2006). Interestingly, however, Coy et al. (2019) recently failed to observe any modulations of the GCE by emotional expression: Across five experiments, the authors manipulated factors such as the number of emotional expressions, the number of gaze-cue identities, and participants’ country of origin, and consistently observed no interaction between cue validity and emotional expression for fearful and happy expressions. Therefore, the reliability of such effects is currently under question.

Certain individual-differences variables have also been claimed to modulate the GCE. For example, males show smaller GCEs than females (e.g., Bayliss et al., 2005; McCrackin & Itier, 2019), which may reflect their reduced sensitivity to nonverbal social stimuli relative to females (Hall, 1978). A reduced sensitivity to social information may also explain the finding that those with autism spectrum disorder, or those scoring highly on measures of autistic-like traits, exhibit a smaller GCE (e.g., Bayliss et al., 2005; Ristic et al., 2005) and reduced modulations of the GCE by the emotional expression of the cue (e.g., Lassalle & Itier, 2015b; McCrackin & Itier, 2019; Uono et al., 2009) relative to controls. Another key finding in the individual-differences domain is that higher levels of trait anxiety are associated with a greater GCE for fearful gaze cues (e.g., Putman et al., 2006; Tipples, 2006), with some authors finding that this modulation may *only* be present in highly trait-anxious participants (e.g., Fox et al., 2007; Holmes et al., 2006; Mathews et al., 2003). These findings are thought to reflect hypervigilance to threat in anxious participants, who may be more responsive to cues that could signal the presence of a threatening stimulus. However, the replicability of this finding has recently been called into question, with more recent studies failing to observe anxiety-related modulations of the GCE (Lassalle & Itier, 2015b; McCrackin & Itier, 2019; Neath et al., 2013).

Therefore, there appears to be some evidence that the GCE can be modulated by individual variations that reflect differences in processing social information (i.e., sex and autistic-like traits), as well as those that reflect hypervigilance to threatening stimuli (i.e., trait anxiety). Given that the magnitude of the GCE appears to depend on an individual’s relative sensitivity to both social information in general and threatening stimuli more specifically, it is possible that the effect may also vary as a function of SA. SA is characterised by a fear of situations in which one could be scrutinised by others (American Psychiatric Association, 2013), with these symptoms of fear distributed normally within the general population (Rapee & Spence, 2004). Socially anxious individuals exhibit a large degree of self-focused attention when confronted with a social context they perceive to be threatening (Clark & Wells, 1995; Rapee & Heimberg, 1997); moreover, they display characteristic processing biases in relation to socially threatening stimuli.

On the one hand, there is evidence that SA is associated with an attentional bias *towards* socially threatening stimuli, such as angry faces (e.g., Gilboa-Schechtman et al., 1999; Mogg et al., 2004); eye-tracking paradigms have further demonstrated that SA is associated with difficulty disengaging from these stimuli (e.g., Buckner et al., 2010; Schofield et al., 2012), and event-related potentials indicate that high-SA individuals may be particularly sensitive to averted gaze, perhaps because this could be interpreted as disinterest in the observer (Schmitz et al., 2012). However, there is also evidence that SA is associated with *avoidance* of socially threatening stimuli (e.g., Heuer et al., 2007; Mansell et al., 1999; Roelofs et al., 2010), including eye-tracking research which shows that socially anxious individuals avoid the eye region in faces, especially those with angry expressions (Horley et al., 2003, 2004). This avoidance may function as a “psychological escape” (p. 686) from a situation in which social interaction is a possibility (Mansell et al., 1999).

In general, socially anxious individuals may be especially sensitive to social threat, with attention biased to such signals (e.g., Gilboa-Schechtman et al., 1999; Mogg et al., 2004; Moriya & Tanno, 2011). Attention may be maintained at these signals (e.g., Buckner et al., 2010; Schofield et al., 2012), or these signals could be avoided in the service of evading social evaluation (e.g., Heuer et al., 2007; Mansell et al., 1999; Roelofs et al., 2010). With respect to gaze cueing, this leads to two main possibilities: SA may be associated with an *increase* in the magnitude of the GCE if the gaze cue is perceived to be socially threatening and attention is maintained on the stimulus, or a *reduction* in the magnitude of the GCE if the gaze cue is perceived to be socially threatening and avoidant behaviour follows.

Despite strong theoretical grounds for SA modulating the GCE, the few studies that have examined this possibility have not observed a modulation. Two studies included a measure of SA in their gaze-cueing experiments and found no variation in the magnitude of the GCE as a function of SA (Gregory & Jackson, 2017; Wei et al., 2019). However, these studies only employed gaze cues with neutral expressions; the lack of a socially threatening context could therefore explain the absence of any modulation. Recently, Gregory et al. (2019) examined *overt* gaze following in a low-SA group and a high-SA group. These authors found no differences between the groups in the frequency of gaze-elicited eye movements, but again, only neutral expressions were used; furthermore, it is possible that differences might only manifest in *covert* attentional shifts (i.e., those occurring without eye movements), given that socially anxious individuals are especially conscious of how they appear to others (Hope & Heimberg, 1988). To our knowledge, the only study to use cues with different emotional expressions in a typical gaze-cueing task was conducted by Boll et al. (2016), who, in one experiment, compared GCEs for angry, fearful, and happy expressions in participants with and without SA. However, these authors only observed the basic GCE when they restricted their analysis to fast RTs, and did not report any effects (or lack thereof) related to emotional expression within that analysis. Therefore, whether SA modulates the GCE for different emotional expressions remains an open question.

In the present study, within a large sample of 100 female participants, we examined whether SA modulates the GCE for three different emotional expressions. We employed an angry gaze cue to symbolise the type of self-relevant threat to which socially anxious participants might be especially sensitive (e.g., Mogg et al., 2004), a fearful gaze cue to represent external threat, and a neutral gaze cue as a “baseline” emotional expression. Furthermore, unlike each of the abovementioned studies that examined SA, we included measures of trait anxiety and autistic-like traits to control for other variables that could modulate the GCE (e.g., Fox et al., 2007; Ristic et al., 2005), allowing us to examine the replicability of these effects. We also included a depression scale, in light of suggestions by McCrackin and Itier (2019) that depression may also modulate the GCE (note, however, that with a sample size of over 100 participants, these authors did not observe such a modulation in their own study). Finally, we included an arrow-cueing task to determine if any modulations of gaze cueing by SA could be explained by variation in the processing of symbolic stimuli or external attentional cues more generally (see, e.g., Heeren et al., 2015, who found that socially anxious participants exhibited diminished orienting in response to a peripheral attentional cue relative to controls). For both the gaze- and arrow-cueing blocks, we used a discrimination task to probe attentional orienting. While a number of previous studies (e.g., Bayless et al., 2011; Lassalle & Itier, 2013, 2015a, 2015b) used a localisation task, in which participants were required to use their left hand to respond to targets appearing on the left-hand side of the display and their right hand to respond to targets appearing on the right-hand side of the display, the use of such a task introduces the possibility that any observed cueing effects are at least partially the result of the gaze cue priming response preparation and execution, and not solely of the cue eliciting a shift of spatial attention (Simon, 1969; see Wiese et al., 2013, for a discussion of this issue in relation to gaze cueing).

If SA modulates the GCE, what might be the nature of this modulation across the different emotional expressions of the gaze cue? For the angry expression, which is likely to be perceived as socially threatening to those high in SA, we foresaw two possibilities: SA—after controlling for the other individual-differences variables—might be associated with an *increase* in the GCE if attention is maintained on the gaze cue due to its threat-signalling potential (e.g., Buckner et al., 2010), or a *decrease* in the GCE if avoidant behaviour or self-focused attention follows its presentation (e.g., Mansell et al., 1999). Given that the fearful face is more likely to be perceived as signalling a nonsocial, environmental threat (Tipples, 2006), we predicted no modulation of the GCE by SA for this expression after controlling for the other individual-differences variables. Finally, for the neutral gaze cue, we also predicted no modulation of the GCE by SA after controlling for the other individual differences. However, given some evidence that socially anxious individuals exhibit an interpretation bias to perceive neutral expressions as angry (e.g., Gutiérrez-García & Calvo, 2017; Yoon & Zinbarg, 2007), the results may resemble those for the angry gaze cue.

Method

Participants

In order to obtain an estimate of the sample size required to detect a small effect (Cohen’s $f = .085$) of SA on gaze-cueing scores—after controlling for trait anxiety, depression, and autistic-like traits—a power analysis was conducted using G*Power (Faul et al., 2007). Note that, to our knowledge, there is no readily available power calculator that can perform sample-size calculations for a repeated-measures analysis of covariance (ANCOVA;

the main analytic technique used in the current study); the power analysis was therefore performed for a hypothetical hierarchical regression in which the unique effect of SA on gaze-cueing scores was assessed after first entering the scores on the other three individual-differences measures. When a power of .8 and alpha of .05 were specified, the analysis estimated a required sample size of 95.

Overall, 106 female, Caucasian students from The Australian National University participated in the study in exchange for course credit or $15 payment. We recruited more participants than required in order to account for any potential exclusions (see Results). The final sample consisted of 100 participants whose ages ranged from 18 to 40 years (*M* = 21.6, *SD* = 4.2). Females were selectively recruited because they have been shown to exhibit greater GCEs than males (Bayliss et al., 2005; McCrackin & Itier, 2019), and because the severity of SA tends to be stronger in females than in males (Asher et al., 2017; Xu et al., 2012), thus maximising the potential for this study to observe any modulation of the GCE by SA. Caucasians were selectively recruited because of known cultural differences in the perception of threat in direct eye contact (e.g., East Asians perceive direct eye contact to be more threatening than do Western Europeans; Akechi et al., 2013); this was a relevant consideration given that our gaze-cueing sequence began with a directly gazing face (see Procedure). The study was approved by the Australian National University Human Research Ethics Committee (protocol number 2016/156), and each participant in the study provided written, informed consent. All participants had normal or corrected-to-normal vision.

Apparatus and Stimuli

Stimuli were presented on an iMac computer with a 1920 × 1080 LCD monitor, which ran at a refresh rate of 60 Hz. Viewing distance to the monitor was fixed at 60 cm with a chinrest. Stimulus presentation was controlled via the Psychophysics Toolbox in MATLAB (Brainard, 1997), and questionnaires were completed on survey platform Qualtrics.

The face stimuli used in the gaze-cueing task were selected from the Radboud Faces Database (Langner et al., 2010), a validated collection of high-quality face photographs. For each expression we chose to study—angry, fearful, and neutral—two Caucasian male and two Caucasian female identities were selected, with direct-gaze, left-averted-gaze, and right-averted-gaze versions chosen for each combination of emotional expression and identity. The four identities were selected based on their high agreement ratings concerning the emotion being expressed (according to the validation study by Langner et al., 2010), as well as their possession of characteristics conducive to gaze cueing (e.g., wide-open eyes clearly averted to the left or to the right).

Graphics software Inkscape was used to convert each image to greyscale, and to crop each face so as to remove all hair and ear detail; any remaining stray hairs were removed using Adobe Photoshop. To ensure that for each combination of emotional expression and identity only the eyes differed between the varying gaze directions, the eyes from the left-averted-gaze and right-averted-gaze versions of the same face were copied and pasted onto those of the direct-gaze version of the face. This resulted in three images for each combination of emotional expression and identity, with only the appearance of the eyes differing between them (dimensions: 6.5˚ × 8.9˚). Figure 1 shows the angry, fearful, and neutral expressions for one of the selected identities.

Figure 1

Examples of Stimuli Used in the Current Study

Note. This figure shows the angry, fearful, and neutral expressions adopted by one of the identities selected from the Radboud Faces Database (Langner et al., 2010). This figure shows only the directly gazing versions of the faces for this identity; left-averted-gaze and right-averted-gaze versions were also created (see text for description).

For the arrow-cueing task, a black arrow containing both an arrowhead and an arrowtail was created. The central line of the arrow was 2.3° in length, with the lines making up the arrowhead and arrowtail spanning 1.1°. All lines had a thickness of 0.2°. For both the gaze- and arrow-cueing tasks, the letters “E” and “F” were used as targets; both letters were black, in Arial font, and subtended 0.8° × 0.8°. The eccentricity of the target letter was fixed at 5.5°. For the gaze-cueing task only, the target letter was located 0.8° above the horizontal meridian of the display so that it was in line with the eye region of the gaze cue.

Self-Report Measures

Participant Screening

A preliminary screening questionnaire was created, which participants completed on Qualtrics. This contained questions about the participant’s handedness, and any past or existing diagnoses of ADHD or ADD, schizophrenia, or a major neurological injury or disease (e.g., brain tumour), disorders which may compromise face perception.

Self-Report Version of the Liebowitz Social Anxiety Scale (LSAS-SR)

Participants completed the self-report version of the Liebowitz Social Anxiety Scale (LSAS-SR; Liebowitz, 1987). The LSAS-SR consists of 24 items, 11 of which describe a social interaction (e.g., “Talking to people in authority”), and 13 of which describe performance situations (e.g., “Eating in public places”). For each item, individuals indicate on a scale from 0 to 4 the extent to which the situation would provoke fear or anxiety (0 – “none”, 4 – “severe”), and how often they would avoid the situation (0 – “never”, 4 – “usually – 67—100%”). The total scores for the “fear” and “avoidance” components are added together to form a total score, which can range from 0 to 144. The LSAS-SR has been found to possess psychometric properties on par with the clinician-administered version of the scale, with strong internal consistency, convergent validity with other SA measures, and discriminant validity (Fresco et al., 2001). The mean total LSAS-SR score in our sample (Table 1) was slightly higher than that observed by Caballo et al. (2013) in a large university-student sample (*M* = 45.7, *SD* = 19.8).

Trait Scale of the State-Trait Anxiety Inventory (STAI)

The trait scale of the State-Trait Anxiety Inventory (STAI; Spielberger et al., 1983) was used to assess trait anxiety. The scale consists of 20 statements (e.g., “I feel rested”), each requiring a response from 1 (“almost never”) to 4 (“almost always”). Possible scores range from 20 to 80, with higher scores indicating a greater trait-anxious character. The trait scale of the STAI possesses good psychometric properties, with strong construct and concurrent validity (Spielberger, 1989), and has been used in previous studies examining trait anxiety and the fearful GCE (Fox et al., 2007; Holmes et al., 2006; Mathews et al., 2003). The mean score in our sample (Table 1) was slightly higher than the mean of 40.4 (*SD* = 10.2) for college students in Spielberger et al.’s normative sample.

Depression Anxiety Stress Scale 21 (DASS-21)

We used the short-form version of the Depression Anxiety Stress Scale (DASS-21; Lovibond & Lovibond, 1995), which assesses symptoms of depression, anxiety, and stress. Note that while participants completed the whole scale, only the depression subscale was scored given the possible association between depression and the GCE (though see McCrackin & Itier, 2019, who did not observe such an association). The scale consists of 21 statements (e.g., “I felt down-hearted and blue”), to which participants must respond on a scale ranging from 0 (“Did not apply to me at all”) to 3 (“Applied to me very much, or most of the time”) in relation to how they had felt over the last week. Possible scores on the depression subscale (consisting of 7 items) range from 0 to 21. The subscale has been found to possess good psychometric properties, with strong internal consistency and concurrent validity (Antony et al., 1998). In our sample, the mean score on this scale (Table 1) was slightly higher than the mean of 2.1 (*SD* = 3.6) observed in a group of nonclinical volunteers (Antony et al., 1998).

Autism-Spectrum Quotient 10 (AQ-10)

We used the shortened version of the Autism-Spectrum Quotient (AQ-10; Allison et al., 2012), which consists of 10 statements that assess autistic-like traits (e.g., “I often notice small sounds when others do not”). For each statement, participants must indicate their response on a four-point scale ranging from “Definitely Agree” to “Definitely Disagree”. Possible scores on the AQ-10 range from 0 to 10, and the scale has excellent predictive validity with respect to the diagnosis of autism spectrum disorder (Booth et al., 2013). The mean AQ-10 score in our study (Table 1) was similar to the mean score of 2.8 (*SD* = 2.0) observed in a large sample of adult controls (Allison et al., 2012).

Table 1

Descriptive Statistics for Questionnaires Administered in the Current Study

Questionnaire	*M*	*SD*	Range Potential	 Actual	Cronbach's α
LSAS-SR (total score)	50.2	22.1	0–144	15–127	.93
STAI (trait scale)	45.3	10.0	20–80	27–69	.92
DASS-21 (depression subscale)	4.4	3.9	0–21	0–20	.87
AQ-10	2.7	1.8	0–10	0–8	.63

Note. The information in this table is based on the questionnaire scores of the final 100 participants. LSAS-SR = self-report version of the Liebowitz Social Anxiety Scale; STAI = State-Trait Anxiety Inventory; DASS-21 = Depression Anxiety Stress Scale 21; AQ-10 = Autism-Spectrum Quotient 10.

Procedure

The study consisted of a gaze-cueing block, an arrow-cueing block, and the series of questionnaires. The gaze-cueing block consisted of 180 valid trials (where the target appeared at the gazed-at location) and 180 invalid trials (where the target appeared at the non-gazed-at location), resulting in a cue validity of 50% (i.e., the cue was nonpredictive with respect to the target location). For each emotional expression, there were 60 valid trials and 60 invalid trials, with an equal distribution of trials across the four gaze-cue identities (i.e., for each combination of emotional expression and identity, there were 30 trials). Trial types were randomly intermixed within the block.

Each trial began with a 1,000-ms presentation of the direct-gaze version of the gaze cue. This was followed by a 350-ms presentation of the right-averted-gaze or left-averted-gaze version of the same face. A 350-ms stimulus-onset asynchrony (SOA) was chosen as 350 ms is a sufficiently long period of time both for GCEs to emerge, and for the integration of emotional expression and gaze information to occur (Conty et al., 2012; McCrackin & Itier, 2018). The target letter ("E" or "F," randomly determined) was then presented either to the left-hand side or to the right-hand side of the gaze cue with equal likelihood. Participants were required to press the letter "E" or the letter "F" on the keyboard depending on which letter appeared, with the target remaining on the display until a response was made.[2] After a response was registered, the letter disappeared and there was a 1,000-ms intertrial interval. Every 90 trials, there was a self-paced rest break. Figure 2 illustrates the trial sequence for a single trial in the gaze-cueing block.

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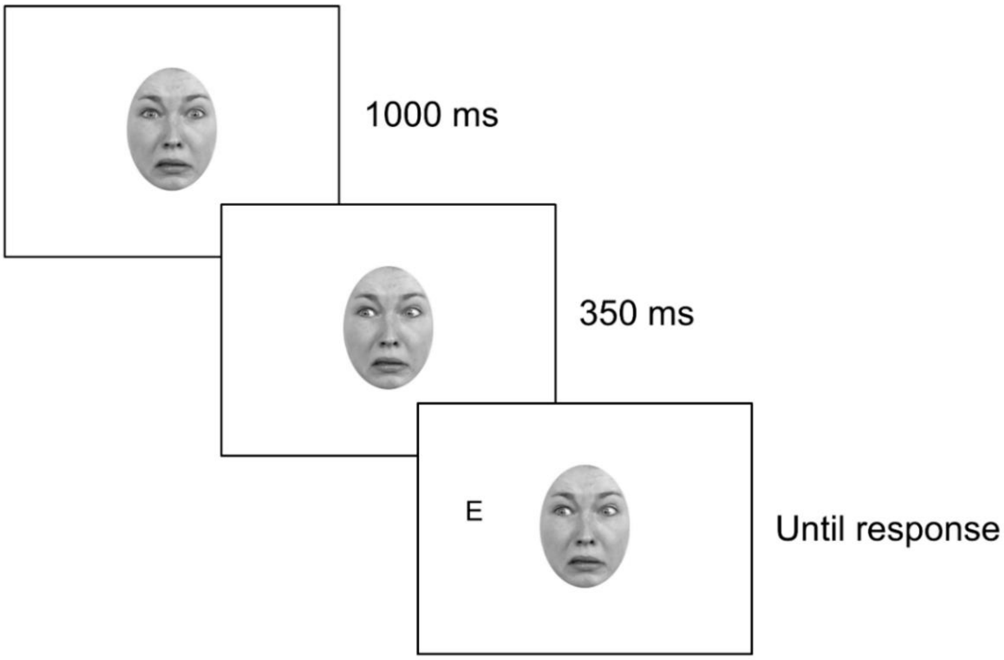
[2] Since the letter "E" was located to the left of the letter "F" on the keyboard, this leads to the possibility that a Simon-like effect (Simon, 1969) emerged whereby responses were faster when the letter "E" was presented on the left and the letter "F" was presented on the right (we thank an anonymous reviewer for raising this possibility). However, since there were no systematic associations between cue validity, target location, and target letter, any cueing effects observed cannot be explained by such a process.

Figure 2

Example of a Single Trial in the Gaze-Cueing Block of the Current Study



Note. This figure shows a valid trial, with a gaze cue displaying the "fearful" emotional expression.

The arrow-cueing block consisted of 120 trials (equivalent to the number of trials for a single emotional expression in the gaze-cueing block), 60 valid and 60 invalid. Following a 1,000-ms presentation of the straight-line component of the arrow, the arrowhead and arrowtail appeared simultaneously for 350 ms. The ensuing letter-discrimination task was the same as that for the gaze-cueing block. Halfway through the block (i.e., after 60 trials), there was a self-paced rest break.

The order in which the gaze- and arrow-cueing blocks were completed was counterbalanced, and each block was preceded by a corresponding 6-trial practice block. Prior to each cueing block, participants were informed that the direction of the gaze or arrow was nonpredictive of the target location, and were instructed to respond as quickly and as accurately as possible to the target letter using their left hand. They were also instructed to maintain fixation on the gaze or arrow cue. Following completion of the experimental blocks, participants completed the screening questionnaire, followed by the LSAS-SR, the trait scale of the STAI, the DASS-21, and the AQ-10. After all tasks were completed, participants were fully debriefed regarding the purpose of the study.

