Contributions of Configuration, Individual Location, and Reference Frame in Contextual Guided Visual Search

Thesis

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Abstract

The thesis investigated the *Contextual Cueing Effect*, characterized by enhanced efficiency in visual search through the acquisition of spatial regularities in repeated visual stimuli. To gain deeper insights into the mechanisms behind such effects, this dissertation analyzes various specific factors that could potentially act as contextual cues, directing visual search in repeated displays. The investigation covered four distinct factors: global configuration, individual location, as well as egocentric and allocentric reference frames. All experimental procedures were conducted with the participation of healthy, young individuals, ensuring a robust foundation for exploring the contextual cueing effect.

Study I scrutinized the influence of global configuration and individual spatial locations on contextual cueing. During the learning session, participants performed 20 searches of 12 displays to comprehensively familiarize themselves with these displays. Subsequently, the transfer session encompassed four conditions: fully repeated configurations (same as the displays in the learning session), recombined configurations (preserving distractor locations but not configuration by combining distractor locations from two learned displays), rotated configurations (preserving configuration but not distractor locations by rotating displays), and new configurations (randomly selected distractor locations). The reaction times for each condition were collected and analyzed.

Building upon study I, study II extended the investigation to the oculomotor dimension with a parallel experimental design. The primary objective of study II was to discern whether learned spatial configuration or individual locations prompted scanpaths similar to those observed in the original displays.

The combined findings from studies I and II revealed that participants exhibited accelerated target detection in both fully and partially repeated displays, indicating contribution from both global configuration and individual location to contextual cueing. Moreover, study II highlighted that the number of fixations and scanpath pattern ratio were higher in