Data Analysis Plan

Trials in which participants responded incorrectly to the letter-discrimination task, had RTs shorter than 100 ms, or had RTs longer than 2.5 *SD*s above their mean RT, were excluded (note that for the gaze-cueing block, RT screening was conducted separately for each emotional expression to account for any potential differences in overall RT between emotional expressions). For the gaze-cueing block, the mean RT for each combination of cueing condition (valid or invalid) and emotional expression (angry, fearful, or neutral) was calculated, collapsed across target location. For the arrow-cueing block, a mean valid RT and a mean invalid RT were calculated, again collapsing across target location. For the gaze-cueing scores, the main analysis consisted of a 2 (cue validity: valid or invalid) x 3 (emotional expression: angry, fearful, or neutral) repeated-measures ANCOVA, with LSAS-SR scores modelled as a continuous covariate. Another ANCOVA including the other scales (also modelled as continuous covariates) was conducted in order to control for other individual-differences variables, and an equivalent Bayesian ANCOVA was performed to quantify the evidence for the effects of interest. Similar analyses were performed on the arrow-cueing scores. Note that each covariate was centred to improve the interpretability of the results (Tabachnick & Fidell, 2013), and where violations of sphericity occurred, the Greenhouse-Geisser correction was employed.

Results

Data Screening

Raw data are available here: https://osf.io/qz3vg/. Two participants' data were excluded due to an indicated diagnosis of ADD or ADHD, and a further four participants' data were excluded because these participants had more than 20% errors in the gaze-cueing block, indicating a lack of engagement with the task. This left a total of 100 participants in the final analysis (see Participants for demographic information). Three univariate outliers (defined as cases with *z*-scores exceeding ±3.29; Tabachnick & Fidell, 2013) were identified, as were three multivariate outliers in the gaze-cueing block and two multivariate outliers in the arrow-cueing block (defined as cases with Mahalanobis distances exceeding 29.59 for the gaze-cueing data and 22.46 for the arrow-cueing data). Given that the results of the analyses reported below were unchanged when these outliers were removed, these cases were retained in the final data set.

Split-Half Reliability of Gaze- and Arrow-Cueing Scores

If a task has poor reliability, this can compromise the ability of a study to observe individual differences in performance on that task (e.g., Goodhew & Edwards, 2019; Hedge et al., 2018). Therefore, we assessed the reliability of our gaze- and arrow-cueing scores by conducting a split-half analysis using the R package “splithalf” (Parsons, 2020). This package provides an estimate of split-half reliability by randomly splitting the data in half for a specified number of repetitions, calculating cueing scores for each half, and then correlating these scores. The final split-half estimate is the average of these correlations.

As recommended by Parsons et al. (2019), 5,000 random splits of the data were performed. For the gaze-cueing scores (collapsed across emotional expression), reliability estimates were as follows: r_s = .95, 95% confidence interval (CI) = [.93, .97] (uncorrected: r = .9, 95% CI = [.87, .93]). The gaze-cueing scores therefore exhibited excellent reliability. For the arrow-cueing scores, reliability was moderate: r_s = .65, 95% CI = [.48, .76] (uncorrected: r = .48, 95% CI = [.32, .62]).

Gaze Cueing

Mean RTs and error rates for the gaze-cueing task are shown in Table 2. RT data for the gaze-cueing block were submitted to an ANCOVA, with cue validity (valid or invalid) and emotional expression (angry, fearful, or neutral) as within-subjects factors, and centred LSAS-SR scores as a continuous covariate. This analysis revealed only a large effect of cue validity, *F*(1, 98) = 25.64, *p* < .001, η_p^2 = .207, with faster RTs in valid trials (*M* = 483 ms) than in invalid trials (*M* = 503 ms); all other main effects and interactions were nonsignificant, including the interaction between cue validity and emotional expression, *F*(1.99, 194.57) = 0.21, *p* = .813, η_p^2 = .002; cue validity and LSAS-SR scores, *F*(1, 98) = 0.45, *p* = .502, η_p^2 = .005; and the critical three-way interaction between cue validity, emotional expression, and LSAS-SR scores, *F*(1.99, 194.57) = 0.62, *p* = .540, η_p^2 = .006. Results were similar when we conducted this analysis separately for each LSAS-SR subscale (see Appendix A for details).

Table 2

Mean RTs for the Gaze- and Arrow-Cueing Tasks

	Gaze						Arrow	
	Angry		Fearful		Neutral			
	Valid	Invalid	Valid	Invalid	Valid	Invalid	Valid	Invalid
RT (ms)	482 (70)	501 (88)	484 (72)	504 (86)	484 (70)	502 (82)	479 (73)	496 (78)
Errors	3.8 (3.6)	3.5 (3.5)	4.1 (3.5)	3.7 (4)	4.1 (4.0)	3.8 (3.4)	3.7 (3.8)	3.7 (3.3)

Note. This table shows the mean reaction time (RT) in ms and mean proportion of errors for each cueing condition of the gaze- and arrow-cueing blocks. *SD*s are presented in parentheses.

It is possible that other individual-differences variables were working in the opposite direction to the effect of SA on the GCE (e.g., autistic-like traits, which have been linked with a reduced GCE; Bayliss et al., 2005), which would mask the presence of this effect in the analysis. Therefore, another ANCOVA was performed on the RT data, with the addition of the STAI, DASS-21 (depression subscale), and AQ-10 scores as centred covariates. Again, only a significant effect of cue validity emerged, $F(1, 95) = 24.94$, $p < .001$, $\eta_p^2 = .208$. None of the other main effects or interactions were significant, including the interaction between cue validity and emotional expression, $F(1.99, 188.79) = 0.20$, $p = .814$, $\eta_p^2 = .002$; cue validity, emotional expression, and STAI scores found in previous studies (e.g., Fox et al., 2007), $F(1.99, 188.79) = 0.99$, $p = .373$, $\eta_p^2 = .010$; cue validity and AQ-10 scores, $F(1, 95) = 0.03$, $p = .860$, $\eta_p^2 < .001$; cue validity, emotional expression, and AQ-10 scores, $F(1.99, 188.79) = 1.55$, $p = .215$, $\eta_p^2 = .016$; cue validity and LSAS-SR scores, $F(1, 95) = 0.75$, $p = .388$, $\eta_p^2 = .008$; and, finally, the critical three-way interaction between cue validity, emotional expression, and LSAS-SR scores, $F(1.99, 188.79) = 0.23$, $p = .793$, $\eta_p^2 = .002$. Results were similar when the separate fear and avoidance LSAS-SR subscales were included as covariates in place of total scores (see Appendix A for details).

Because our conclusions are based on null results, an equivalent Bayesian ANCOVA was conducted using JASP (JASP Team, 2020a). This revealed a BF_{10} of 4.49e + 17 for the effect of cue validity, indicating “decisive” evidence for a GCE (Jeffreys, 1961). For each of the other effects, $BF_{10} < 1$, which is evidence in favour of the null hypothesis for these effects (Jeffreys, 1961). In particular, the BF_{10} for the three-way interaction between cue validity, emotional expression, and LSAS-SR scores was 0.08, indicating “substantial” evidence for the null hypothesis (Jeffreys, 1961). Figure 3 shows scatterplots of the GCE for each emotional expression as a function of centred LSAS-SR scores.[3]

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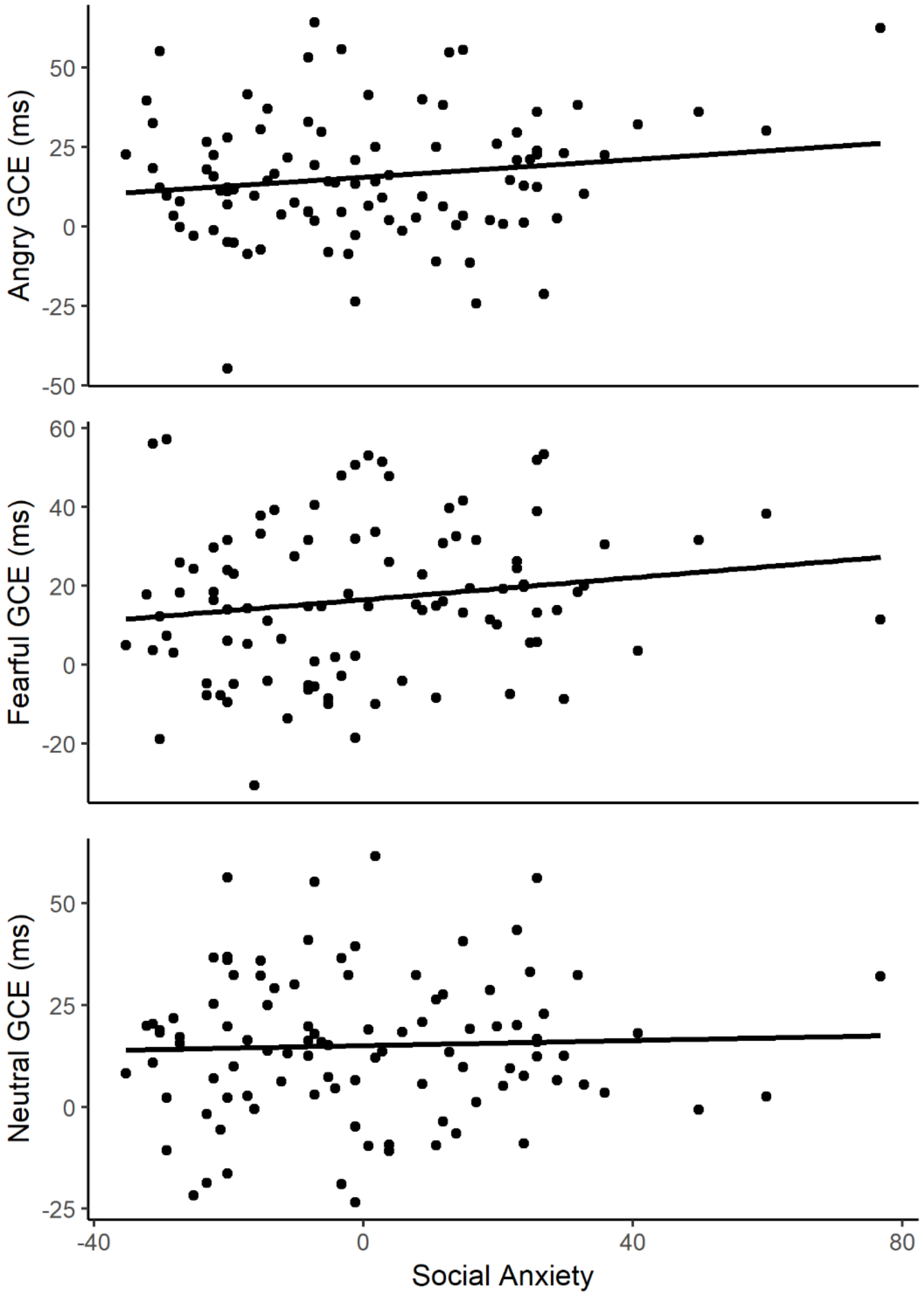
[3] We also examined error rates (i.e., the proportion of times that participants pressed “E” when the letter “F” appeared or pressed “F” when the letter “E” appeared), which are reported in Table 2. Overall, error rates were low: The mean error rate across all gaze-cueing conditions was only 3.8%, and for the arrow-cueing task, only 3.7%.

Figure 3

Relationship Between Social Anxiety and GCEs for Angry, Fearful, and Neutral Expressions



Note. Social anxiety is indexed by centred Liebowitz Social Anxiety Scale (self-report) scores, and angry, fearful, and neutral gaze-cueing effects (GCEs) were calculated by subtracting mean valid reaction times (RTs) from mean invalid RTs. Note that one participant had a particularly large cueing score for each emotional expression due to unusually long invalid-trial RTs. Although outliers were not excluded in the final analysis (see Data

Screening), this participant's data are not plotted in order to more clearly depict the relationship between social anxiety and GCEs.

Arrow Cueing

In light of previous research showing that socially anxious participants have a general impairment in the orienting network of attention (e.g., Heeren et al., 2015), we went on to examine whether SA modulated arrow-cueing scores. Mean RTs and error rates for the arrow-cueing task are shown in Table 2. We performed an ANCOVA on RTs in the arrow-cueing block, which contained the cue validity factor (valid or invalid) and the centred LSAS-SR scores as a covariate. This analysis again revealed only a significant effect of cue validity, $F(1, 98) = 36.5$, $p < .001$, $\eta_p^2 = .271$, with faster RTs in valid trials ($M = 479$ ms) compared to invalid trials ($M = 496$ ms); of note, the interaction between cue validity and LSAS-SR scores was not significant, $F(1, 98) = 1.17$, $p = .282$, $\eta_p^2 = .012$. Another ANCOVA with STAI, DASS-21 (depression subscale), and AQ-10 scores included as additional covariates again revealed only a significant main effect of cue validity, $F(1, 95) = 35.61$, $p < .001$, $\eta_p^2 = .273$; the interaction between cue validity and LSAS-SR scores was not significant, $F(1, 95) = 1.18$, $p = .281$, $\eta_p^2 = .012$. A Bayesian equivalent of this ANCOVA revealed a BF_{10} of 390,188.10 for the effect of cue validity ("decisive" evidence for an arrow-cueing effect; Jeffreys, 1961), and a $BF_{10} < 1$ for each of the other effects (evidence for the null hypothesis). Results were unchanged when separate analyses were conducted for both subscales of the LSAS-SR (see Appendix A for details).

Discussion

In this study, we investigated whether SA modulates the GCE for different emotional expressions. While we observed reliable GCEs, we obtained clear evidence that these effects were not modulated by SA; in other words, in spite of SA being associated with a range of attentional biases, we have shown that gaze following is a process that remains intact across levels of SA. Interestingly, and contrary to some published findings, we also observed no modulations of the GCE by emotional expression, or modulations of the GCE by trait anxiety, depression, or autistic-like traits. Before turning to the implications of these findings, we first consider possible explanations for these null results.

Alternative Explanations

One possibility for the lack of any effects involving SA is that we did not observe sufficient range in LSAS-SR scores to be able to detect an effect. First, it should be noted that SA symptoms are normally distributed within the general population (Rapee & Spence, 2004), and that the use of a continuous variable is preferable to dichotomisation in most circumstances (e.g., DeCoster et al., 2009; MacCallum et al., 2002). Therefore, our operationalisation of SA as a continuous variable was appropriate. The mean LSAS-SR score in our study was 50.2, with scores ranging from 15 to 127 (note that the maximum possible score was 144). Mennin et al. (2002) recommended a cutoff score of 30 for social anxiety disorder, and 60 for its more severe, generalised subtype. In our sample, 82 of our 100 participants had scores of 30 or above, and 33 participants had scores of 60 or above. One possibility, then, is that we did not have enough participants with *low* LSAS-SR scores. Note, however, that our mean total LSAS-SR score of 50.2 was only slightly higher than the mean total LSAS-SR score of 45.7 found in a large university-student sample (Caballo et al., 2013), with the spread of scores similar between the two studies (*SD* = 22.1 in our study; *SD* = 19.8 in Caballo et al., 2013). Furthermore, in another study where LSAS-SR scores were used as a continuous covariate, significant effects of these scores were found on attentional engagement to angry faces (Delchau et al., 2019) despite a mean LSAS-SR score that was higher than ours (*M* = 55.4), and with a similar standard deviation (*SD* = 22.9). Finally, when we compared the 33 highest LSAS-SR scorers with the 33 lowest LSAS-SR scorers in a between-subjects analysis, we again found no effect of SA on cueing scores (see Appendix B for details). Therefore, it seems unlikely that an insufficient spread of LSAS-SR scores could account for our null findings.

Another possibility is that our study lacked a sufficiently threatening context for a modulation of GCEs by SA to emerge. Mansell et al. (2002), for instance, found that socially anxious participants only avoided emotional faces when they were under social-evaluative threat (i.e., when participants were informed that they would have to deliver a speech following the experimental blocks). Our study did not contain such a manipulation.[4] However, there are many examples of socially anxious participants exhibiting attentional biases, such as a bias towards angry faces (e.g., Gilboa-Schechtman et al., 1999; Mogg et al., 2004), in the absence of such a condition. Unless the GCE is somehow less sensitive to modulations than these other attentional processes, it is unlikely that the lack of a threatening context is responsible for our null findings.

It could also be argued that the dynamics of the gaze-cueing paradigm we employed may not have been appropriate for revealing modulations of the GCE by *emotional expression*. Our sequence began with the direct-gaze version of the face already expressing the relevant emotion, and then averting its gaze; in other words, the emotional content of the gaze cue remained constant throughout the trial sequence. It has been argued that a dynamic sequence in which the gaze cue only assumes the relevant expression after the eyes have been averted is more likely to reveal modulations of the GCE by emotional expression, given that it reflects a more naturalistic scenario in which an emotion is expressed after an object is noticed (e.g., a neutral face assumes a fearful expression when a spider appears; Lassalle & Itier, 2015a). However, McCrackin and Itier (2019) have argued that the sequence used in the current study may tap into the differential sensitivity of particular populations to different emotions, and therefore may be the most ideal for revealing *individual differences* in gaze cueing; the authors offered this as a potential explanation for why they did not observe modulations of the GCE by trait anxiety, since they employed the aforementioned “gaze-shift-first” sequence. For SA specifically, the initial presentation of a directly gazing face expressing a socially threatening emotion—such as anger—would be the most likely to elicit an affective response in high-SA participants, since

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[4] Note, however, that the experimenter was present in the room with the participant as they completed the gaze- and arrow-cueing blocks, which may have created somewhat of a socially threatening environment.

high-SA participants are averse to such expressions when they are gazing directly at the participant (e.g., Heuer et al., 2007; Mansell et al., 1999; Roelofs et al., 2010). In other words, if SA had modulated gaze following, it would likely have done so via a perception of threat in the gaze cue, and subsequent attentional maintenance on the face (potentially leading to an enhanced GCE) or avoidance (potentially leading to a diminished GCE). Therefore, while the type of sequence we used may be able to explain why no interaction between cue validity and emotional expression emerged, it cannot explain the lack of modulation by SA, or by any of the other individual-differences variables.

The lack of any modulation of the GCE by emotional expression might also be explained by the nature of the task (i.e., letter discrimination). For example, it has been argued that simply identifying a target letter—as opposed to making a more complex judgement about a target (e.g., “safe” versus “dangerous”; e.g., Dawel et al., 2015)—can lead to a weaker, or absent, effect of emotional expression (Friesen et al., 2011). However, Coy et al. (2019)—across five experiments—failed to replicate the enhanced GCE for fearful faces even when a “safe” versus “dangerous” image-categorisation task was employed, and modulations of the GCE by emotional expression have been observed even when simpler tasks, such as target localisation, have been used (e.g., Bayless et al., 2011; Lassalle & Itier, 2013, 2015a, 2015b). It has also been argued that localisation tasks are better able to reveal modulations of the GCE by emotional expression than discrimination tasks like ours, particularly for fearful expressions; this is because the hybrid of emotion and gaze information conveyed by a gaze cue could inform the viewer of where a dangerous target is located, which aligns more closely with the requirements of a localisation task (Lassalle & Itier, 2013). However, as we argued earlier, discrimination tasks are more appropriate for revealing the *attentional* effects of orienting in response to a gaze cue, since cueing effects revealed by localisation tasks may instead reflect the priming of response preparation and execution (Wiese et al., 2013). Therefore, while we may have observed modulations of the GCE by emotional expression had we used a localisation task instead of a discrimination task, we would not have been able to determine whether this was an entirely *attentional* modulation.

Finally, it is worth considering the possibility that our choice of SOA explains why we did not observe modulations of the GCE by any of the individual-differences variables, any of the emotional expressions, or by the combination of these two variables. Previous gaze-cueing studies have used a wide variety of SOAs, ranging from approximately 200 ms (e.g., Bayless et al., 2011; Graham et al., 2010; Putman et al., 2006) to around 700 ms (e.g., Tipples, 2006). Our 350-ms SOA was therefore comfortably within the range of those used in previous studies, and in particular, was similar to the SOAs used in studies that have observed modulations of the GCE: Fox et al. (2007), for instance, found an enhanced fearful GCE in high-trait-anxious participants with an SOA of 300 ms. Indeed, our SOA was also sufficiently long to allow for the integration of emotional expression and gaze information, which can occur as early as 200 ms after cue onset (Conty et al., 2012; McCrackin & Itier, 2018). Therefore, our null results are unlikely to be the product of the SOA we chose to employ. It should be noted, however, that some literature on vigilance-avoidance processes in anxiety indicates that engagement with threatening stimuli varies as a function of time course, such that anxious individuals experience rapid engagement with threatening stimuli, followed by disengagement (e.g., Mogg et al., 2004); this hints at the possibility that temporal factors such as SOA may play a role in attentional processes such as gaze cueing. Nevertheless, the fact that we obtained robust GCEs in spite of each face preceding stimulus onset for over a second (including the duration of the direct-gaze version of the face) suggests that avoidance of the stimulus did not occur; furthermore, if differences in the time course of GCEs were to differ across SA, this would likely occur as a function of total time of exposure to the face, rather than SOA per se. Nevertheless, future research could examine the time course of gaze cueing in SA.

Overall, then, it appears unlikely that the absence of any interactions involving cue validity could be attributed to insufficient spread in LSAS-SR scores, the lack of a sufficiently threatening context, the gaze-cueing sequence employed, the nature of the task, or the particular SOA used in our study. We therefore turn now to the implications of our findings.

Implications for Social Anxiety

SA is characterised by a range of attentional biases, including engagement towards, avoidance of, and delayed disengagement from socially threatening expressions (e.g., Buckner et al., 2010; Mansell et al., 2002; Mogg et al., 2004). However, our data suggests that gaze-following is an attentional process that is unaffected by SA, even for expressions that could be perceived as threatening to high-SA participants (e.g., anger). Our findings align with those of Gregory et al. (2019), who found that those with SA do not show differences in overt gaze-following behaviour compared to a control group; however, we have extended this finding to the gaze-cueing paradigm, which can capture *covert* shifts of attention. In showing that this lack of modulation extends to gaze cueing by angry expressions, for which a range of attentional biases in SA have been demonstrated (e.g., Mogg et al., 2004), we have also extended the findings of Gregory and Jackson (2017), Wei et al. (2019), and Boll et al. (2016), who used only neutral expressions. The sparing of gaze cueing across SA perhaps attests to the fundamental importance of gaze-following behaviour, particularly as a means of detecting important environmental events, gauging the intentions of others, and facilitating social communication (Baron-Cohen, 1995).

At first blush, our results for both the gaze-cueing task and the arrow-cueing task are inconsistent with Heeren et al.'s (2015) finding that the orienting network of attention is impaired in those with SA. These authors found that compared to a nonclinical group, socially anxious participants exhibited a diminished orienting effect in response to a predictive peripheral cue. In our study, we observed no modulations of gaze- or arrow-induced orienting by SA. One explanation for this seeming inconsistency is that gaze and arrow cues carry more social and symbolic relevance than do peripheral cues, and therefore by virtue of their functional significance, are more resistant to modulations by SA. Another possibility relates to the fact that our gaze and arrow cues were nonpredictive, whereas in

Heeren et al.’s study, the cue was 100% valid. Therefore, altered orienting effects in those with SA could reflect differences in how the informative value of the cue was processed. Whatever the explanation for these discrepant findings, it is clear from our results that the ability to shift attention per se is unaffected by SA, since no diminished cueing effects were found in the current study.

Modulation of Gaze Cueing by Other Individual Differences

As well as being unaffected by individual differences in SA, the GCEs we obtained in our study were robust to both the emotional expression of the gaze cue and the other individual-differences variables. As argued earlier, one possibility for the lack of any modulations by emotional expression (irrespective of any individual differences) was that we did not use a gaze-cueing sequence in which the face changed expression *after* averting its gaze, which some (e.g., Lassalle & Itier, 2015a; McCrackin & Itier, 2019) have argued is the most appropriate sequence for revealing such effects. While it has been suggested that the gaze-cueing sequence used in our study may be more appropriate for revealing *individual differences* in the magnitude of the GCE (McCrackin & Itier, 2019), the fact that we obtained no modulation of the GCE by any of the individual-differences variables in spite of this calls into question the relevance of this variable in explaining the presence or absence of these modulations. As mentioned previously, it is also unlikely that the nature of the task or our choice of SOA can explain our null findings. Therefore, we now explore each individual-differences variable in more depth.

Considering trait anxiety, previous studies have found that high-trait-anxious participants exhibit an enhanced GCE in response to fearful faces (Fox et al., 2007; Holmes et al., 2006; Mathews et al., 2003; Putman et al., 2006; Tipples, 2006). We observed no such effect. Interestingly, Mathews et al. (2003) and Fox et al. (2007) used a virtually identical gaze-cueing sequence to ours, and an identical measure of trait anxiety (the trait scale of the STAI).[5] These authors did not report the overall mean or spread of scores on this scale, so it is difficult to assess whether this inconsistency could be attributed to differences in the participant sample. However, it is worth noting that our sample size of 100 vastly exceeds that of both Mathews et al. (*N* = 45) and Fox et al. (*N* = 40), as well as those of the other studies (*N* = 36 in Holmes et al., 2006; *n* = 30 in Experiment 1 of Putman et al., 2006; *N* = 38 in Tipples, 2006); it is therefore likely that our study possessed more power to detect such an effect. Furthermore, when we dichotomised our participant sample into "low-trait-anxious" and "high-trait-anxious" groups for comparability to these earlier studies, we also obtained no effect of trait anxiety on GCEs (see Appendix B for details of this analysis). Our results therefore seriously call into question the robustness of this effect.

We also did not find any effects of depression or autistic-like traits on gaze-cueing scores. With regard to depression, McCrackin and Itier (2019) have previously suggested that the purported trait-anxiety modulation of the fearful GCE may be driven by this construct; however, they failed to find any effect of depression on GCEs in their own data. Consistent with their results, in our study, we obtained no significant effects involving depression, providing further evidence that this variable does not modulate gaze cueing. With regard to autistic-like traits, previous studies have reported diminished GCEs in autism (e.g., Ristic et al., 2005); McCrackin and Itier (2019) also reported that high scores on the Attention to Detail subscale of the full AQ were associated with reduced modulations of the GCE by emotional expression, especially for happy expressions (see also Lassalle & Itier, 2015b). This may be because in order for such modulations to emerge, the face must be processed holistically; high scorers on the Attention to Detail subscale may instead use a local processing strategy (Lassalle & Itier, 2015b; McCrackin & Itier, 2019). Perhaps we did

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[5] It should be noted that we used a different discrimination task to that used in either of these studies ("E" versus "F" as opposed to "T" versus "L"), and there is a possibility that our task was more cognitively demanding due to a slightly greater visual similarity between the letters. However, errors in our study were infrequent (see Table 2 and Footnote 3). Furthermore, both Mathews et al. (2003) and Fox et al. (2007) only reported their total proportion of excluded trials (including trials that fell above or below particular RT cutoffs), rendering a comparison of our error rates to theirs impossible. However, given the infrequency of error rates in our study, we find it unlikely that there were substantial differences in the cognitive demands engendered by the two tasks.

not obtain an effect of autistic-like traits on the GCE because we administered the AQ-10 (a shortened version of the AQ), which did not allow us to probe the different facets of autistic-like traits, or because we did not include gaze cues with happy expressions. Another potential explanation lies in the fact that we used an all-female participant sample, which may have resulted in few high AQ-10 scores being observed (see Baron-Cohen et al., 2001, for a discussion of sex differences in autistic-like traits). Indeed, in our sample of 100 participants, only 11 had an AQ-10 score of 6 or above, where a score of 6 represents the proposed cutoff point for a potential diagnosis of autism spectrum disorder (Allison et al., 2012). Nevertheless, our inability to replicate the trait-anxiety modulation of the GCE for fearful faces—within a large sample—suggests that the reliability of effects relating to autistic-like traits might also merit further investigation.

Reliability of Gaze Cueing

That gaze-cueing scores were not modulated by SA, or by any of the other individual-differences variables, could be attributed to the profound social importance of attending to locations gazed at by another. Indeed, it may be the case that this process is so fundamental to everyday social functioning that it is resistant to any differences across SA in how the emotional content of a face is perceived (i.e., as socially threatening versus socially benign). Support for the potential innateness of gaze following comes from studies showing that humans possess dedicated neural circuitry for processing gaze direction (e.g., Allison et al., 2000; Perrett et al., 1992; see Emery, 2000, and Carlin & Calder, 2013, for reviews), and that gaze-following behaviour occurs early in life (e.g., Farroni et al., 2000; Hood et al., 1998). Additionally, if the GCE is indeed greater for females than it is for males (e.g., Bayliss et al., 2005; McCrackin & Itier, 2019), perhaps because females exhibit a relatively heightened sensitivity to nonverbal social cues (Hall, 1978), then our all-female participant sample may have further contributed to buttressing the GCE against modulation by SA and the other individual-differences variables. Nevertheless, our gaze-cueing scores exhibited excellent rank-order consistency when a split-half analysis of these scores was conducted (r_s

= .95; see Results). This indicates that there may be systematic individual differences in the magnitude of the GCE. Our null findings, however, suggest that SA, trait anxiety, depression, and autistic-like traits are not the source of these differences; therefore, further research should be devoted to examining the robustness of individual-differences variables that have been claimed to modulate the GCE, and to uncovering other contextual variables that may modulate the effect (e.g., Dalmaso et al., 2020).

Conclusion

SA is associated with a range of attentional biases. However, the current study shows that attentional orienting in response to one's gaze direction—a cue with powerful social meaning—is unaffected by individual differences in SA, even for emotional expressions that high-SA participants find especially threatening (i.e., anger). In the process of controlling for other individual-differences variables that have been claimed to modulate the GCE, we also failed to replicate the results of previous studies that have shown modulations of the fearful GCE by trait anxiety, and also found no effect of depression or autistic-like traits. We suggest that the gaze cueing and individual differences literature may be faced with the same replicability issues as the literature on the modulation of gaze cueing by emotional expression, echoing Coy et al.'s (2019) recent call for these ostensible modulations to be reinvestigated.

Appendix A

Separate Analyses of Gaze- and Arrow-Cueing Scores for Each LSAS-SR Subscale

In addition to the analyses containing the total score of the LSAS-SR that are reported in the main text, we conducted separate ANCOVAs for the fear and avoidance subscales, for both the gaze- and arrow-cueing blocks.

Gaze Cueing

An ANCOVA with cue validity (valid or invalid) and emotion (angry, fearful, or neutral) as within-subjects factors, and centred fear scores as a covariate, revealed only a significant effect of cue validity, $F(1, 98) = 25.86$, $p < .001$, $\eta_p^2 = .209$; all other effects were not significant, including the interaction between cue validity and fear scores, $F(1, 98) = 1.28$, $p = .261$, $\eta_p^2 = .013$, and the three-way interaction between cue validity, emotional expression, and fear scores, $F(1.98, 194.38) = 1.29$, $p = .278$, $\eta_p^2 = .013$. A similar ANCOVA with centred avoidance scores included as a covariate also only revealed a significant effect of cue validity, $F(1, 98) = 25.53$, $p < .001$, $\eta_p^2 = .207$; again, all other effects were not significant, including the interaction between cue validity and avoidance scores, $F(1, 98) = 0.04$, $p = .852$, $\eta_p^2 < .001$, and the three-way interaction between cue validity, emotional expression, and avoidance scores, $F(1.99, 194.70) = 0.16$, $p = .855$, $\eta_p^2 = .002$. When both fear and avoidance scores were included in the same analysis with the other covariates (STAI, DASS-21 [depression subscale], and AQ-10 scores), again only an effect of cue validity emerged, $F(1, 94) = 25.51$, $p < .001$, $\eta_p^2 = .213$; of note, the interaction between cue validity, emotional expression, and fear scores was not significant, $F(1.99, 186.71) = 2.02$, $p = .136$, $\eta_p^2 = .021$, and neither was the interaction between cue validity, emotional expression, and avoidance scores, $F(1.99, 186.71) = 1.11$, $p = .331$, $\eta_p^2 = .012$.

Arrow Cueing

Another ANCOVA with cue validity (valid or invalid) as a within-subjects factor, and centred fear scores as a covariate, revealed only a significant effect of cue validity, $F(1, 98)$

= 36.22, $p < .001$, $\eta_p^2 = .270$ (all other *p*s > .3). A similar ANCOVA with centred avoidance scores included as a covariate also only revealed a significant effect of cue validity, $F(1, 98) = 36.81$, $p < .001$, $\eta_p^2 = .273$ (all other *p*s > .1). When both fear and avoidance scores were included in the same analysis with the other covariates (STAI, DASS-21 [depression subscale], and AQ-10 scores), again only an effect of cue validity emerged, $F(1, 94) = 36.01$, $p < .001$, $\eta_p^2 = .277$ (all other *p*s > .08).

Appendix B

Between-Subjects Analyses

While we treated our individual-differences measures as continuous covariates, other authors have dichotomised their participant sample on the basis of questionnaire scores (e.g., Fox et al., 2007). We reanalysed our data using this approach.

Social Anxiety

We performed a mixed ANCOVA on gaze-cueing scores by creating a “low-SA” group (lowest 33 scorers on the LSAS-SR; $M = 26.9$, $SD = 5.7$) and a “high-SA” group (highest 33 scorers on the LSAS-SR; $M = 74.8$, $SD = 15.6$), and including “SA group” as a between-subjects factor. Note that each participant in the “high-SA” group had scores exceeding 61, above the cutoff score of 60 suggested by Mennin et al. (2002) as indicative of generalised SA; participants in the “low-SA” group had a maximum score of 36. The analysis revealed a significant main effect of cue validity, $F(1, 61) = 120.43$, $p < .001$, $\eta_p^2 = .664$, and a significant interaction between emotional expression and AQ-10 scores, $F(2, 60) = 4.63$, $p = .025$, $\eta_p^2 = .116$; none of the other effects were significant, including the critical three-way interaction between cue validity, emotional expression, and SA group, $F(2, 63) = 0.40$, $p = .670$, $\eta_p^2 = .013$. Because the interaction between emotional expression and AQ-10 scores was not relevant to our main research question, and did not emerge in the other analyses, it was not considered further. A similar mixed ANCOVA on arrow-cueing scores revealed only a significant main effect of cue validity, $F(1, 61) = 22.3$, $p < .001$, $\eta_p^2 = .268$ (all other *p*s > .1).

Trait Anxiety

Both Mathews et al. (2003) and Fox et al. (2007) grouped participants into “low-trait-anxious” and “high-trait-anxious” groups. We took the bottom 33 scorers on the trait scale of the STAI and the top 33 scorers on this scale (bottom scorers: $M = 34.9$, $SD = 4.2$; top scorers: $M = 56.7$, $SD = 6.2$), and included “trait-anxiety group” as a between-subjects variable in a 2 (cue validity: valid or invalid) × 3 (emotional expression: angry, fearful, or neutral) × 2 (group: low-trait-anxious or high-trait-anxious) mixed ANOVA. This revealed only a significant main effect of cue validity, $F(1, 64) = 115.4$, $p < .001$, $\eta_p^2 = .643$; in particular, the critical interaction between cue validity, emotional expression, and trait-anxiety group was not significant, $F(2, 63) = 0.24$, $p = .785$, $\eta_p^2 = .008$. Note that the mean trait-anxiety scores for the low-trait-anxious and high-trait-anxious groups in our study (34.9 and 56.7, respectively) were similar to those in Mathews et al. (31 for the low-trait-anxious group and 53 for the high-trait-anxious group); Fox et al. reported only that their low-trait-anxious group had scores below 35 and their high-trait-anxious group had scores exceeding 45.

Chapter 7

The Effects of Attentional Orienting on Visual Perception

Chapter Overview

The first part of this thesis focused on the factors that may influence responsiveness to social and nonsocial cues. This section of the thesis yielded several insights, including the stability of social orienting across levels of social anxiety (Chapter 4); the inability of a nonsocial motion signal equivalent in magnitude to a pupil shift in a dynamic gaze cue to elicit attentional orienting (Chapter 5); and variable results concerning the efficiency of orienting by arrow cues, yet consistent findings that orienting by gaze cues survives secondary task demands (Chapter 6). These findings speak to the robustness of social orienting, and show that the social content of dynamic gaze cues is important in eliciting this attentional response. Additionally, while Chapter 6 yielded mixed findings regarding the efficiency of nonsocial orienting (i.e., orienting by arrow cues), it appears that orienting by gaze cues is particularly robust to the depleted top-down processing resources engendered by a working memory load, regardless of whether the gaze cue is dynamic or static.

In the second part of this thesis, I turn to the *perceptual consequences* of attentional orienting, focusing specifically on the effects of attention on temporal resolution (Chapter 8) and ensemble processing (Chapter 9), two important aspects of visual perception. The purpose of this chapter is to provide an overview of research on the perceptual effects of attention that is necessary for contextualising the issues addressed by Chapters 8 and 9. In doing so, I move away from the distinction between social and nonsocial cues to the perceptual effects of attentional orienting more generally.[1]

This chapter differentiates between the effects of attention on the perception of single items and the effects of attention on the perception of *collections* of items (i.e., ensemble

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[1] Note, however, that the distinction between voluntary and involuntary forms of attentional orienting will become relevant at times, given that these two forms of attention can have differential effects on perception.

stimuli). When studying the effects of attention on single items, it is also important to distinguish between spatial processing and temporal processing—that is, how attention affects our perception of variation in luminance across space and across time, respectively. Much research on the effects of attention on spatial aspects of visual processing has focused on contrast sensitivity (i.e., the ability to distinguish an object from its background), which is enhanced by attention (e.g., Carrasco, 2006; Carrasco et al., 2000). However, it is also important to consider how attention affects spatial and temporal *resolution*—that is, the visual system's sensitivity to spatial and temporal detail. The distinction between spatial and temporal resolution is noteworthy because these processes are mediated by different pathways: The visual system's greatest spatial resolution (i.e., spatial acuity) is mediated by the parvocellular visual pathway, while its greatest temporal resolution (i.e., temporal acuity) is mediated by the magnocellular visual pathway (Edwards et al., 2021). The fact that spatial and temporal acuity are mediated by different visual pathways introduces the possibility that they may be differentially affected by attention, and Chapter 8 offers a test of Yeshurun and Levy's (2003) proposal that involuntary attention, while enhancing spatial resolution, can impair temporal resolution. Chapter 9 then moves beyond single items to examine the effects of attentional orienting on ensemble processing—the ability to extract summary information from a collection of items.

Before discussing the research informing these studies, I address the specific methodological issues that are involved in studying the effects of attention on visual perception, and which have influenced the design of the experiments presented in Chapters 8 and 9. It should also be noted that my focus is specifically on the effects of attention on observers' *performance* on visual tasks, rather than the appearance of stimuli. The latter body of research is concerned with how attention alters the perceived qualities of a stimulus (e.g., as indexed by participants' judgments about which of two stimuli appears to have higher contrast; see Carrasco & Barbot, 2019, for a review). While the effects of attention on appearance and those on performance are correlated (e.g., Barbot & Carrasco, 2018), these remain two separate lines of research with distinct methods, and my focus is on the latter aspect of perception.

Studying the Effects of Attentional Orienting on Visual Perception

There are several methodological issues that must be considered when examining the perceptual consequences of attentional orienting. The first issue concerns the appropriate dependent measure for assessing these effects. Reaction time—the main dependent variable used in the first three empirical chapters of this thesis—is not appropriate for assessing whether attention truly changes the quality of visual representations, because changes in reaction time can reflect changes in variables such as motor preparation and decisional processes, not just perceptual modulations (Shiu & Pashler, 1994). More appropriate measures for determining whether attention modulates perception include accuracy (i.e., proportion of correct responses), sensitivity (i.e., *d′*), and psychophysical thresholds (i.e., the stimulus intensity required for an observer to achieve a specific level of performance). For a detection task involving a judgment about the presence or absence of a stimulus or stimulus feature (i.e., a “yes/no” task), sensitivity should be used; this is because in such tasks, changes in accuracy can be contaminated by changes in response criterion (i.e., how liberal or conservative participants are in making this judgment). For a discrimination task involving a forced choice between two or more alternatives (e.g., the location of a gap in a square), criterion effects are removed and thus accuracy becomes an appropriate dependent measure (Stanislaw & Todorov, 1999). Finally, when there are considerable individual differences in performance that would make it difficult to select a single intensity at which to present the stimulus, thresholds (determined through forced-choice responses to a stimulus varying in intensity) are preferable to either accuracy or sensitivity. Overall, attentional modulations of perception are revealed via differences in such measures between valid trials and invalid trials (neutral trials can also be used, but see Chapters 3 and 8 for the interpretational difficulties posed by neutral cues).[2]

Another issue to consider is what mechanism underlies any changes in performance between trial types. When asking the question of whether attention affects perception, most researchers are interested in knowing whether attention directly acts on the perceptual representation of the target—this is referred to as the *signal enhancement* account of attentional modulation (Carrasco, 2011; Serences et al., 2004). According to this account, attention acts by enhancing the signal generated by the features of the stimulus, which results in an increase in the signal-to-noise ratio of the neural activity evoked by that stimulus; such an increase is required to produce enhanced perceptual performance. Enhanced performance via an increase in the signal-to-noise ratio could also come about through attention reducing variability in the responses of single neurons, or reducing the degree of correlated noise between neural populations (i.e., through noise reduction of local population responses; Serences, 2011). But changes in performance could also, in some instances, be attributed to a reduction in noise from other stimuli—for instance, attention suppressing the processing of distractors in the display (Carrasco, 2011). This explanation does not involve any modulation of the sensory responses produced by the target in its own right. To make sure that any changes in performance can be attributed to modulations of the neural responses produced by the target, the stimulus acting as the target should be presented well above threshold (i.e., it should be clearly visible, thus minimising location uncertainty—a source of internal noise) and without any distractors or masks (i.e., sources of external noise; Carrasco et al., 2002).

Finally, when the interval between the onset of the cue and the onset of the target is longer than around 200 ms—the approximate latency of a saccade, albeit with some

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[2] Reaction times should also be examined to rule out the presence of speed-accuracy trade-offs—for instance, a case where an observer is only more accurate on valid trials than on invalid trials because they respond more slowly in the former, and not because true perceptual enhancement has occurred (e.g., Carrasco et al., 2002).

interindividual variability (Carpenter, 1988)—the monitoring of eye movements with an eye-tracker, coupled with the instruction to maintain fixation, is required to ensure that any differences between trial types is the result of attention independent of any eye movements. That is, while an eye movement to the target involves a shift of attention—albeit an overt one—the more critical question is whether attention on its own (i.e., *covert* attention) modulates perception. Given the rapid decline in spatial acuity as eccentricity (i.e., the distance between the fovea and the part of the retina on which the stimulus is projected) increases, it would be unsurprising to find that observers are better at a visual task requiring the perception of fine spatial detail when they have moved their eyes towards it (i.e., on a valid trial) compared to when they have moved their eyes to another location (i.e., on an invalid trial).

The Effects of Attentional Orienting on the Processing of Single Items

Much of the research on attention and visual perception has focused on how attention modulates processing of a single stimulus, such as contrast sensitivity to a single Gabor patch (e.g., Carrasco et al., 2000). In this section, I focus specifically on the effects of attentional orienting on spatial and temporal resolution in order to contextualise Chapter 8 of this thesis, which tests an alternative account of reported attentional effects on the latter aspect of perception. The studies investigating these effects have typically used single acuity targets to tap the visual system’s resolving power—that is, the highest spatial or temporal resolution the visual system can achieve—and determine how it is affected by attention. As discussed previously, spatial and temporal acuity are mediated by the parvocellular and magnocellular pathways, respectively (Edwards et al., 2021), which introduces the possibility that these aspects of perception are differentially affected by attention.

Attention and Spatial Resolution

In order to read the text on a far-off display, discern a small detail in a visual scene, or thread a needle, we require high spatial resolution. High spatial resolution is achieved through sensitivity to the high spatial frequencies in an image, which are defined by rapid variation in luminance across space corresponding to the fine spatial detail in that image; relatively lower spatial frequencies, on the other hand, are defined by less rapid variation in luminance corresponding to the image's coarser spatial detail (Edwards et al., 2021). A number of studies have examined the effects of attention on spatial resolution, with most finding that attention *enhances* this aspect of perception. In one study, Yeshurun and Carrasco (1999) examined whether transient attention (a largely involuntary form of attention) modulates performance on acuity tasks, such as determining which side of a square contains a small gap and whether a vertical line is broken or continuous. Such acuity tasks call on the visual system's highest spatial resolution, and thus are ideal for examining the effects of attention on the ability to perceive fine spatial detail (Carrasco, 2011). Across three such acuity tasks, Yeshurun and Carrasco found that performance was more accurate (i.e., the proportion of correct responses was higher) on cued trials, where the location of the target was indicated via the brief presentation of a cue at the target location, than on neutral trials, where the cue was presented in the centre of the display.[3] This pattern of results indicates that transient attention enhanced the visual system's spatial resolution, and thus the observers' ability to perceive fine spatial detail.

Such enhancements of spatial acuity by involuntary forms of attention have since been observed in numerous studies (e.g., Bocanegra & Zeelenberg, 2011; Carrasco et al., 2002), and more voluntary forms of attention (elicited by centrally presented, predictive cues) have been found to produce similar effects on acuity (e.g., Montagna et al., 2009). Moreover, for both types of attention, spatial acuity is not only enhanced at validly cued locations, but also *impaired* at invalidly cued locations (Montagna et al., 2009). However, results from texture-segmentation tasks—where observers must identify which of two stimulus

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[3] As discussed in Chapter 3, while attention operationalised in this way is likely to elicit an involuntary form of orienting (like exogenous attention), it is typically termed "transient" instead of "exogenous" attention because the cue is 100% predictive and therefore the orienting response is likely to be at least partially volitional. Indeed, perceptual effects of purely exogenous orienting (elicited by a nonpredictive cue) can be difficult to observe (e.g., Kerzel et al., 2010; Pack et al., 2013).

presentations contained a “texture target” (a patch of lines oriented differently to the rest of the lines in the display)—have shown that voluntary attention will not enhance spatial resolution if this is detrimental to performance on the task, as is the case when enhancing spatial resolution would make it too high for the scale of the texture (e.g., Barbot & Carrasco, 2017; Yeshurun et al., 2008).[4] Transient attention, however, enhances spatial resolution regardless of task demands; this is evidenced by impaired performance on such tasks in central vision, where spatial resolution is already high (e.g., Yeshurun & Carrasco, 1998, 2000).

How does attention modulate spatial resolution, and how could the underlying mechanism lead to differential effects of attention on *temporal* resolution? One possibility is that attention scales the sensitivity of the visual system to high and low spatial frequencies; involuntary attention may specifically enhance the visual system’s sensitivity to high spatial frequencies, while more voluntary forms of attention may enhance sensitivity to high or low spatial frequencies depending on task demands (in line with the behavioural effects observed with texture-segmentation tasks; e.g., Yeshurun et al., 2008). This explanation has received support via computational modelling (Jigo et al., 2021), and this scaling might be achieved through involuntary attention selectively enhancing the activity of parvocellular neurons (which mediate our spatial acuity) to enhance spatial resolution, while voluntary attention might enhance or reduce the activity of parvocellular neurons depending on whether the task requires higher or lower spatial resolution. The enhancement of parvocellular activity by involuntary attention could come with a concomitant reduction in temporal resolution, since parvocellular neurons exhibit sluggish responses; it may also reduce the activity of magnocellular neurons (which mediate our temporal acuity) through interchannel inhibition (Yeshurun, 2004; Yeshurun & Sabo, 2012). Another possibility is that attention attracts receptive fields to the attended location, leading to a greater concentration of processing

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[4] The fact that such tasks involve collections of items means that they are likely to be examples of ensemble stimuli, but they are described in this section because performance on these tasks is limited by spatial resolution.

resources at that location (Anton-Erxleben & Carrasco, 2013). Receptive fields are the regions of space processed by visual neurons, so this attraction of receptive fields to the attended location would mean that more visual neurons are processing that region of space, thereby leading to enhanced spatial resolution. Attention may also *contract* receptive fields, resulting in a smaller spatial integration area (i.e., a smaller region over which visual information is processed) and, ultimately, higher spatial resolution (Anton-Erxleben & Carrasco, 2013). Indeed, both shifts and shrinkage of receptive fields have been observed in neurophysiological studies (e.g., Womelsdorf et al., 2006). However, the consequences of such remapping for temporal resolution are unclear, and this explanation fails to explain the differential effects of voluntary and involuntary attention on spatial resolution.

Attention and Temporal Resolution

In general, the effects of attention on temporal aspects of perception have not been as extensively studied as those on spatial aspects of perception. Nevertheless, some researchers have investigated how attention affects temporal resolution—an aspect of perception just as critical to our experience of the visual world as spatial resolution. While spatial resolution refers to the processing of variation in luminance over space, temporal resolution refers to the processing of variation in luminance across time (Edwards et al., 2021). Our visual environment is constantly changing over time—lights flicker, spiders scuttle, and cars and cyclists rapidly pass us by while we are navigating a busy road—and it is thus imperative that we are sensitive to change. In addition, the faster objects in the environment move, the higher their temporal-frequency information, and the higher our temporal resolution must be to perceive these changes. As discussed above, spatial acuity and temporal acuity are mediated by different visual pathways: spatial acuity by the parvocellular visual pathway, and temporal acuity by the magnocellular visual pathway. This leaves open the possibility that the effects of attention on temporal acuity (the visual system's greatest temporal resolution) may differ from those on spatial acuity described in the previous section.

One of the first experiments to examine the effects of attention on temporal resolution was conducted by Yeshurun and Levy (2003), who specifically examined transient attention. The participants' task was to determine whether a briefly presented circle had flickered, or had simply appeared and disappeared. This is known as the temporal gap-detection task, which provides an effective way of tapping temporal acuity. Interestingly, Yeshurun and Levy found that sensitivity (*d'*) to detect the flicker was significantly lower on neutral trials, where no information was given as to the location of the target (i.e., because the cue spanned the entire display), relative to cued trials, where the presentation of the circle was preceded by a cue appearing just above its location. These results indicate that transient attention actually *impaired* temporal resolution, given that performance was worse in the condition where participants had attended to where the target was about to appear. A similar pattern of results was observed in several later studies (Baek et al., 2007; Hein et al., 2006; Nicol et al., 2009; Rolke et al., 2008; Yeshurun, 2004), including some that have used a "valid versus invalid" comparison, and subsequent research has shown that more voluntary forms of attention yield the opposite pattern of results (i.e., an enhancement of temporal resolution at the cued location; Hein et al., 2006). Indeed, the impairment of temporal resolution is most commonly observed specifically when attention is elicited by a briefly presented, peripheral cue.[5]

This last point—that the impairment in temporal resolution has largely been observed in studies using a peripheral cue that is quickly flashed on and off—inspired Chapter 8 of this thesis, which tests an alternative account of the effects of involuntary attention on temporal resolution. Specifically, in this chapter, a "spatiotemporal-confusion" account of the observed temporal impairment is assessed. According to this account, temporal resolution is impaired on valid trials because here, individuals confuse the luminance transients produced by the cue with those produced by the target; this manifests as less accurate performance on valid

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[5] An exception to this is an experiment conducted by Hein et al. (2006), where a nonpredictive arrow cue was used. In this experiment, performance on a temporal order judgment task was impaired on valid relative to invalid trials, indicative of a temporal-resolution impairment. This experiment is discussed more fully in Chapter 8 of this thesis.

trials relative to invalid (or neutral) trials, where the potential for such confusion is relatively small given the greater spatial separation between the cue and target. Therefore, Chapter 8 tests whether the harmful effect of involuntary attention on temporal resolution is a genuine attentional effect, or simply an artefact of the cueing procedure. This is important for establishing whether involuntary attention does, in fact, have differential effects on spatial and temporal resolution.

The Effects of Attentional Orienting on the Processing of Multiple Items

Although much of the research on attention and visual perception has focused on the processing of particular features of single stimuli, in reality, the visual system does not process stimuli in isolation. Our visual world is incredibly detailed, and a mechanism is needed to efficiently process the large degree of information in our environment. The visual system achieves this efficiency by forming *ensemble representations*: summary representations of the multitude of elements in our visual environment (Alvarez, 2011; Whitney & Yamanashi Leib, 2018). Examples of ensemble representations include the mean size of objects, the mean direction of motion (of, say, a flock of birds), and the perception of texture in a scene.

Does attention modulate ensemble processing? It is clear that attention can influence the nature of the ensemble representation that is formed—for instance, attention to a single element in an ensemble biases the nature of the subsequently formed ensemble representation so it is skewed towards the features of the attended element (e.g., de Fockert & Marchant, 2008). But the more general question of whether ensemble processing suffers when attentional resources are limited, or whether it is unaffected by the (un)availability of attention, has produced mixed findings. On the one hand, some studies have found that ensemble processing is unaffected by attentional resources being restricted in some way (e.g., Bronfman et al., 2014; Joo et al., 2009). Indeed, ensemble processing—since it involves the visual system condensing large amounts of information into a single summary representation—is thought to be performed in the name of efficiency (Alvarez, 2011), and a lack of reliance on attentional resources is a hallmark of an efficient process (Moors & De Houwer, 2006). On the other hand, some research has found that ensemble processing is impaired when attentional resources are limited (e.g., Brand et al., 2012; Huang, 2015; Jackson-Nielsen et al., 2017; McNair et al., 2017), similar to how more local aspects of perception, such as spatial resolution, suffer when attentional resources are diverted away from the stimulus (e.g., Montagna et al., 2009).

A key limitation of the literature on attention and ensemble processing is that in many of these studies, the researchers do not make it clear which type of attention they are manipulating. Furthermore, even when the type of attention under investigation is clearly specified, the procedure employed sometimes does not adequately manipulate that form of attention (e.g., because the procedure renders it possible that the “unattended” ensemble may still be attended). This could explain some of the mixed findings regarding whether ensemble processing is harmed by limiting the availability of attentional resources. Studies also tend to use relatively artificial ensemble stimuli, such as arrays of geometric shapes. Chapter 9 of this thesis examines the effects of orienting visual spatial attention on the processing of a global motion stimulus, a naturalistic ensemble that requires the observer to pool local motion signals to extract the global motion signal (e.g., to determine whether the dots in the global motion stimulus are moving clockwise or anticlockwise). Such pooling is vital to processes like optic flow, which is critical for navigating our environment (Gibson, 1950). To address this question, the spatial cueing paradigm is used to clearly and unambiguously manipulate the allocation of visual spatial attention.

Summary

In this chapter, I have outlined some of the key research informing the final two empirical chapters of this thesis. Numerous studies have shown that attention modulates spatial resolution, with involuntary attention consistently enhancing spatial resolution (e.g., Yeshurun & Carrasco, 1999). While there is some evidence that involuntary attention *impairs* temporal resolution (e.g., Yeshurun & Levy, 2003), Chapter 8 of this thesis tests an alternative account for this observed temporal impairment: the spatiotemporal-confusion account. Turning to the effects of attention on collections of stimuli—specifically, ensemble representations—there are currently mixed findings regarding whether the formation of ensemble representations suffers when attentional resources are limited, which may be due to unclear specifications and operationalisations of the type of attention being investigated. Therefore, in Chapter 9 of this thesis, I examine whether the orienting of visual spatial attention—manipulated via the spatial cueing procedure—modulates the processing of a naturalistic ensemble.

Chapter 9

No Effect of Spatial Attention on the Processing of a Motion Ensemble: Evidence from Posner Cueing

Chapter Overview

While Chapter 8 of this thesis examined the effects of attention on the perception of a single stimulus, Chapter 9 examined the effects of attention on the processing of multiple stimuli: specifically, the effects of attention on the perception of an ensemble stimulus, where the visual system must pool local detail to extract a global percept. Previous literature is littered with inconsistent findings regarding the reliance of ensemble processing on attentional resources, and this chapter aims to add clarity to this literature by clearly specifying the type of attention being manipulated (shifts of visual spatial attention) and the type of ensemble stimulus being investigated (a global motion stimulus). This chapter is the final chapter examining the perceptual consequences of attentional orienting, and also the final empirical chapter of this thesis.

Abstract

The formation of ensemble codes is an efficient means through which the visual system represents vast arrays of information. This has led to the claim that ensemble representations are formed with minimal reliance on attentional resources. However, evidence is mixed regarding the effects of attention on ensemble processing, and researchers do not always make it clear how attention is being manipulated by their paradigm of choice. In this study, we examined the effects of Posner cueing—a well-established method of manipulating *spatial* attention—on the processing of a global motion stimulus, a naturalistic ensemble that requires the pooling of local motion signals. In Experiment 1, using a centrally presented, predictive attentional cue, we found no effect of spatial attention on global motion performance: Accuracy in invalid trials, where attention was misdirected by the cue, did not differ from accuracy in valid trials, where attention was directed to the location of the motion stimulus. In Experiment 2, we maximised the potential for our paradigm to reveal any attentional effects on global motion processing by using a threshold-based measure of performance; however, despite this change, there was again no evidence of an attentional effect on performance. Together, our results show that the processing of a global motion stimulus is unaffected when spatial attention is misdirected, and speak to the efficiency with which such ensemble stimuli are processed.

Introduction

Our visual environment is complex, dynamic, and densely occupied. To make sense of this environment, our visual system relies on attention to select a subset of input for preferential processing. In keeping with this notion of selective processing, a vast body of research indicates that attention modulates performance on tasks involving the processing of a single stimulus, including—but not limited to—orientation discrimination (e.g., Lee et al., 1997), letter identification (e.g., Luck et al., 1996), and spatial-gap localisation (e.g., Yeshurun & Carrasco, 1999).

By and large, the effects of visual attention on these local aspects of visual perception have been well-characterised (see Carrasco, 2011, for a review). However, some percepts—such as those of ensemble representations—arise from the pooling of many items. *Ensemble stimuli* consist of multiple elements that can be perceived as a single set, even when a single item within that set cannot be recognised (Alvarez, 2011; Whitney & Yamanashi Leib, 2018). While a commonly studied ensemble representation is the average of features across space (e.g., mean size), there are also other, pattern-based, ensemble representations (Alvarez, 2011; Alvarez & Oliva, 2009). Examples of these are global motion, which involves the visual system pooling multiple local motion signals so that a coherent motion direction is perceived (e.g., clockwise versus counterclockwise; Newsome & Paré, 1988), and global form (Glass, 1969), where local orientation signals are pooled to create a percept of a coherent spatial pattern (e.g., a concentric arrangement of dots). These stimuli have strong ecological validity: We receive optic flow signals as we move through our environment, and therefore the visual system is constantly pooling motion signals; similarly, the visual system continually pools orientation signals in the service of object recognition (Gibson, 1979).

Ensemble processing is believed to be a means through which the visual system efficiently represents vast arrays of visual information. This has led some authors to make the claim that ensemble processing occurs with minimal, or even no, reliance on attention (e.g., Bronfman et al., 2014; Joo et al., 2009). If it is assumed that ensemble representations are computed in the name of efficiency, then such claims seem plausible, and they are part of a broader argument for ensemble coding being an automatic process (Yildirim et al., 2018). However, evidence is mixed regarding the role of attention in ensemble processing. While some studies have found that limiting attentional resources has no effect on the representation of ensembles (e.g., Bronfman et al., 2014; Joo et al., 2009), others have found that limiting attentional resources either renders ensemble processing impossible, or at least impairs ensemble processing (e.g., Brand et al., 2012; Huang, 2015; Jackson-Nielsen et al., 2017; McNair et al., 2017). Importantly, attention does appear to have a modulatory role (Whitney & Yamanashi Leib, 2018)—for instance, it is known that a broad attentional breadth facilitates mean size estimation relative to a narrow attentional breadth (Chong & Treisman, 2005), and attention to a single item biases the perception of mean size (de Fockert & Marchant, 2008). However, whether attention also modulates the processing of pattern-based ensembles that have greater ecological validity (e.g., global motion) is unclear.

When considering the question of whether attention modulates the processing of more naturalistic ensembles, it is important to delimit this issue by specifying which *type* of attention is being examined. Part of the reason for the mixed findings regarding whether attention is necessary for ensemble processing may be due to the plethora of methods that have been used to manipulate attention. These methods include the attentional blink (Joo et al., 2009; McNair et al., 2017); inattentional blindness (Jackson-Nielsen et al., 2017); multiple object tracking of target objects moving amongst distractors (Alvarez & Oliva, 2008, 2009); explicit instructions to attend to one set of items intermixed with another, to-be-ignored, set (Oriet & Brand, 2013); precue versus postcue comparisons, where participants are either forewarned about the aspect of an ensemble that they must report, or are only informed after the presentation of the stimulus (e.g., Huang, 2015); dual-task paradigms in which participants must process an aspect of a cued location, while the ensemble is assumed to be either inside or outside the focus of attention (Bronfman et al., 2014; Preston et al., 2020; Ward et al., 2016); and visual search, where the ensemble information is contained in the distractors (e.g., Chetverikov et al., 2016). This variety of methods may be a product of the general lack of clarity regarding what type of attention authors are intending to examine. To allow for conclusions to be drawn about the involvement of attention in ensemble processing, and about the extent to which the studies are consistent with or contradict one another, the need for clarity is paramount.

But what do we mean by a “lack of clarity” regarding the method of attentional manipulation? We believe this lack of clarity manifests in two forms. First, researchers in the field often do not acknowledge that attention is a multifaceted construct, and therefore do not make clear what type of attention they are manipulating (or aiming to manipulate). For instance, in an investigation of mean size encoding, Oriet and Brand (2013) asked participants to attend to only the horizontal lines in an array consisting of both horizontal and vertical lines. The authors claimed to be examining “selective attention,” but given that all forms of attention are necessarily selective, this description fails to specify the nature of attentional allocation entailed by the task requirements (e.g., the deployment of multiple foci of object-based attention, or the allocation of feature-based attention). To take another example, Alvarez and Oliva (2009) examined the effects of “reduced attention” on the processing of an orientation ensemble by having participants perform a change detection task while they tracked moving objects; however, they did not make it clear what type of attention they were aiming to “reduce” with the requirement to track moving stimuli (e.g., the authors may have been referring to a reduction in working memory resources available to perform the ensemble task, or to a *redeployment*—rather than a reduction—of *spatial* attention). By contrast, in the attention and low-level perception literature, different types of attention are clearly distinguished—for instance, exogenous (i.e., stimulus-driven) attention versus endogenous (i.e., goal-driven) attention (e.g., Barbot et al., 2012), and spatial attention versus temporal attention (e.g., Sharp et al., 2018)—and there is a concerted research effort to unearth the differences in their perceptual effects (see Carrasco, 2011, for a review). The existence of these differences at lower levels of visual processing leads to the logical possibility that the effects of attention on *ensemble* processing also depend on the type of attention being examined; therefore, attempting to reconcile the findings of studies that have used different paradigms to examine this relationship may be futile.

Second, for a given method of attentional deployment, the nature of attentional allocation is sometimes ambiguous. For example, one previously used manipulation involved a dual task where participants were instructed to prioritise one (nonensemble) task that had been precued, and their performance on the other task (the ensemble under investigation), which could be presented either within the cued location or at the uncued location, was assessed (Bronfman et al., 2014; Ward et al., 2016). It is likely that this type of procedure is manipulating the allocation of attention over space, or object-based attention given that the to-be-attended region is circumscribed by a visual cue.[1] However, in such a paradigm, it is not clear how participants are allocating their attentional resources when asked to prioritise the nonensemble task, since participants know that their performance on both tasks will be assessed (Preston et al., 2020). Therefore, even when the type of attention being investigated is somewhat clear, some paradigms may not actually be manipulating the intended aspect of attention.

In this study, we examined the effects of misdirecting attention on ensemble processing using a paradigm that clearly manipulates *spatial* attention: the Posner—or spatial—cueing paradigm (Posner, 1980; Posner et al., 1978). Spatial attention is an important mechanism for prioritising different regions of the visual field for enhanced processing and is constantly deployed as we interact with our environment, making it an important aspect of attention to study. As a manipulation of spatial attention, the Posner cueing paradigm has been frequently used in the attention and low-level perception literature (Carrasco, 2011), and involves comparing performance in valid trials—where attention is directed to the location of an upcoming target by a visual cue—against performance in invalid

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[1] We thank an anonymous reviewer for suggesting that the paradigm may have elicited object-based attention.

trials—where attention has been directed to a nontarget location. In our study, 75% of trials were valid, and 25% of trials were invalid; the high validity of the cue provided a clear incentive for participants to attend to the cued location, which meant that there was little ambiguity regarding where attentional resources were being allocated. Indeed, there has been a recent call for the use of spatial cueing in light of exactly this advantage (Preston et al., 2020).

Yet another benefit of this paradigm is that the “attended” (validly cued) and “unattended” (invalidly cued) regions are well spatially separated, which makes it unlikely that both locations are within the focus of spatial attention. Some previous studies (e.g., Oriet & Brand, 2013) have presented to-be-attended and to-be-ignored sets of stimuli in a spatially intermixed fashion, which—for the purposes of investigating the effects of focal, spatial attention on ensemble processing—is clearly problematic. To take another example, Chen, Zhuang, et al. (2021) recently examined the effect of an “unattended” ensemble on another ensemble that had been briefly cued, and found that when the unattended ensemble contained information that matched the target category, processing of the “attended” ensemble was facilitated; conversely, processing of the attended ensemble was impaired when the unattended ensemble contained target-incongruent information. However, the “attended” and “unattended” ensembles were in relatively close spatial proximity, with an interstimulus distance of only 2°, making it unlikely that the unattended ensemble was indeed outside the focus of attention. We believe the cleanest method of examining the effect of attention on ensemble processing is to maximise the spatial separation between “attended” and “unattended” locations while presenting one ensemble stimulus at a time, either at a cued or at a noncued location. Using this simple, yet effective, manipulation, we asked the basic question: Does *spatial* attention *enhance, impair,* or *have no effect* on ensemble processing?

To examine the effect of spatial attention on ensemble processing, we used a global motion stimulus. While most ensemble processing research has focused on the coding of summary features such as mean size (e.g., Chong & Treisman, 2005), the need for researchers to consider more ecologically valid spatial regularities has been highlighted (Alvarez & Oliva, 2009). Global motion stimuli comprise many moving dots, a proportion of which move in a consistent direction and the remainder of which move in random noise directions (Newsome & Paré, 1988); integrating these local signals results in a percept of global motion (e.g., the dots generally moving in a clockwise or counterclockwise direction). The pooling of local motion signals is imperative for the perception of optic flow—the sensation of motion we experience as we move around our environment (Gibson, 1950)—as well as the perception of object motion. Cortical areas specialised for the processing of this information have been identified, including V1 for the extraction of local motion signals, and areas V5/MT and MSTd for the pooling of these signals (Duffy & Wurtz, 1991; Tootell et al., 1995). Performance on tasks requiring the pooling of motion signals tends to be very good, with individuals able to discriminate global motion signals at low coherence levels (e.g., Edwards et al., 1998), and exhibiting high sensitivity to large-field optic flow stimuli (e.g., Edwards & Ibbotson, 2007); the ability of individuals to perceive such patterns of motion attests to the functional significance of pooling motion signals. Global motion stimuli, which entail such pooling, therefore possess strong ecological validity. Finally, the well-characterised pooling mechanisms that underlie global motion processing give them an advantage over other ensembles (e.g., mean size) with less clear pooling mechanisms (Alvarez, 2011).

In Experiment 1, we used a centrally presented, predictive attentional cue and a rotational global motion stimulus to examine the effects of spatial attention on global motion processing. In Experiment 2, we used a translational global motion stimulus and altered the cueing procedure to maximise our chances of detecting an attentional modulation; that is, we improved the potential for our paradigm to reveal a performance difference between the valid and invalid trials by using a more sensitive motion signal and performance measure, and a cue that simplified task demands. To preview our results, in both experiments, we found no evidence that spatial attention affected global motion processing, as revealed through accuracy (Experiment 1) and coherence thresholds (Experiment 2). This is despite evidence from the reaction time (RT) data that participants were effectively using the cue to guide their attention. Together, our results indicate that naturalistic global motion stimuli are remarkably impervious to misdirected spatial attention.

Experiment 1

In Experiment 1, we examined the effect of spatial attention on the processing of a rotational global motion stimulus. We compared accuracy in detecting the direction of motion (clockwise versus anticlockwise) across valid and invalid trials, using a 75% predictive cue that was presented in central vision. Prior to this cueing block, we determined performance thresholds for the global motion stimulus using the psi adaptive method (Kontsevich & Tyler, 1999), which gives a threshold estimate corresponding to a performance level of 75%; this threshold estimate is equivalent to the proportion of dots that must be moving in the signal direction in order for performance to be 75% correct. A 75% performance level corresponds to the most sensitive portion of the psychometric curve for a two-alternative forced choice procedure, and therefore setting stimulus coherence at this threshold in the cueing block maximised our chances of observing performance differences between the valid and invalid trials (Goodhew & Edwards, 2019). If global motion processing is affected by spatial attention, accuracy on the task should be lower in invalid trials (where attention is misdirected) than in valid trials (where attention is guided to the location of the subsequently presented stimulus).

Our attentional cue was a number that correctly indicated the location of the global motion stimulus on 75% of trials. The number presented could be either “1,” “2,” “3,” or “4,” and each number was associated with one of the four possible target locations with 75% validity; in other words, on 75% of trials, the global motion stimulus appeared at the location with which the presented number was paired. Importantly, because the number-location associations were arbitrary, this type of cueing promoted the voluntary allocation of spatial attention (Olk et al., 2008; Olk et al., 2014); there is evidence that this form of orienting more reliably modulates perception than does involuntary attention (e.g., Esterman et al., 2008; Prinzmetal et al., 2005), and therefore our use of a predictive number cue ensured that we had created the optimal conditions for revealing an attentional modulation of global motion processing. Participants were informed of the number-location associations at the beginning of the experiment and completed a simple letter-discrimination task so they could learn to use the cue to guide their attention.

Method

Participants

To obtain an estimate of the required sample size, we used the web version of the within-subjects sample-size planning calculator developed by Anderson et al. (2017; available from https://designingexperiments.com/), along with the data from Experiment 2 in Kerzel et al. (2009).[2] With $N = 17$, this experiment yielded an effect size of $\eta_p^2 = .422$ for the main effect of cue validity. After specifying a desired power of .8, a desired assurance of .7, and an alpha of .05 for both the previous and the current study, the analysis yielded a recommended sample size of 29 participants, which we rounded up to 30.

Overall, 30 individuals (18 female) with an average age of 20.5 years ($SD = 2.0$) participated in exchange for either course credit or $10 payment. All participants had either normal vision or vision that had been corrected to normal with contact lenses. Each participant provided written informed consent, and both experiments in this study were approved by the Australian National University Human Research Ethics Committee.

Apparatus and Stimuli

Stimuli were presented on a gamma-corrected, Philips Brilliance (Netherlands) 202P4 CRT monitor with a refresh rate of 85 Hz and a background of mid-grey (39.3 cd/m^2). The

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[2] We chose this study as the basis for our power analysis because it is similar in its use of a centrally presented, predictive cue to examine accuracy in a perceptual task.

viewing distance to the monitor was fixed at 50 cm with a chinrest. Stimuli were presented using the Psychophysics Toolbox (Brainard, 1997) in MATLAB, and the Palamedes Toolbox (Prins & Kingdom, 2009) was used for the thresholding blocks. Eye movements were monitored with the Cambridge Research Systems (UK) 50 Hz Video Eyetracker Toolbox.

The global motion stimulus consisted of 50 white dots spanning 0.1° of visual angle in diameter. These dots had a luminance contrast of 109% (Weber value) and fell within a viewing aperture that had an inner radius of 0.1° and an outer radius of 2.5°, resulting in a dot density of 2.6 dots/deg^2. The motion sequence consisted of 5 pages each lasting 3 frames,[3] resulting in a total stimulus duration of approximately 150 ms. A proportion of the dots in this stimulus moved in a clockwise or anticlockwise direction, with the remaining dots moving in random directions. The spatial step size of the motion stimulus was 0.3°, resulting in a dot speed of 8.9 deg/sec. The direction in which each dot moved was randomly assigned at the start of each frame.

The experiment display consisted of a black fixation dot surrounded by four white, circular placeholders (diameter: 6°; thickness: 0.1°), which were located 12° above, below, to the left of, and to the right of the fixation dot. The number cue could be either “1,” “2,” “3,” or “4,” and was presented in white, Arial font, and measured approximately 1.5°. The target for the letter-discrimination task was the letter “E” or “F,” which was presented in white, Arial font, and measured approximately 2.3°; this letter target appeared at an eccentricity of 12°.

Design and Procedure

This experiment consisted of a global motion thresholding block, a letter-discrimination task with cueing, and a global motion block with cueing. These blocks were completed in the same order by all participants. Each thresholding block comprised two 60-trial runs of the psi adaptive method (Kontsevich & Tyler, 1999), which gives a threshold

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[3] When using the term “pages”, we refer to the number of still images making up the motion sequence; when using the term “frames”, we refer to the number of monitor refreshes making up the duration of each page.

estimate corresponding to a performance level of 75%; here, participants were required to determine whether the dots were moving in an anticlockwise or clockwise direction (left-arrow-key response for “anticlockwise”; right-arrow-key response for “clockwise”). Each trial began with 50 ms of fixation, after which the stimulus appeared randomly inside one of the four placeholders for approximately 150 ms. Following response, a blank screen appeared for 1,000 ms before the next trial began. Participants were encouraged to maintain fixation at all times, and to prioritise accuracy over speed. The threshold estimated by the second run of this adaptive method determined the coherence of the global motion stimulus in the cueing block.

Participants then completed a 100-trial letter-discrimination task involving the number cue. The purpose of this block was for participants to learn the number-location pairings, and required participants to indicate whether the letter “E” or “F” had been presented on any given trial. In this block, each trial began with 1,000 ms of fixation, followed by the number “1,” “2,” “3,” or “4” appearing in the centre of the display. Each number was associated with a particular target location, such that when a given number appeared, there was a 75% chance that the target would appear at the location with which it was paired. There were four possible “sets” of associations (see Table 1), and the set that each participant received was randomly determined. Participants were informed of these associations, as well as the validity of the cue, prior to completing the letter-discrimination task. After a 600-ms delay (sufficient time to allow for interpretation of the cue and a subsequent attentional shift; e.g., Olk et al., 2008), the letter “E” or “F” appeared in one of the four placeholders, and participants had to indicate which letter appeared by pressing the corresponding letter key on the keyboard as quickly and as accurately as possible. The letter remained visible until response. The letter-discrimination block consisted of 75 valid trials, where the letter appeared at the location associated with the presented number, and 25 invalid trials, where the letter appeared at one of the other three locations.

Table 1

Possible Number-Location Associations in Experiment 1

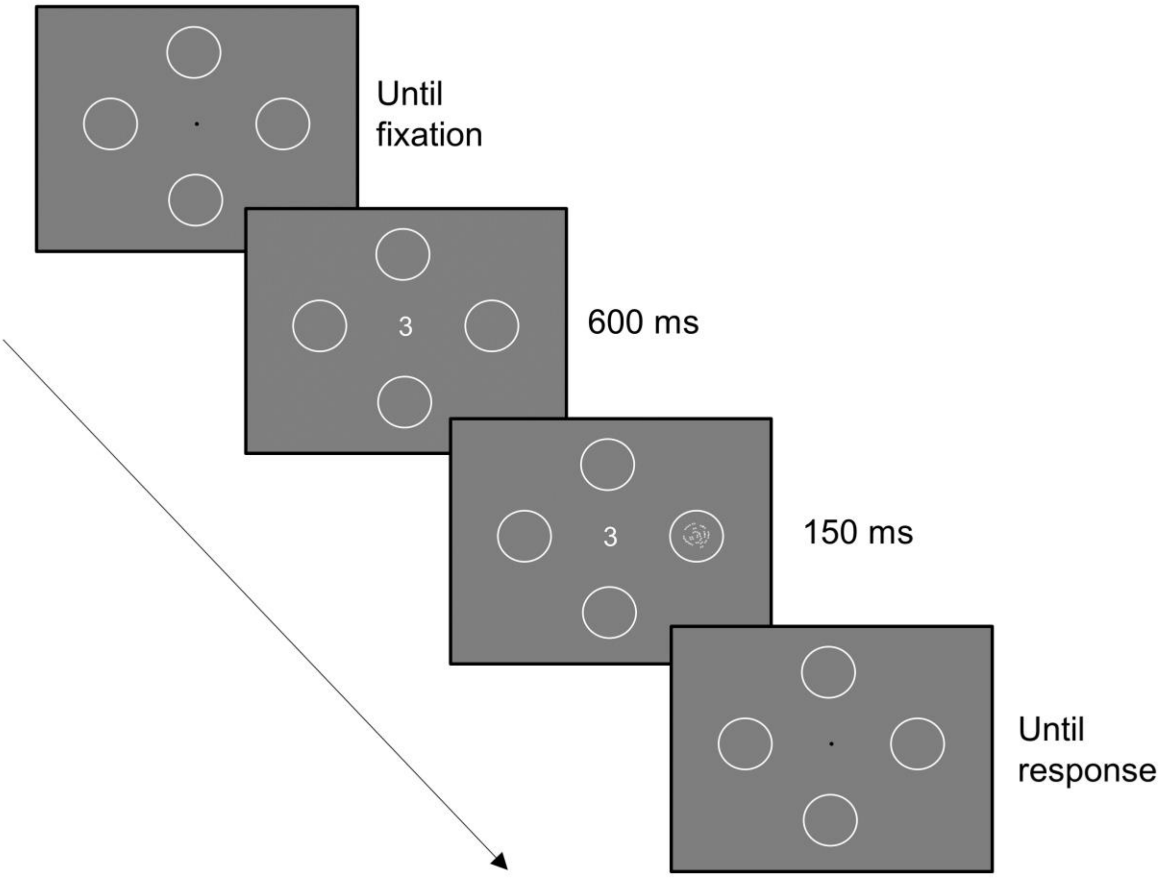
Set	Number-location associations
1	“1” = top, “2” = right, “3” = bottom, “4” = left
2	“2” = top, “3” = right, “4” = bottom, “1” = left
3	“3” = top, “4” = right, “1” = bottom, “2” = left
4	“4” = top, “1” = right, “2” = bottom, “3” = left

Note. This table shows the four possible sets of number-location associations used in Experiment 1. See text for further detail.

After this letter-discrimination block, participants were run on a 200-trial global motion block with 150 valid trials and 50 invalid trials. The sequence of a single trial in this block was identical to that of a single trial in the letter-discrimination block, except for the presentation of the global motion stimulus instead of the letter (see Figure 1), and the instruction to again prioritise accuracy over speed. The coherence of the motion stimulus was set at the threshold estimate given by the second run of the psi adaptive method. Initiation of each trial was contingent on 250 ms of continuous fixation inside the defined fixation region (a 1.5° invisible square), and if the participant’s gaze was not within the fixation region when the number cue was first presented, at the beginning of the motion sequence (600 ms after initiation of the trial), or at the end of the motion sequence (750 ms after initiation of the trial), the trial was discarded. This ensured that we were able to examine the effect of covert spatial attention on global motion processing, as opposed to any modulation that reflects the combined effect of covert spatial attention and eye movements.

Figure 1

Example of a Single Trial in the Global Motion Block of Experiment 1



Note. This figure shows the presentation sequence of a single trial in the global motion block of Experiment 1. If the number “3” was associated with the rightmost target location, this would be an example of a valid trial; if it was associated with one of the other three locations, this would be an example of an invalid trial. See text for further detail.

Results and Discussion

We first analysed the RT data from the letter-discrimination block. Trials in which participants responded incorrectly or pressed a nondesignated response key, as well as those in which RTs were below 100 ms or exceeded 2.5 SDs above that participant’s mean RT, were removed (3.2% of all trials). A paired *t* test on mean RTs revealed faster responding in the valid trials (*M* = 859 ms, *SD* = 201) compared to the invalid trials (*M* =

1,077 ms, *SD* = 345), *t*(29) = 5.76, *p* < .001, Cohen's *d* = 1.05.[4] We conducted an equivalent paired Bayesian *t* test using JASP (JASP Team, 2020b). BF_{10} values above 1 indicate evidence in favour of the alternative hypothesis, while values below 1 indicate evidence in favour of the null hypothesis (with clear evidence for the alternative and null hypotheses typically indexed by a BF_{10} of at least 3 or at most 1/3, respectively). This analysis revealed a BF_{10} of 6171.81: "decisive" evidence of a cueing effect.[5] This indicates that participants were able to use the symbolic cue to guide their attention to the appropriate target location.

We then analysed the accuracy and RT data for the global motion block, which are illustrated in Figure 2. Average global motion thresholds were 21.4% in the first run and 20.9% in the second run of the psi adaptive method. We examined the accuracy (mean percentage correct) data for the global motion block to identify any participants whose performance was below an average of 60% or above an average of 90% correct in both cue validity conditions; this was done to identify participants who were performing at floor or at ceiling, and thus whose data may have been obscuring a cueing effect (see Argyropoulos et al., 2013; Goodhew, 2019). No participants met these criteria, and therefore all participants' data were retained. Trials in which the participant's gaze fell outside of the fixation region were excluded (8.1% of all trials), and 3.3% of trials were excluded based on the same RT cutoffs used for the letter-discrimination task.

A paired *t* test on the mean percentage correct responses in the valid trials (*M* = 77.2%, *SD* = 8.3) compared to the invalid trials (*M* = 77.4%, *SD* = 7.1) revealed no significant difference in accuracy, *t*(29) = 0.17, *p* = .866, Cohen's *d* = 0.03. Therefore, there was no evidence that attention affected performance on the global motion task. The equivalent Bayesian *t* test yielded a BF_{10} of 0.20: "substantial" evidence *against* a cueing effect on accuracy. Another paired *t* test on the mean RTs in this block revealed significantly faster

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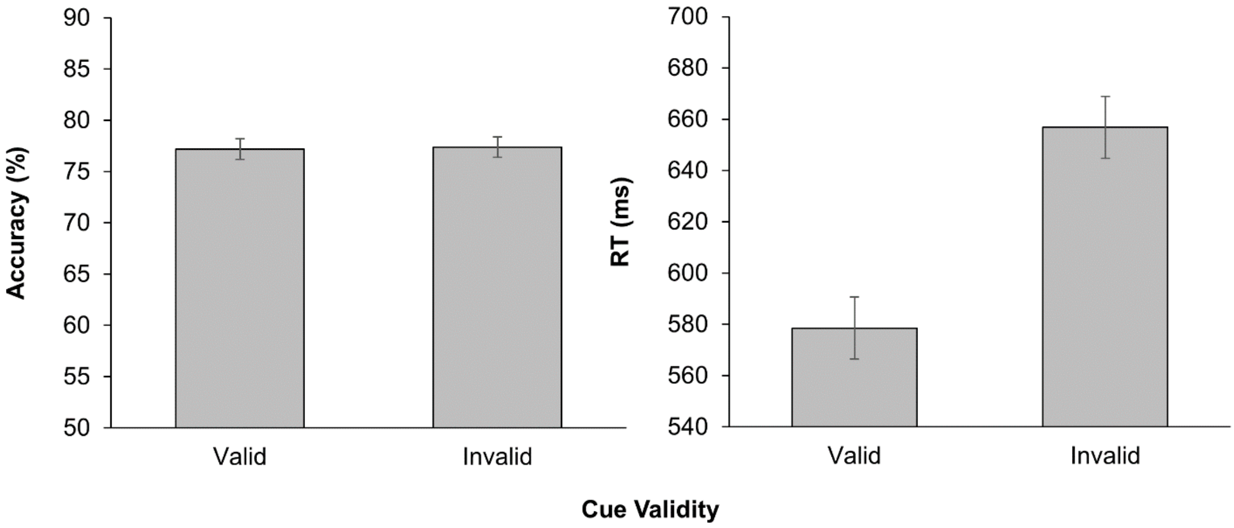
[4] When calculating Cohen's *d*, we used the standardised mean difference score (the average mean difference score divided by the SD of the mean difference scores).

[5] We adopted the criteria proposed by Jeffreys (1961) when interpreting the degree of evidence provided by the Bayesian analyses.

responding in the valid trials (*M* = 579 ms, *SD* = 150) compared to the invalid trials (*M* = 657 ms, *SD* = 199), *t*(29) = 4.55, *p* < .001, Cohen's *d* = 0.83, with a BF_{10} of 288.07 showing "decisive" evidence for a cueing effect on RTs. Therefore, while cueing did not produce any differences in accuracy, there was strong evidence that participants were attending to the cued location.

Figure 2

Results for the Global Motion Block of Experiment 1



Note. This figure shows the mean accuracy (percentage correct responses) and reaction time (RT) in ms for each cueing condition of the global motion block in Experiment 1. Error bars represent standard errors and were calculated according to the Cousineau-Morey method (Cousineau, 2005; Morey, 2008; O'Brien & Cousineau, 2014).

Overall, there was no evidence from Experiment 1 that spatial attention modulated global motion processing. Indeed, mean accuracies for the valid and invalid trials were almost identical (77.2% and 77.4%, respectively), and there was "substantial" support for a null effect from the Bayesian analysis. However, while there was no cueing effect on accuracy, there was strong evidence that participants were attending to the cued location:

RTs were significantly faster in valid compared to invalid trials. Such RT effects can be taken to show that attention has been shifted to the cued location, and importantly, are common even in experiments where accuracy is emphasised over speed (e.g., Montagna et al., 2009; Yeshurun & Carrasco, 1999). Therefore, we can be confident that attention was shifted to the cued location in this experiment, but that this allocation of attentional resources did not result in improved performance on this particular ensemble task. Nevertheless, we sought to obtain further evidence for this null effect in a subsequent experiment.

Experiment 2

In Experiment 1, there was no evidence for an effect of spatial attention on global motion processing. Nevertheless, we performed another experiment to enhance the sensitivity of our paradigm for detecting any influence of spatial attention on performance. First, instead of analysing percentage correct responses at the global motion threshold estimated by the psi adaptive method, we directly compared thresholds between the valid and invalid trials. Thresholds may be a more sensitive measure of performance than percentage correct responses because they correspond directly to a 75% performance level (the most sensitive part of the psychometric curve for a two-alternative forced choice task; Goodhew & Edwards, 2019), and by only sampling a proportion of the valid trials in order to compute this threshold, we were able to compare equal numbers of valid and invalid trials (cf. 150 valid trials versus 50 invalid trials in Experiment 1); this, in turn, may improve estimates of cueing effects.

We also attempted to reduce sources of experimental noise that may have been present in Experiment 1. We removed the top and bottom target locations so that there were now two possible target locations—one to the left and one to the right of the fixation stimulus. This change was made in view of asymmetries in motion sensitivity along the vertical meridian (Edwards & Badcock, 1993), which may have unduly added noise to the data of the previous experiment. To further reduce the variability in motion thresholds, the nature of the global motion signal was changed from rotational to translational, with a proportion of the dots now moving either upwards or downwards on any given trial.[6] Finally, we employed an arrow cue rather than a number cue, and reduced the cue-target interval from 600 ms to 300 ms. This change was made to simplify task demands as much as possible, since interpretation of an arrow cue may be less taxing than interpretation of a number cue arbitrarily associated with a particular location. Notably, this stimulus configuration (i.e., a predictive arrow cue with two possible target locations and a 300-ms cue-target interval) has been shown to reliably elicit attentional shifts (e.g., Posner et al., 1978).

Method

Participants

Thirty individuals (17 female) with an average age of 23.5 years (*SD* = 5.6) participated in exchange for either course credit or $15 payment. All participants had either normal vision or vision that had been corrected to normal with contact lenses.

Apparatus and Stimuli

Stimuli were presented on a 1920 x 1080 LCD monitor with a refresh rate of 100 Hz and a background of mid-grey (71.1 cd/m^2). The viewing distance to the monitor was fixed at 86 cm with a chinrest. As in Experiment 1, stimuli were presented using the Psychophysics Toolbox (Brainard, 1997) in MATLAB, and the Palamedes Toolbox (Prins & Kingdom, 2009) was used to obtain threshold estimates. Eye movements were monitored with the SR

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[6] Here, we outline the reason for this change. Global motion encoding is a signal-to-noise process, with the “signal” being dots moving in the signal direction (Edwards & Badcock, 1994). Thus, for stable and accurate thresholds, it is crucial for the signal dots to move in the intended signal direction. When the motion is coarsely sampled, as it is here, this is not possible for rotational motion given that the signal direction varies continuously as a function of where that particular signal dot is in relation to the centre of the stimulus; specifically, the direction is orthogonal to a line joining that dot to the centre of the stimulus. When a dot moves a relatively small number of pixels between each frame of motion it is not possible to have it move in all possible directions, and only a few of those directions can be accurately presented. However, the vertical directions can be accurately presented, and as long as the noise dots move in other directions that cover the full 360° range (excluding the signal direction), they effectively act as noise; that is, they do not require accurate directional resolution.

Research (Canada) Eyelink 1000 desktop-mounted eye-tracker, which has a sampling rate of 1000 Hz.

The spatial and temporal properties of the global motion stimulus were similar to those of Experiment 1; however, rather than moving clockwise or anticlockwise, a proportion of the dots now moved either upwards or downwards. The placeholders and arrow cue were the same as in Experiment 1, except now there were only two placeholders—one to the left and one to the right of the fixation stimulus. The fixation stimulus was a bullseye and crosshair combination target, which has been found to produce especially stable fixations relative to other fixation stimuli (Thaler et al., 2013). The outer circle of this stimulus had a radius of 0.5°, and the inner circle had a radius of 0.2°.

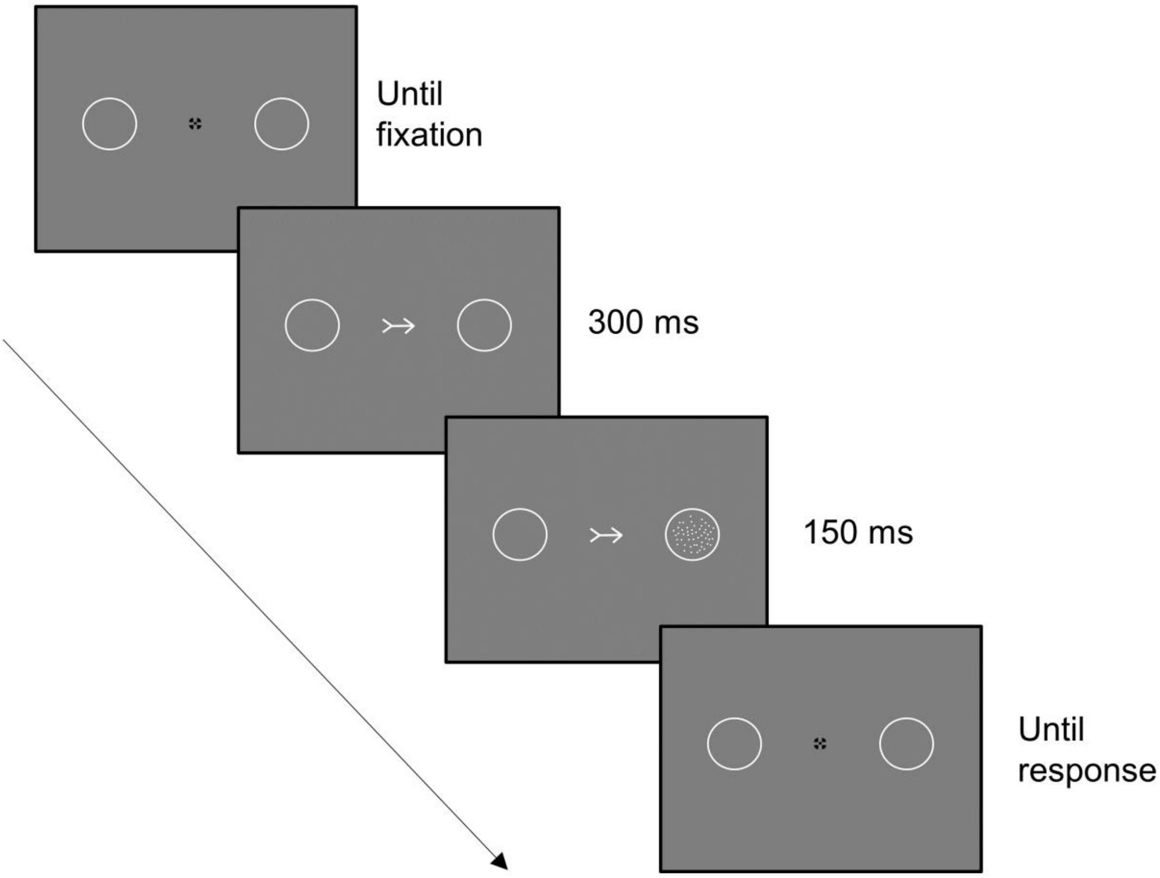
Design and Procedure

The main cueing block consisted of two independent psi adaptive staircases running simultaneously, one for the valid trials and one for the invalid trials. Each staircase estimated a global motion threshold corresponding to a 75% performance level. There were a total of 400 trials in this block: 300 valid trials and 100 invalid trials. To ensure that threshold estimates for valid and invalid trials were computed over an equivalent number of trials, only every third trial in the valid condition was sampled when the threshold for this condition was being computed. The block was configured in such a way that each consecutive quarter of the block contained an equal proportion of valid and invalid trials; this way, we could be sure that threshold estimates were not disproportionately derived from trials occurring earlier or later in the block. For all blocks, participants were asked to prioritise accuracy over speed, and to maintain fixation.

Participants first completed a 32-trial practice block of the global motion task with accuracy feedback, which did not involve the arrow cue. Here, the global motion stimulus appeared randomly to the left or to the right of the fixation stimulus, and participants were required to press the “up” arrow key to indicate that the dots were moving upwards and the “down” arrow key to indicate that the dots were moving downwards. Participants then completed a 32-trial practice block of this task with the arrow cue (see Figure 3), which was 75% valid with respect to the target location; here, the global motion stimulus appeared 300 ms after the onset of the arrow. Participants were informed of the cue’s validity and instructed to use the cue to guide their attention. After the practice block, participants completed the 400-trial experimental block. Trials were excluded if participants were found to be fixating outside of the defined fixation region at the onset of the arrow cue, at the onset of the global motion stimulus, or at the offset of the global motion stimulus.

Figure 3

Example of a Single Trial in Experiment 2



Note. This figure shows the presentation sequence of a single (valid) trial in the main cueing block of Experiment 2.

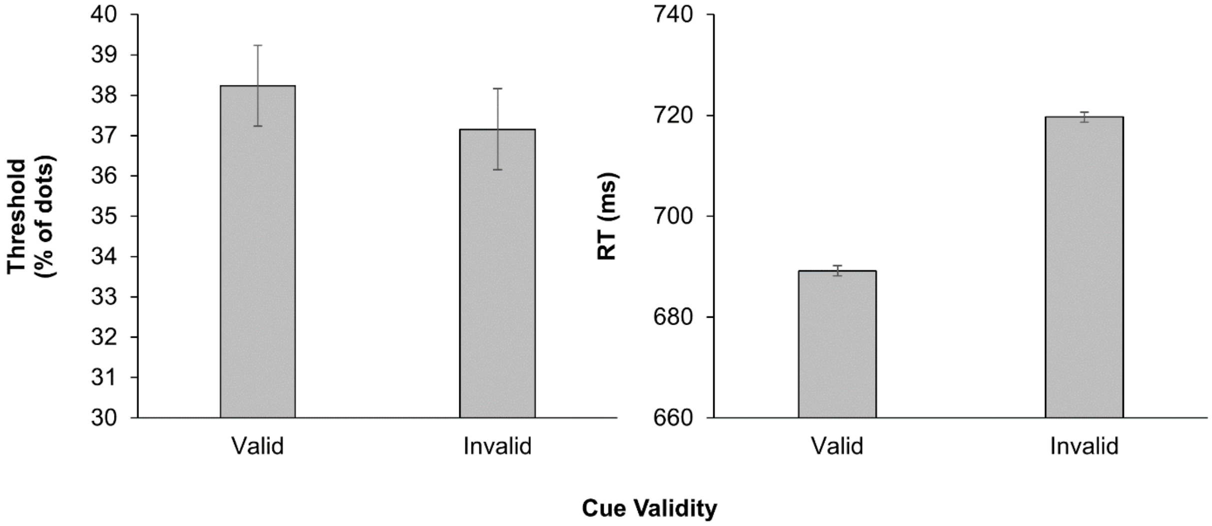
Results and Discussion

Trials in which the participant's gaze fell outside of the fixation region were excluded (10.4% of all trials), and 3.1% of trials were excluded based on the same RT cutoffs used in Experiment 1. We then conducted a paired *t* test on the global motion thresholds (proportion of dots) for the valid and invalid cueing conditions (Figure 4). The mean global motion threshold in the valid trials (*M* = 38.2%, *SD* = 18.2) did not significantly differ from the mean global motion threshold in the invalid trials (*M* = 37.2%, *SD* = 18.4), *t*(29) = 1.00, *p* = .324, Cohen's *d* = 0.18. The corresponding Bayesian *t* test showed "substantial" evidence for no difference between the thresholds, BF_{10} = 0.31. Another paired *t* test on mean RTs revealed significantly faster responding in the valid trials (*M* = 689 ms, *SD* = 120) compared to the invalid trials (*M* = 720 ms, *SD* = 114), *t*(29) = 3.02, *p* = .005, Cohen's *d* = 0.55, with the corresponding Bayesian *t* test showing "substantial" evidence for this effect, BF_{10} = 7.88.

Overall, the results of Experiment 2 aligned with those of Experiment 1: Global motion performance did not significantly differ between the valid and the invalid trials; however, there was evidence of attention being shifted to the cued location in that participants were faster to respond in the valid trials compared to the invalid trials. This indicates that the cueing procedure effectively shifted participants' attention, but that these shifts had no measurable impact on the perception of this ensemble stimulus. An advantage of Experiment 2 over Experiment 1 is that it involved a direct comparison of performance thresholds between valid and invalid trials, and these thresholds were computed across equivalent numbers of trials. With this improvement in the sensitivity of the design for revealing cueing effects, as well as the additional measures we introduced to reduce experimental noise (e.g., changing the nature of the motion signal), we again found no evidence that spatial attention affected global motion processing.

Figure 4

Results of Experiment 2



Note. This figure shows the mean threshold (proportion of dots) and reaction time (RT) in ms for each cueing condition of Experiment 2. Error bars represent standard errors and were calculated according to the Cousineau-Morey method (Cousineau, 2005; Morey, 2008; O'Brien & Cousineau, 2014).

General Discussion

In this study, we used Posner cueing to examine the effect of spatial attention on the processing of a global motion stimulus, a highly naturalistic ensemble. Posner cueing is a highly effective way of manipulating the locus of spatial attention, and involves the attended and unattended stimuli being presented at separate spatial locations. Overall, the results of Experiments 1 and 2 converged to provide evidence *against* an effect of spatial attention on global motion processing. This was so despite strong evidence from both experiments that attention was being shifted to the cued location, as indexed by faster responding in valid trials compared to invalid trials. The fact that this result emerged across different measures (percentage correct responses versus performance thresholds), cue types (number versus arrow), and types of motion signal (rotational versus translational) is evidence of its robustness. Overall, our results show that global motion processing is remarkably impervious to the misallocation of spatial attention.

Since our results showed no effect of spatial attention on the processing of a motion ensemble, how do they align with the ensemble processing literature more broadly? As discussed earlier, evidence is mixed regarding the effects of attention on ensemble processing. While some studies have found that limiting attentional resources has no effect on ensemble coding (e.g., Bronfman et al., 2014; Joo et al., 2009), others have found that limiting attentional resources precludes ensemble coding, or at least has a harmful effect (e.g., Brand et al., 2012; Huang, 2015; Jackson-Nielsen et al., 2017; McNair et al., 2017). Our results are consistent with the former group of studies. One advantage of our study over these previous efforts, however, is that we have been very clear about the type of attention we were manipulating with our paradigm of choice, and can therefore conclude that the misdirection of *spatial* attention has no effect on a task requiring ensemble processing. This is not to say that other attentional manipulations might produce different effects; for example, one study found evidence of inattentional blindness to ensemble stimuli (Jackson-Nielsen et al., 2017), and given that inattentional blindness may not be equivalent to misdirected spatial attention (e.g., Memmert, 2010), it could be that this paradigm reveals an attentional cost to ensemble coding that is the consequence of limiting an altogether different type of attentional process. Additionally, while other researchers have used paradigms that may have been manipulating spatial attention, an advantage of our paradigm is that it involved only one stimulus being presented at a time—thereby simplifying task demands (cf. Bronfman et al., 2014)—and we spatially separated the attended and unattended locations to limit the amount of attentional resources being directed to the “unattended” location (cf. Chen, Zhuang, et al., 2021; Oriet & Brand, 2013).

Interestingly, a previous study examined the effects of withdrawing attention on global motion processing and observed somewhat counterintuitive results. Specifically, Motoyoshi et al. (2015) investigated the effect of “limited attention” on global motion processing by using a dual-task paradigm in which participants completed a challenging digit discrimination task presented within a rapid serial visual presentation stream, which was embedded within the global motion array. They found that global motion thresholds for determining the direction of motion were reduced in the dual-task condition compared to the single-task condition, indicating that limiting attentional resources actually *improved* performance on the task. An analogous pattern of findings was later obtained by Pavan et al. (2019) for Glass patterns (which tap the processing of coherent form, rather than motion); when attention was diverted away from a Glass pattern with a rapid serial visual presentation stream embedded within the stimulus, form adaptation was stronger—this indicates more extensive processing of the Glass pattern in the “limited attention” condition. Therefore, both of these studies indicate that limiting attentional resources not only spares the processing of at least some naturalistic ensemble stimuli, but can actually improve their processing. Motoyoshi et al. attributed their findings to limited attention attenuating centre-surround inhibition in the high-level receptive fields dedicated to motion processing; this produces an increase in the spatial extent of motion-signal integration, which facilitates performance on the global motion task. Pavan et al. invoked a similar explanation for their Glass-pattern findings.

Our manipulation differs from that used by Motoyoshi et al. (2015) and Pavan et al. (2019) in that it was specifically a manipulation of *spatial* attention and its locus, rather than an attempt to divert attentional resources more generally through the use of a secondary task (i.e., a process more akin to “distraction” rather than a redirection of spatial attention). With our paradigm, we found no effect of spatial attention on global motion processing. However, it is important to note that Motoyoshi et al. found no difference in performance between the single-and dual-task conditions when they reconfigured their global motion stimulus into an annulus that only stimulated peripheral vision; this could be seen as consistent with the lack of cueing effect on performance we observed in our experiments, where the ensembles were also presented peripherally. Indeed, what may be a critical factor determining whether limiting attention benefits ensemble processing is the spatial separation between the “attended” and “nonattended” conditions: The greater the separation, the more likely it is that a lack of attention becomes harmful—or at least nonconsequential—rather than beneficial. To take another example, Preston et al. (2020) examined whether spared colour-diversity processing in the “absence” of attention (originally observed by Bronfman et al., 2014) generalised to situations where the target is presented in the far visual periphery, a configuration which resulted in a greater distance between the cued and uncued regions. They found that under these conditions, colour-diversity processing incurred an attentional cost (note that this study was a direct extension of Bronfman et al., 2014, so it is unclear if similar results would be observed with Posner cueing). Altogether, the discrepancy between our results and the facilitative effect of limited attention on global motion processing observed by Motoyoshi et al. may be due to the spatial separation of the attended and nonattended locations in our experiments. It should be noted, however, that our stimuli and attentional paradigm differed from those in these earlier studies, so caution should be exercised when drawing comparisons between them.

Recently, Baek and Chong (2020) have proposed that “distributed” attention is necessary for ensemble processing and “focused” attention is necessary for the processing of individual objects. How can the results of our study be reconciled with this distinction, given that the cueing procedure we used is most likely manipulating the locus of spatial attention, rather than attentional breadth? We believe it is more applicable in situations where the ensemble stimulus is presented in central vision—when this is the case, attention can either be broadened to encompass the entire ensemble, or narrowed to encompass a single element within the array. In the spatial cueing paradigm, it is not clear whether attention is “distributed” or “focused”. Since we observed no difference in performance between the valid and invalid cueing conditions, one possibility is that there was a diffuse allocation of attention across the entire display that enabled ensemble processing to occur at the “unattended” location (even highly naturalistic motion, such as biological motion, has been found to rely on some amount of attentional allocation; e.g., Cavanagh et al., 2001; Thornton et al., 2002), but that the application of focal attention to the cued location did not provide additional benefits to performance. In other words, there may be a “baseline” level of attention that is required for ensemble coding to take place, but our results show that the misdirection of focal, spatial attention has no effect on this process.

If our finding for a particular type of naturalistic ensemble stimulus is indicative of how spatial attention affects all ensemble stimuli, why might ensemble processing be impervious to its effects, especially since it is known to improve many aspects of low-level visual perception (see Carrasco, 2011, for a review; see also evidence that attention can affect the activity of single neurons; e.g., Treue & Maunsell, 1996)? Ensemble coding is a unique process in that it may be a means through which the visual system maximises efficiency in the face of a highly detailed visual environment, and therefore can occur with minimal input from attention; indeed, findings from the ensemble processing literature have been used as examples of how visual awareness can occur in the absence of mechanisms such as attention and working memory (e.g., Bronfman et al., 2014; see Hutchinson et al., 2021, for a general discussion of this issue). However, it is worth highlighting a series of studies by Yeshurun and colleagues that have shown effects of spatial cueing (manipulated via a procedure broadly similar to ours) on a texture segmentation task, which can be seen as requiring a type of ensemble coding. In these studies, participants were required to identify which of two presented textures contained a small set of lines (the “texture target”) that was oriented differently to the lines making up the background of the stimulus (Yeshurun & Carrasco, 1998, 2000; Yeshurun et al., 2008). In this task, attention elicited via a peripheral cue enhances performance when the target is in the visual periphery, but impairs performance when the target is presented in central vision (Yeshurun & Carrasco, 1998, 2000); when attention is elicited via a central cue, performance is uniformly improved (Yeshurun et al., 2008). Our results are at odds with these findings in that they indicate no effect of spatial attention on ensemble processing.

This discrepancy serves to highlight that just as attention is not a monolithic construct, neither is ensemble processing—there are many different types of ensemble processes, ranging from the computation of mean size to the perception of variance in the emotions expressed by multiple faces (Whitney & Yamanashi Leib, 2018). This is in addition to the less commonly studied pattern-based ensembles that do not require the computation of a summary statistic per se, but which nevertheless require the visual system to collapse across individual elements, such as patterns of spatial orientation or frequency (e.g., Alvarez & Oliva, 2009; Brady et al., 2017; Yeshurun & Carrasco, 1998, 2000; Yeshurun et al., 2008); our global motion stimulus falls primarily into the latter category of ensemble stimuli in that it is naturalistic and pattern-based.[7] The fact that there is no correlation between performance on high-level and low-level ensemble tasks (Haberman et al., 2015) further demonstrates the variability in the visual processes that different ensemble stimuli might entail. The potential, and indeed very likely, consequence of this diversity is that spatial attention may not affect all ensemble tasks in the same way, and that it would be worthwhile to see whether our findings for global motion processing can be replicated with other ensemble representations. Indeed, in an event-related-potential study, Ji et al. (2018) observed no differences in accuracy between valid and invalid trials for mean emotion judgments, which shows that our results may extend to higher-order ensemble representations that involve the computation of a single summary statistic.[8] However, it is unclear how some of the most commonly studied ensemble representations—such as that of mean size—are affected by spatial attention as

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[7] We say “primarily” because the global motion stimulus arguably involves the calculation of an average, but a vector average as opposed to a scalar average. Many ensemble processes (e.g., the calculation of mean size) involve the pooling (or averaging) of magnitudes—that is, a scalar average. For a global motion stimulus, determination of the signal direction (e.g., clockwise versus anticlockwise, or upwards versus downwards) involves the pooling of vectors, which are defined by both magnitude and direction. For dot motion specifically, when the directions of the noise dots are uniformly distributed, the direction of the signal dots is equivalent to their average direction (Amano et al., 2009).

[8] Note that while Ji et al. (2018) used a spatial cueing paradigm, it was a “double-cueing” procedure in which two stimuli were presented at the same time, and following the main attentional cue (which indicated one of the two locations), another cue was presented to indicate which was the to-be-judged stimulus. As the authors themselves acknowledged, this second cue may have inhibited shifts of attention prompted by the main attentional cue, and the authors encouraged future studies to only present one stimulus at a time.

manipulated through Posner cueing, and it is clear that spatial attention *can* have an effect on texture segmentation (e.g., Yeshurun & Carrasco, 1998, 2000; Yeshurun et al., 2008). It is therefore imperative that future studies systematically examine how different attentional manipulations affect the processing of different types of ensembles.

In sum, with the use of Posner cueing, we have shown that misdirecting spatial attention has no effect on the processing of a naturalistic motion ensemble. While we do not believe that differences in attentional manipulations can explain all discrepant findings in the attention and ensemble processing literature (conclusions have differed even between studies using the same attentional paradigm; e.g., the attentional blink; Joo et al., 2009; McNair et al., 2017), we believe future studies would do well to clearly specify the type of attention being examined and how it is being deployed. Moreover, we believe the field would benefit from a more systematic examination of how different types of attention affect different types of ensemble representations in view of their heterogeneity. Nevertheless, our results clearly demonstrate that global motion processing—a naturalistic form of ensemble coding—is remarkably resistant to misdirected spatial attention.

Chapter 10

Summary and Future Directions

Chapter Overview

The goal of this thesis was to address outstanding questions regarding the factors that influence orienting in response to social and nonsocial cues, as well as the perceptual consequences of attentional shifts. In this chapter, I summarise the findings of the five empirical chapters of this thesis, considering the factors that may affect orienting (addressed by Chapters 4, 5, and 6) and the perceptual consequences of orienting (addressed by Chapters 8 and 9) in turn. Outstanding questions and avenues for future research are considered within each section.

Factors Affecting Responsiveness to Social and Nonsocial Cues

If we wish to know more about attentional orienting, it is important that we understand the factors that influence responsiveness to cues that tend to elicit orienting. The first part of this thesis focused on this issue, examining both social orienting—the attentional response elicited when viewing another's gaze direction—as well as orienting by nonsocial cues. Here, I considered the characteristics of the observer, the nature of the information in the cue, and secondary task demands as factors that may determine the extent to which social and nonsocial cues orient attention. I specifically examined whether levels of social anxiety modulate the gaze-cueing effect (GCE; Chapter 4); whether a motion signal equivalent in magnitude to that in a dynamic gaze cue is sufficient to guide attention (Chapter 5); and whether shifts of attention in response to arrow cues, dynamic gaze cues, and static gaze cues are influenced by demands placed on working memory (Chapter 6). Together, these studies have yielded several insights about the factors that may affect responsiveness to important attentional cues, and I discuss these studies in each of the following sections.

Does Social Anxiety Modulate the Gaze-Cueing Effect?

When considering individuals' responsiveness to attentional cues, it is important to consider how the characteristics of the observer may influence these responses. In other words, it is important to examine individual differences in attentional orienting, particularly with respect to orienting processes that have critical social importance, such as attending to where someone else is looking. While a number of individual differences have been examined in relation to social orienting, such as trait anxiety (e.g., Fox et al., 2007; Holmes et al., 2006; Mathews et al., 2003), no study had comprehensively studied the potential role of social anxiety—which is characterised by a fear of situations in which one may be negatively evaluated—as a potential moderator of the GCE. Previous investigations were limited in only using neutral gaze-cue expressions (Gregory & Jackson, 2017; Gregory et al., 2019; Wei et al., 2019), only examining overt orienting (Gregory et al., 2019), or not observing a robust GCE (Boll et al., 2016), which could explain their null findings regarding social-anxiety related modulations of the GCE. The lack of a thorough examination of social anxiety in relation to the GCE is surprising considering the range of attentional biases previously observed in social anxiety, such as a bias towards faces exhibiting socially threatening expressions (e.g., Gilboa-Schechtman et al., 1999; Mogg et al., 2004).

Therefore, Chapter 4 of this thesis examined the potential role of social anxiety in modulating the GCE. This study employed angry, fearful, and neutral gaze-cue expressions; a large, female-only sample to ensure that robust GCEs (Bayliss et al., 2005; McCrackin & Itier, 2019) and higher levels of social anxiety (Asher et al., 2017; Xu et al., 2012) could be observed; and an arrow-cueing task to ensure that any modulations of the GCE by social anxiety were not reflective of more general differences in processing attentional cues (e.g., Heeren et al., 2015). Other individual-differences variables that have been found to modulate the GCE—namely, trait anxiety, depression, and autistic-like traits—were controlled for, and the inclusion of these measures allowed for the examination of the replicability of modulations of the GCE by these variables, as well as their interaction with the emotional expression of the gaze cue. Given that social anxiety is characterised by a fear of negative social evaluation, it was anticipated that social-anxiety related modulations of the GCE may only be observed for the angry gaze-cue expression, characterised by either an enhancement or a diminishment of the effect depending on whether socially anxious participants exhibit a bias towards, or away from, socially threatening expressions (e.g., Buckner et al., 2010; Mansell et al., 1999).

Chapter 4 found no variation in the magnitude of the GCE as a function of social anxiety, irrespective of gaze-cue emotion; no modulation of the GCE by gaze-cue emotion in its own right (in contrast to previous research showing, for instance, an enhanced GCE for fearful faces; e.g., Lassalle & Itier, 2013); and no modulation of the GCE by trait anxiety, depression, or autistic-like traits, regardless of gaze-cue emotion. This was despite the GCE having excellent split-half reliability ($r_s = .95$)—in other words, strong rank-order consistency—and therefore the data being well-positioned to reveal any individual-differences effects, should they have been present (e.g., Goodhew & Edwards, 2019).

These findings have several implications. First, they show that while social anxiety is associated with a range of attentional biases (e.g., Buckner et al., 2010; Mansell et al., 1999; Mogg et al., 2004), the GCE remains intact across levels of social anxiety. This is important because orienting in response to others’ gaze direction is a critical social function, and any impairment in this process (i.e., a reduction in the GCE) would necessarily result in social and communicative difficulties. The second implication of these findings is that previously reported modulations of the GCE by the emotional expression of the gaze cue (e.g., McCrackin & Itier, 2019) and other individual-differences variables (e.g., Fox et al., 2007) may not be robust, given that there was no effect of any of these variables in Chapter 4. This indicates that the GCE is a robust effect that may be impenetrable to individual-differences variables more generally, and to the emotion expressed by the cue (however, see below for a necessary qualification of this latter point). Finally, Chapter 4 has shown that the GCE is an extremely reliable effect, as demonstrated through its excellent split-half reliability. This is the first time the reliability of the GCE had been established in this way. Interestingly, this excellent rank-order consistency indicates that there are, in fact, individual differences in the magnitude of the GCE (e.g., Goodhew & Edwards, 2019). However, the results of Chapter 4 appear to indicate that social anxiety, trait anxiety, depression, and autistic-like traits are not variables that can account for these differences.

The second implication of these findings—that the GCE is robust to the emotion expressed by the gaze cue, as well as the four individual-differences variables that were examined in that study—warrants further discussion. Arguably, the findings of Chapter 4 are less conclusive with respect to the former, because the cueing paradigm was not optimised for revealing such effects. More specifically, it is possible that had we used a sequence in which the gaze cue expressed the relevant emotion only *after* it had averted its gaze, we would have observed an emotional modulation, since this sequence gives the impression that the gaze cue has "reacted" to an object appearing in its periphery. Indeed, this sequence is the one typically used by studies that have observed emotional modulations, such as those finding an enhanced GCE for fearful faces (e.g., McCrackin & Itier, 2019). On the other hand, Chapter 4 used a sequence in which the emotion was expressed from the beginning of the trial (i.e., when the gaze cue was looking straight ahead), which may have been more optimal for revealing individual differences (McCrackin & Itier, 2019); for instance, it is known that individuals high on social anxiety exhibit avoidant behaviour for faces with angry expressions that are gazing directly at them (e.g., Heuer et al., 2007), so this sequence may have been ideal for probing the effects of social anxiety on the GCE elicited by emotional faces.

Another factor that might affect whether emotional modulations of the GCE are observed is the nature of the task. The study presented in Chapter 4 used a discrimination task, where participants had to indicate the identity of the target letter. However, a recent study by Chen, McCrackin, et al. (2021) found evidence that emotional modulations may be uniquely present when a localisation task is used, where participants must determine the location at which a target is presented. Using a within-subjects design, these authors directly compared the GCEs generated under discrimination and localisation tasks, and found that as well as the magnitude of the GCE being generally greater when a localisation task was used, an enhanced GCE for fearful faces relative to neutral faces was only observed with the localisation task. The authors explained these findings by arguing that discrimination tasks consume more cognitive resources than do localisation tasks, and that the reduced GCEs observed with this task come about because cognitive resources are required in both the basic gaze-cueing response and the integration of gaze information with the emotional expression of the face. If this interpretation is correct, the findings of this study would seem to indicate that localisation tasks engender a greater attentional response than do discrimination tasks. As argued in Chapter 4, however, there is the possibility that localisation tasks tap nonattentional processes such as priming of motor responses (Wiese et al., 2013); therefore, a combination of attentional and nonattentional processes could explain why greater GCEs have been observed with localisation tasks than with discrimination tasks (Chen, McCrackin, et al., 2021). Whether using a localisation task provides a valid way of investigating emotional modulations of the GCE is unclear, and additional research is required to shed light on the nature of the response tapped by localisation versus discrimination tasks. In any case, the paradigm used in Chapter 4 was optimised for revealing individual-differences effects, which were not observed in that chapter.

Chapter 4 suggests some important directions for future research, particularly with respect to individual differences in the GCE. The first concerns the relationship between social anxiety and the GCE. In Chapter 4, there was no evidence of an association between levels of social anxiety and the magnitude of the GCE, despite the paradigm being optimised for revealing individual-differences effects, and despite the GCE showing excellent reliability. Nevertheless, a future study could manipulate contextual factors in order to “boost” the potential for the GCE to be modulated by social anxiety. For example, perhaps the GCE for angry expressions is modulated by social anxiety when participants face a social threat that alters their sensitivity to socially threatening expressions. Support for this possibility lies in the finding that high-socially-anxious individuals, relative to low-socially-anxious individuals, exhibit an attentional bias away from emotional faces only when they know they will have to give a speech in the near future (Mansell et al., 2002). Implementing a similar social threat in a study similar to the one presented in Chapter 4 would therefore provide another test of the idea that social anxiety modulates the GCE. It should be noted that face-related attentional biases in social anxiety have been observed under conditions where no social threat was present (Gilboa-Schechtman et al., 1999; Mogg et al., 2004). However, given the seeming robustness of the GCE—a robustness that makes sense in light of the importance of gaze-following behaviour—it is possible that the presence of social threat is necessary to amplify any underlying attentional biases.

Whether or not social anxiety modulates the GCE, it is critical to reiterate that the GCE has excellent reliability. This reliability—that is, that individuals can be consistently rank-ordered with respect to the magnitude of their GCE—raises the intriguing possibility that there are individual differences in the magnitude of the GCE that were not captured by the variables studied in Chapter 4. Therefore, another direction for future research might be to uncover what factors can explain those individual differences. Apart from the variables studied in Chapter 4, past research has shown that gender, age, and political affiliation are other variables that modulate the magnitude of the GCE, with greater cueing effects for females (e.g., Bayliss et al., 2005), younger individuals (e.g., McKay et al., 2022; Neath et al., 2013), and liberals (Dodd et al., 2011), respectively. However, the participants in Chapter 4 were all female university students with a mean age of 21.6 (with most participants aged between 18 and 23), making it unlikely that these variables were responsible for individual differences in the GCE.[1]

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[1] Although the political orientation of the participants in Chapter 4 was not measured, there is evidence that students from Australian universities tend towards a more left-wing or liberal political orientation (Hastie, 2007), so it is possible that there was insufficient variation in political views to account for the individual differences observed in Chapter 4.

One possibility is that individual differences in *cognitive* variables could explain the strong rank-order consistency of the GCE. In this regard, one variable that warrants consideration is attentional control. Attentional control is a construct that includes such processes as attentional selection of relevant stimuli, the "filtering out" of irrelevant stimuli, and switching attention from one stimulus to another (Clarke & Todd, 2021). Interestingly, a previous study found increases in the magnitude of the GCE with increases in *self-reported* attentional control (Tipples, 2008); that is, the GCE was of a greater magnitude for those individuals who reported greater attentional control, even though the GCE occurs when the cue is nonpredictive (and therefore appears to be an involuntary response). A future study could test whether this finding holds for *objective* attentional control, given the lack of shared variance between objective and subjective measures (Clarke & Todd, 2021). In addition to extending our understanding of which individual-differences variables modulate the GCE, such results would have implications for debates about the extent to which the GCE depends on top-down control processes. If it is found, for example, that increases in objective attentional control are associated with increases in the GCE, then this would support the conjecture that even though the GCE appears to be involuntary (e.g., it occurs even when the cue is nonpredictive), it still relies on processes associated with voluntary control (e.g., Vecera & Rizzo, 2004, 2006).

Is the Motion Signal in a Dynamic Gaze Cue Sufficient to Elicit an Attentional Shift?

Chapter 5 saw a transition from a focus on the characteristics of the observer (i.e., individual differences) in modulating attentional orienting to a more specific focus on the characteristics of the cue itself. Specifically, Chapter 5 examined whether the attentional response elicited by a particular type of gaze cue—a dynamic gaze cue—can at least partially be attributed to a nonsocial aspect of the cue. Dynamic gaze cues involve gaze being actively averted, with the pupils shifting to the left or right, and therefore carry with them a motion signal. Static gaze cues, by contrast, appear with gaze already averted, and therefore lack this motion signal. The specific aim of Chapter 5 was to assess the possibility that the type of motion signal seen in dynamic gaze cues is sufficient to drive a shift of attention, even if this signal lacks any social information. Previous research has hinted at the possibility that dynamic gaze cues are responded to differently than static gaze cues; for instance, infants show selective gaze-following behaviour for faces with visible pupil shifts (Farroni et al., 2000). Furthermore, recent research has shown strong motion input into neural regions associated with social perception, including those that process gaze direction (Pitcher & Ungerleider, 2021). However, previous studies examining whether the type of motion signal seen in dynamic gaze cues can guide attention have been limited in using motion cues that resembled social stimuli (Wei et al., 2019; Zhang et al., 2019), or used a localisation task, which, as discussed earlier, may tap nonattentional processes (Wiese et al., 2013). Other studies employed long intervals between the appearance of the motion cue and that of the target, which may have dampened any attentional effects (Chandler-Mather et al., 2019; Shi et al., 2010), or only examined overt shifts of attention (Chawarska et al., 2003).

Therefore, Chapter 5 used a motion cue consisting of a dot array that shifted to the left or right on each trial, and this motion signal was of the same magnitude as the pupil shift in a dynamic gaze cue that was also examined in that study. Importantly, this cue lacked any social information (as verified by participant responses in one experiment), and a letter-discrimination task requiring manual responses was used, which made it likely that the cueing procedure was tapping attentional processes (cf. localisation tasks; Wiese et al., 2013) and was capable of revealing covert shifts of attention (i.e., shifts of attention without any eye movements). Both short and long stimulus-onset asynchronies were used to examine potential differences in the time course of any observed effects. Across three experiments, no cueing effect for the motion cue was observed: that is, there was no difference in reaction times (RTs) between valid and invalid trials, and in the one experiment where there was a difference suggestive of motion-induced orienting (Experiment 1), an opposing pattern of error-rate data rendered the RT data virtually uninterpretable. The lack of cueing effects also occurred despite the potency of the motion signal being enhanced in

Experiment 3. A gaze cue, on the other hand, reliably generated shifts of attention (Experiments 1 and 3). It was concluded on the basis of these results that the motion signal in a dynamic gaze cue is not sufficient to elicit a shift of attention in its own right.

The key implication of this finding is that the social information in a dynamic gaze cue is critical for eliciting an attentional response, and that responses to this cue cannot be attributed solely to the motion signal (a nonsocial factor) carried by the pupil shift. In this sense, these findings dovetail with those that have used other methods to determine whether the social content of a gaze cue is critical in eliciting the GCE. For example, one line of research has shown that when barriers are placed between the gaze cue and the target, giving the impression that the face cannot “see” the target, the GCE is diminished (Nuku & Bekkering, 2008; Teufel et al., 2010; but see Kuhn et al., 2018). Thus, these studies also highlight the important role of perceived social meaning in the cue for generating an attentional shift, albeit using a different approach. However, as discussed later, our results do not rule out the potentially unique role of motion in the GCE, and future studies should seek to investigate dynamic gaze cues more closely. Another implication of these findings, albeit one that must be made more tentatively, is that a nonpredictive, directional motion cue does not appear to guide attention. Previous research has shown that motion can *capture* attention (e.g., Abrams & Christ, 2003, 2005; von Mühlenen & Lleras, 2007), but the results of Chapter 5 would seem to suggest that directional motion cannot guide, or “push,” attention in the direction of motion. However, the study presented in Chapter 5 can only be seen as a conservative test of this claim because the magnitude of the motion signal was relatively small, a choice made deliberately to bring this signal in line with the magnitude of the pupil shift in the gaze cue. Therefore, to be able to establish stronger conclusions with respect to the attention-guiding capabilities of directional motion, a motion signal of a greater magnitude should be used. It would also be interesting to examine whether a motion stimulus containing fewer dots might elicit an attentional shift, given that our motion stimulus was made up of a relatively large number of dots (50 dots in Experiments 1 and 2; 150 dots in Experiment 3);

however, there is no a priori reason to believe that such a stimulus would be effective in doing so, assuming that the magnitude of the motion signal was identical.

While Chapter 5 found that a motion signal equivalent in magnitude to that of a pupil shift is not sufficient to elicit an attentional shift, this does not mean that dynamic gaze cues are responded to in exactly the same way as static gaze cues. While it is true that dynamic gaze cues and static gaze cues appear to produce cueing effects of equal magnitudes (Hietanen & Leppänen, 2003), the finding that infants only follow gaze which has been actively averted (Farroni et al., 2000) suggests that motion may have a key role to play in the GCE. Therefore, future research should continue to investigate potential differences between dynamic and static gaze cues, especially given recent evidence for strong motion input into social perception (Pitcher & Ungerleider, 2021). One intriguing possibility is that dynamic and static gaze cues differ with respect to their automaticity. Specifically, one possibility is that dynamic gaze cues are more socially relevant than static gaze cues—for instance, because seeing someone actively avert their gaze might indicate the sudden occurrence of an event that immediately requires the observer's attention—and this could result in those cues being responded to more automatically. Indeed, one study found evidence for this possibility when examining the "unconscious" feature of automaticity (Moors & De Houwer, 2006).[2] Specifically, Chen et al. (2014) found that subliminally presented gaze cues only produced a GCE when they were dynamic; subliminally presented static gaze cues, on the other hand, did not produce cueing effects. This indicates that the GCE elicited by dynamic gaze cues may indeed be more automatic than that elicited by static gaze cues.

Chapter 6 of this thesis also examined dynamic and static gaze cues with respect to their automaticity by examining the efficiency feature of this construct (Moors & De Houwer, 2006), finding that the GCEs for both cue types consistently survived a concurrent working memory load (WML). Note, however, that our analyses in that chapter did not allow us to

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[2] As discussed in Chapters 3 and 6, automaticity is a multifaceted construct (Moors & De Houwer, 2006), making it necessary for studies to be specific about which aspect of automaticity is being investigated.

directly compare these cue types because those analyses were focused on examining the efficiency of each cue type in its own right, and not on detecting interactions between cue types. Future studies could more directly compare dynamic and static gaze cues along different dimensions of automaticity, such as intentionality and controllability (Moors & De Houwer, 2006). As it currently stands, the typical approach in the literature examining the automaticity of social orienting is to simply use either a dynamic or static gaze cue, and examine the automaticity of the GCE only for that specific cue type. This typically occurs without any justification for why a particular cue type was chosen (e.g., Galfano et al., 2012; Ristic et al., 2007). Therefore, future research could investigate whether the automaticity of the GCE is contingent on the type of gaze cue employed by directly comparing dynamic and static gaze cues within the same experiment, similar to the study by Chen et al. (2014), but for other features of automaticity.

Are Arrow- and Gaze-Induced Attentional Responses Efficient?

Having examined the properties of the cue in generating an attentional response, Chapter 6 turned to the effects of secondary task demands on responsiveness to attentional cues. Specifically, Chapter 6 examined the efficiency of arrow-induced orienting, as well as that of the GCE. Arrows are similar to gaze cues in that they elicit attentional shifts even when they are nonpredictive of the target location (e.g., Tipples, 2002); however, this response is thought to reflect individuals' experience with the symbolic relevance of arrows, rather than any biological or social imperative to attend to the cued location (as has been argued to underlie attentional responses to gaze cues; e.g., Frischen, Bayliss, & Tipper, 2007). These ideas have led to the claim that arrow-induced orienting may be less automatic than the GCE (e.g., Ristic et al., 2007), and indeed, some evidence suggests that this may be the case (e.g., the *unintentionality* of the orienting response may be greater for gaze cues than for arrow cues; Friesen et al., 2004).

A particularly important aspect of automaticity is *efficiency*: that is, the extent to which a particular response requires top-down processing resources (Moors & De Houwer, 2006).

This is an important aspect of automaticity to investigate for such critical processes as arrow- and gaze-induced orienting, where exposure to such cues is often accompanied by demands on top-down processing resources (e.g., someone mentally planning a shopping list while engaged in a conversation with someone who may avert their gaze). While some research had examined the efficiency of the GCE (e.g., Hayward & Ristic, 2013; Law et al., 2010), and found that this response was impervious to secondary task demands that ostensibly consume top-down processing resources, no study had specifically examined the efficiency of arrow-induced orienting. Therefore, the aim of Chapter 6 was to examine the efficiency of arrow-induced orienting, while also examining the efficiency of orienting by dynamic and static gaze cues. Given established links between spatial working memory and attentional processes (e.g., Awh & Jonides, 2001), Chapter 6 employed a visuospatial WML, where participants were required to memorise the locations of dots as they completed the cueing task for each cue type.

The study began by investigating arrow-induced orienting, with Experiment 1 finding that attentional responses to arrow cues were eliminated under a concurrent WML. By contrast, orienting by dynamic gaze cues—examined in Experiment 2—survived this same load. Subsequent experiments examined different combinations of cue types, with Experiment 3 finding an elimination of arrow-induced orienting by the WML, and a survival of the static GCE under the same load; Experiment 4 then found a survival of the GCE under the WML for both dynamic and static gaze cues. Finally, Experiments 5 and 6 both examined all three cue types, and found no evidence of a WML affecting attentional responses to arrows, dynamic gaze cues, or static gaze cues, even under more demanding WMLs that contained a greater number of to-be-remembered dots. That is, the final two experiments, in contrast to the earlier experiments, found no evidence of arrow-induced orienting being diminished under a concurrent WML.

Altogether, the results of the experiments presented in Chapter 6 are consistent with respect to the GCE, but inconsistent with respect to arrow-induced orienting. That is, none of the experiments showed evidence of the GCE being affected by the WML, irrespective of whether the gaze cue was dynamic or static; however, arrow-induced orienting was sometimes eliminated by the load (Experiment 1; Experiment 3), and sometimes found to persist in spite of the load (Experiment 5; Experiment 6). Therefore, it can be concluded that the GCE appears to be highly efficient for both dynamic and static gaze cues, with this persistence of the GCE dovetailing with the results of previous studies (e.g., Hayward & Ristic, 2013; Law et al., 2010; Yokoyama et al., 2019, 2020), and potentially reflecting the inherent social and communicative value of this signal. This efficiency provides evidence for the automaticity of the GCE.[3] By contrast, arrow-induced orienting may be somewhat inefficient (as shown by Experiments 1 and 3), which could reflect the fact that the meaning of arrows must be learned through experience. However, the fact that Experiments 5 and 6 showed a persistence of arrow-induced orienting under a WML (also shown by Yokoyama et al., 2020, after data collection for Chapter 6 was completed) means this conclusion cannot be made with certainty.

These equivocal results for arrow-induced orienting point directly to the need for a follow-up study that investigates factors influencing susceptibility to a WML, and thus could account for whether or not arrow-induced orienting is observed under a concurrent load. More specifically, in Chapter 6, the possibility was raised that between-experiment inconsistencies in the results for arrow cues could reflect the fact that different individuals participated in each experiment, and therefore differences in working memory capacity could explain why some experiments showed an elimination of arrow-induced orienting under a WML, while others did not. Put simply, low-working-memory-capacity participants may be more susceptible to a WML than high-working-memory-capacity participants (Murphy et al., 2016). This idea was not tested in Chapter 6 because of practical constraints concerning experiment duration, as well as the difficulties posed in choosing an appropriate measure of

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[3] As mentioned in Chapters 3 and 6, this statement must be made with the caveat that because the GCE can be influenced by social variables, such as the political orientation of the observer (Dodd et al., 2011), this automaticity is conditional on the presence of the appropriate social factors (Dalmaso et al., 2020).

working memory capacity: that is, one that maps directly onto the visuospatial WML used in that study.

Nevertheless, it is important that a future study endeavours to examine the relationship between the efficiency of arrow-induced orienting and individual differences in working memory capacity. A common measure of visuospatial working memory capacity is the symmetry span task (Kane et al., 2004), which requires participants to remember the locations of squares appearing on a grid. However, this task could be said to require pattern recognition, which may rely on different mechanisms to those underpinning visuospatial working memory (e.g., Finke et al., 2006). Interestingly, one study has used a working memory capacity measure resembling our WML manipulation; Dai et al. (2019) used a task in which a group of coloured squares was presented, and upon its second presentation, participants had to determine whether one of the squares had changed colour. Importantly, these authors showed that this measure of capacity had high test-test reliability, which would be important for unearthing a relationship between individual differences in working memory capacity and differences in the effects of a WML on attentional orienting (Goodhew & Edwards, 2019). To bring it in line with the WML used in Chapter 6 (which tapped *visuospatial* working memory), this change-detection task could be modified to involve a location change rather than a colour change. Should this adapted version also exhibit high reliability, a study could use this task to examine whether individual differences in working memory capacity scores are associated with individual differences in the effects of an arrow cue under a WML. Findings from this study would further our understanding of how the efficiency of responding to symbolic cues—that is, the degree to which these responses draw on top-down processing resources—may depend on individual-differences variables.

Factors Affecting Responsiveness to Social and Nonsocial Cues: Conclusion

The first part of this thesis has produced several important insights about the factors influencing responsiveness to attentional cues, especially with regard to the attentional response elicited by eye gaze, an important social cue. Chapter 4 found evidence that the

GCE may be robust to levels of social anxiety, as well as other individual differences; Chapter 5 found that the motion signal in a dynamic gaze cue is not sufficient to provoke an attentional response, pointing to the importance of the social information contained in a dynamic gaze cue; and Chapter 6 found a survival of the GCE under WMLs of varying difficulty—across both dynamic and static gaze cues—while observing inconsistent results for arrow cues. These findings speak to the impressive robustness of attentional responses to eye gaze, in that these responses were not modulated by any of the variables examined in Chapter 4 (the emotional content of the gaze cue and individual differences); it was consistently observed in Chapter 5; and it survived a demanding WML in Chapter 6. In showing the robustness of the GCE, these findings therefore attest to the critical social importance of observing others' gaze direction.

Apart from the directions for future research discussed above, it will be important for future studies to examine the generalisability of these findings to real person-to-person interactions, as well as to gaze information conveyed by robots and avatars instead of simple photos and schematics. It is theoretically possible that social orienting operates differently in these contexts, especially when considering the complexity of real-world interactions. Indeed, over the last few years, studies have emerged that have focused on gaze cueing in such contexts (e.g., Macdonald & Tatler, 2018; Willemse et al., 2018). At the same time, while some have criticised traditional gaze- and arrow-cueing tasks for a lack of ecological validity (e.g., Kingstone et al., 2020), studies using these tasks have provided, and continue to provide, a strong empirical foundation for research performed in more naturalistic settings.

Perceptual Consequences of Attentional Orienting

Just as important as understanding the factors that influence responsiveness to attentional cues is understanding the consequences of attentional orienting for perception, and therefore our experience of the visual world. As such, the second part of this thesis examined two outstanding issues regarding the consequences of attention for visual perception. Chapter 8 assessed an alternative account of reported detrimental effects of involuntary attention on temporal resolution, which is our ability to perceive variation in luminance across time. Chapter 9 then examined whether attentional shifts can affect perception of a naturalistic ensemble stimulus, which involves the visual system pooling together a number of local elements to form a summary percept. Together, these studies have added clarity to two existing debates regarding the effects of attention on visual perception.

Does Involuntary Attention Impair Temporal Resolution?

Attention appears to enhance many aspects of visual perception, including our ability to perceive fine spatial detail (i.e., spatial resolution; Yeshurun & Carrasco, 1999). However, some studies (e.g., Yeshurun & Levy, 2003) have found evidence to suggest that involuntary attention—specifically, attention elicited by a brief, peripherally presented cue—impairs temporal resolution. Evidence for this notion comes primarily from the temporal gap-detection task, where participants must determine whether the target (usually a circle or a ring) flickered or did not flicker. Studies have shown that performance on such tasks is worse on “cued,” or “valid,” trials, relative to “neutral,” or “invalid,” trials (Baek et al., 2007; Hein et al., 2006; Nicol et al., 2009; Rolke et al., 2008; Yeshurun, 2004; Yeshurun & Levy, 2003). Chapter 8 of this thesis tested an alternative account of this effect, which proposes that this impairment in temporal-resolution performance is the consequence not of attention, but of spatiotemporal confusion: that is, participants confusing the temporal signals generated by the cue with those of the target. In other words, the spatiotemporal-confusion account proposes that the impairments in temporal resolution observed in previous studies are the product of a confound in the cueing procedure, rather than a true effect of attention.

Chapter 8 tested the spatiotemporal-confusion account by manipulating two factors that could contribute to spatiotemporal confusion: first, the spatial proximity of the cue to the target (Experiment 1), and second, the amount of high temporal-frequency information in the cue (Experiment 2).[4] Experiment 1 used four different cue types that varied in their spatial proximity to the target: a small peripheral cue, a large peripheral cue, an arrow cue, and a gaze cue, with these latter two cue types having the advantage of being capable of eliciting attentional shifts even when they are centrally presented and nonpredictive (Ristic et al., 2002). The spatiotemporal-confusion account predicts a diminished potential for confusion with increasing distance between the cue and target, and consistent with this prediction, a temporal impairment (i.e., lower sensitivity on valid versus invalid trials) was observed only for the two peripheral cues; there was no evidence of either of the central cues modulating performance on the temporal task. In Experiment 2, only the two peripheral cues were examined, and whereas in Experiment 1, the cues flickered on and off prior to the appearance of the target, in Experiment 2 they were made to remain on the display until participants responded to the temporal target. The spatiotemporal-confusion account predicts that the potential for confusion should be reduced under these conditions, because the cue is eliciting less high temporal-frequency information prior to the appearance of the target—information that could impair perception of the target's temporal qualities. Consistent with this prediction, no evidence of a temporal impairment was found for either the small peripheral cue or for the large peripheral cue; this was in spite of evidence from that experiment that both cues were effective in eliciting attentional shifts, as shown through cueing effects on RTs in a letter-detection task. Overall, Chapter 8 provided evidence for the spatiotemporal-confusion account, and indicated that involuntary attention does not affect temporal resolution.

The key implication of this finding is that it provides evidence against one model of how involuntary shifts of attention affect perception. This model—the "modulated visual pathways" model—proposes that involuntary attention enhances the activity of parvocellular neurons, which mediate our highest spatial resolution, which then diminishes the activity of

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[4] The third factor that could contribute to spatiotemporal confusion is the temporal proximity between the cue and target, but this could not be manipulated because it needed to be kept short for involuntary orienting to be elicited (e.g., Müller & Rabbitt, 1989).

magnocellular neurons, which mediate our highest temporal resolution (Yeshurun, 2004; Yeshurun & Levy, 2003; Yeshurun & Sabo, 2012). The results of Chapter 8 pose problems for this account because it is difficult to reconcile a diminishment of magnocellular activity—those neurons that mediate our highest temporal resolution—with no detrimental effect of attention on temporal resolution. It is still possible that involuntary attention enhances the activity of parvocellular neurons, given the findings that involuntary attention enhances spatial resolution (e.g., Yeshurun & Carrasco, 1999) and prolongs perceived duration (with this finding potentially reflecting the sluggish activity of parvocellular neurons; e.g., Yeshurun & Marom, 2008), but our results are inconsistent with the "magnocellular impairment" portion of the modulated visual pathways account. Interestingly, selective modulations of magnocellular and parvocellular activity have also been called into question with respect to other cognitive phenomena. For example, it has been proposed that near-hand space can modulate magnocellular and parvocellular contributions to visual processing (e.g., Goodhew & Clarke, 2016; Gozli et al., 2012). However, some studies have failed to find evidence for near-hand-space modulations of tasks designed to tap the activity of magnocellular or parvocellular neurons (e.g., Dosso & Kingstone, 2018), calling into question the existence of such modulations. Therefore, just as this model is not viable for attentional shifts, it may also not be viable for other aspects of cognition.

The results also have implications for measuring the effects of involuntary attention on visual perception. In particular, they highlight the importance of ensuring that the influence of any potential cue-target interactions that could affect perception of the target are eliminated. The results of Chapter 8 show that when potential confounds are eliminated—in this case, spatiotemporal confusion between the signals generated by the cue and those generated by the target—previously reported, ostensibly attentional effects on visual perception can fail to materialise, even if the cues employed are known to be effective attentional cues. These issues are unique to studies investigating involuntary attention because the typical manipulation for eliciting these shifts of attention involves a cue being presented at, or near, the location of the upcoming target—a problem that has also been acknowledged by other authors (e.g., Taylor et al., 2018). Therefore, the results of Chapter 8 indicate that caution should be exercised when examining the effects of involuntary attention on visual perception, where perception of the target may be influenced by the physical properties of the cue.

The findings of Chapter 8 also suggest some directions for future research. The study presented in that chapter used a “valid versus invalid” comparison, where the cue was nonpredictive of the target location and the target either appeared at the location indicated by the cue or at the opposite location. This was a deliberate choice made in light of the possibility that neutral cues may be more alerting than the cues in “cued” trials (e.g., because they are often bigger than these cues), and this, in part, may have led to enhanced temporal-resolution performance on those trials in previous studies (e.g., Yeshurun & Levy, 2003). Furthermore, there is ambiguity with respect to how attention is distributed on neutral trials that is not present in a “valid versus invalid” comparison. However, although the valid versus invalid comparison is preferable because it does not pose these issues, it would be worthwhile performing a follow-up experiment in which the spatiotemporal-confusion account is tested for a “cued versus neutral” comparison, given that this is the comparison some of the previous studies investigating the effects of involuntary attention on temporal resolution have used (e.g., Yeshurun, 2004; Yeshurun & Levy, 2003). Indeed, I am currently collecting data for such an experiment, where cues that flicker on and off and those that stay on until response are being compared within the same group of participants, and a speed-accuracy trade-off control is in place to ensure that participants cannot strategically trade accuracy for speed (as may have occurred in some studies investigating attention and temporal resolution; e.g., Hein et al., 2006).

Future studies could also clarify the effects of more voluntary forms of attention on temporal resolution. As discussed in Chapter 8, attention elicited by a predictive, centrally presented arrow cue—that is, one that is likely to elicit a more voluntary form of orienting than a peripheral cue—appears to enhance performance on a temporal order judgment task, where participants must determine which of two targets appeared first (Hein et al., 2006). This type of task, like the temporal gap-detection task, calls on the visual system's highest temporal resolution, and therefore these results would seem to indicate that voluntary attention enhances temporal resolution. However, Sharp et al. (2018) recently found evidence that voluntary attention can also promote temporal *integration*—the pooling of temporal signals, which is the opposite of the temporal *segregation* required to discriminate temporal signals—depending on the demands of the task. In another study, using the proportion of trials on which participants perceived element motion in a Ternus display as an index of temporal integration, Hochmitz et al. (2021) found that voluntary attention enhances temporal integration over temporal segregation. Therefore, Hochmitz et al. provided evidence that even when task demands do not favour one type of processing over the other, voluntary attention enhances temporal integration, which is clearly inconsistent with the findings of Hein et al. (2006). Interestingly, Hochmitz et al. invoked the "modulated visual pathways" account to explain their results, which was originally developed to explain the effects of *involuntary* attention specifically, and cannot explain why Sharp et al. observed evidence of both temporal integration and segregation for voluntary attention. Therefore, just as work was needed to clarify the effects of involuntary attention on temporal resolution, the effects of voluntary attention on temporal perception also need further examination. In particular, it may be worthwhile for future research to more clearly define the conditions under which voluntary attention will promote temporal integration over temporal segregation and vice versa.

Does Visual Spatial Attention Modulate Naturalistic Ensemble Processing?

While Chapter 8 focused on the effects of attention on a single stimulus, Chapter 9 focused on the effects of attention on the processing of *multiple* stimuli. This chapter specifically examined ensemble processing, which involves the visual system collapsing across local detail to extract a summary representation of a scene (e.g., the mean size of objects in an array; the mean emotion expressed by multiple faces; Whitney & Yamanashi

Leib, 2018). This type of processing might be performed in the name of efficiency—it would simply be too computationally costly for the visual system to individually process each element in a scene. This idea has led to the claim that ensemble processing may require minimal, or no, attentional resources (e.g., Bronfman et al., 2014; Joo et al., 2009). However, the literature focused on testing this claim has been marred with inconsistent results, with some studies showing a sparing of ensemble processing under conditions that ostensibly limit attention (e.g., Bronfman et al., 2014), and others showing a detrimental effect of limited attention on ensemble processing (e.g., Jackson-Nielsen et al., 2017). In Chapter 9, the case was made that this was due to attention being inadequately conceptualised or manipulated in studies examining the effects of attention on ensemble processing.

These issues motivated the study presented in Chapter 9, which specifically examined the effects of visual spatial attention on naturalistic ensemble processing, using the spatial cueing paradigm to manipulate attention. This study differed from previous research in that it clearly defined the type of attention being examined, and used a well-established method of manipulating that form of attention. A naturalistic ensemble—a global motion stimulus—was also used, given that previous studies have tended to use relatively artificial ensembles, such as arrays of geometric shapes. A global motion stimulus involves the extraction of a coherent motion signal from a group of moving dots, a proportion of which are moving in the signal direction, and the rest of which are noise dots moving in random directions (Newsome & Paré, 1988). The motion pooling that is required to extract this signal underlies our perception of optic flow—that is, our sense of objects moving around us as we move through our environment (Gibson, 1950)—and extracting a global motion signal can therefore be seen as a naturalistic form of ensemble processing. As in earlier chapters, Chapter 9 used the spatial cueing paradigm to manipulate attention. Experiment 1 used a centrally presented number cue that correctly indicated the location of the global motion stimulus on 75% of trials (thus providing an incentive for participants to use the cue), and Experiment 2 used a 75% predictive arrow cue.

Across two experiments, Chapter 9 found no evidence of attention modulating performance on the global motion task. In Experiment 1, accuracy in determining the direction of motion was equivalent across valid and invalid trials, and in Experiment 2, global motion thresholds (another index of performance on this task, where lower thresholds indicate greater sensitivity to the global motion signal) were equivalent between valid and invalid trials. These results were obtained despite evidence from both experiments that the cues were effective in eliciting attentional shifts. These findings are consistent with literature indicating that ensembles are impervious to diminished attentional resources (e.g., Bronfman et al., 2014), but inconsistent with studies showing harmful effects of attentional withdrawal on ensemble processing (e.g., Jackson-Nielsen et al., 2017). In being consistent with the first group of studies, the results of Chapter 9 speak to the remarkable efficiency of naturalistic ensemble processing. This efficiency seems particularly impressive when considering that the type of attention being manipulated was visual spatial attention: a form of attention that modulates a plethora of lower-level visual processes (e.g., Carrasco, 2011).

In Chapter 9, care was taken to clearly define the type of attention being manipulated (visual spatial attention) and to select a method that was clearly manipulating that form of attention (the spatial cueing paradigm). This was done in view of many studies in the ensemble processing and attention literature lacking such specifications. For example, Oriet and Brand (2013) claimed to be examining the effects of “selective” attention on ensemble processing, but this says almost nothing about the type of attention being investigated—attention is, by definition, a selective process. To take another example, studies claiming to be comparing “attended” and “unattended” conditions also used paradigms that made it very likely that attentional resources had been directed to the “unattended” ensemble (e.g., Chen, Zhuang, et al., 2021). Apart from making it difficult to reconcile the results of different studies, these issues pose a challenge for attempts to document how different forms of attention might be affecting different types of ensemble processes.

This latter point speaks directly to the need for a program of research that examines the effects of different types of attention on different types of ensemble stimuli. There are two reasons why it is not only possible, but rather very likely, that there are varied effects of attention on different types of ensembles. The first is that different types of attention are known to have differential effects on lower-level visual processes (e.g., there are differential effects of voluntary versus involuntary attention on spatial resolution; Yeshurun & Carrasco, 1998; Yeshurun et al., 2008). It stands to reason, then, that different types of attention could also have differential effects on higher-level visual processes such as ensemble coding, and knowing what these differences are could help constrain theories regarding how ensemble processing is affected by attention. The second reason is that there are many different types of ensemble stimuli, and there is evidence that performance on different ensemble tasks is not always correlated—particularly with respect to ensemble stimuli that cut across different levels of complexity (Chang & Gauthier, 2021; Haberman et al., 2015). Therefore, it is possible that different types of ensemble stimuli are differentially affected by even the same type of attention.

The benefits of adopting this program of research would be twofold. First, findings from this line of research could help reconcile the studies that have observed a sparing of ensemble processing when attention is limited, with those that have seen ensemble processing suffer under conditions that limit attention. Second, and more importantly, this line of research would give us a greater understanding of how ensemble processing is affected by different attention types. This would be informative not only in terms of the degree to which ensemble processing is an efficient process, but also with respect to our understanding of different types of attention and their perceptual consequences. Regarding attentional shifts specifically, a useful distinction to begin with might be that between voluntary and involuntary shifts of attention, given that these forms of orienting show differential effects across several lower-level aspects of visual perception (Carrasco, 2011). The aim of Chapter 9 was to examine shifts of visual spatial attention more broadly, but a follow-up study could use cues that elicit either voluntary or involuntary forms of orienting, and see whether these modes of orienting have differential effects on global motion processing. This research approach would represent a shift away from the predominant approach to examining the effects of attention on ensemble processing, which has resulted in a profusion of attentional paradigms being employed and, consequently, a number of inconsistent findings.

Perceptual Consequences of Attentional Orienting: Conclusion

To summarise, the second part of this thesis has provided insight into two somewhat contentious issues regarding the effects of attention on visual perception, focusing on how attention affects the processing of *single* elements and how it affects the processing of *multiple* elements. First, Chapter 8 showed that previous, seemingly detrimental, effects of involuntary attention on temporal resolution can be attributed to spatiotemporal confusion between the cue and target, rather than a true effect of attention. The results of this chapter provide evidence against the “modulated visual pathways” theory of the effects of involuntary attention on perception, which is based on findings of temporal impairments. Next, Chapter 9 showed that perception of a naturalistic ensemble stimulus, which involves the visual system pooling local elements, survives the misallocation of visual spatial attention. In doing so, Chapter 9 demonstrated the remarkable efficiency of naturalistic ensemble processing.

Apart from clarifying the consequences of attention for the visual processes studied in each chapter, Chapters 8 and 9 have both demonstrated the importance of carefully manipulating the chosen form of attentional allocation, and of being explicit about the type of attention under study. Chapter 8 showed that artefacts in the cueing paradigm appear to be responsible for previously reported effects of involuntary attention on temporal resolution, and the point was made in Chapter 9 that inconsistent findings in the ensemble processing and attention literature may be attributable to a lack of clarity regarding the chosen form of attention, as well as problematic manipulations of attention. Indeed, another study using the global motion stimulus found different results to those presented in Chapter 9 with the use of a different attentional paradigm (Motoyoshi et al., 2015). Therefore, it is critical that researchers investigating the perceptual consequences of attentional orienting remove potential artefacts from the cueing procedure, particularly when involuntary attention is being examined and thus the potential for cue-target interactions is likely. It is also important that they clearly define the type of attention they are examining to facilitate understanding of different types of attention and their perceptual consequences, as well as to enable clearer comparisons between studies.

Attentional Orienting and Other Modes of Attentional Allocation

This thesis has presented studies examining attentional orienting—shifts of attention across space. This mode of attentional allocation is important in allowing us to prioritise different aspects of our visual environment depending on what is relevant at any given moment. However, shifting attention is not the only way of allocating our attentional resources. Another important mode of attentional allocation is attentional-breadth resizing (Eriksen & St. James, 1986; Eriksen & Yeh, 1985), which was discussed in Chapter 2. Consider how the tourist described at the beginning of Chapter 1 might perceive their surroundings. In addition to shifting their attentional resources from one object (e.g., a billboard) to another (e.g., a food stall), the tourist might also expand their attentional breadth to take in the whole scene (for instance, if they want to obtain an overall impression of the city they have just arrived in) or contract their attentional breadth to focus on just one element (for instance, a street performer who has just started up an impressive routine). Not only is it the case that these two forms of attentional allocation can occur individually, but it is also likely that they interact. The tourist might adopt a “default” broad attentional breadth to take in the scene, and simultaneously shift their attentional resources around within that attentional window to take in different aspects of that scene. Furthermore, the tourist might adjust the size of the attentional spotlight they are shifting around depending on what they are attending to; for instance, their spotlight of attention would necessarily be much larger when they are shifting their attention from one skyscraper to another versus one person to another.

However, little research has examined potential interactions between attentional orienting and attentional-breadth resizing. This is surprising considering that just as attentional orienting has consequences for perception (Carrasco, 2011), so does attentional-breadth resizing (e.g., Lawrence, Edwards, & Goodhew, 2020), and therefore it is possible that the nature of any perceptual modulations by attention are contingent on both the size of the attentional spotlight and the nature of the orienting response (e.g., whether it is endogenous or exogenous). While a few studies have examined the effects of manipulating cue size—and therefore the size of the attentional spotlight that is being shifted—on some aspects of perception (e.g., spatial resolution; Yeshurun & Carrasco, 2008), studies examining these issues are rare. This is especially the case for the issue of whether the effects of attentional orienting differ when they have been executed within a small or a large attentional window; for instance, though some research (e.g., Weber et al., 2000) has examined how the frequency of attentional shifts changes depending on whether attentional breadth is small or large, it is unclear what consequences this might have for visual perception. Overall, while the compartmentalisation of different types of attention is useful from an empirical perspective, in that it allows us to isolate the factors that influence a particular type of attentional allocation and understand the consequences of different modes of allocation, it is important to remember that attention is dynamic. Therefore, researchers should endeavour to understand how different modes of attentional allocation interact with one another.

Conclusion

This thesis has produced several insights regarding both the factors influencing orienting in response to attentional cues and the perceptual consequences of attentional shifts. The findings of this thesis have all come from the use of a simple, yet effective and elegant, method of manipulating shifts of visual spatial attention: the spatial cueing paradigm.

While it is important that future research examining attentional orienting tests the applicability of these findings to more naturalistic contexts, this thesis has shown that the use of this paradigm—and the study of attentional orienting in laboratory conditions more generally—provides a strong foundation for such work, and can yield important insights in its own right.

What do these findings mean in relation to the tourist described in Chapter 1? The results of this thesis suggest that even if the tourist is socially anxious, they will likely attend to where they see a fellow pedestrian suddenly avert their gaze, even if that person wears a hostile expression as a result of being jostled by the people around them. They indicate that the tourist might attend to the location indicated by a fellow pedestrian’s gaze even if that observer is simultaneously preoccupied with trying to navigate their surrounds in an unfamiliar city, and that this might occur regardless of whether they have seen that pedestrian actively avert their gaze, or whether they have looked up from their phone to see the pedestrian looking in a particular direction. They indicate that the tourist will be just as capable of perceiving the subtle flickering of a failing streetlight when they have involuntarily attended to it because they have noticed a bird flying nearby, compared with when they are attending elsewhere. Finally, they indicate that whether the tourist is attending to a group of pedestrians will have no bearing on their ability to determine the pedestrians’ general walking direction. Future research will no doubt shed further light on the factors affecting where and when such an observer will shift their attentional spotlight, and the consequences of these shifts for their experience of the visual world.

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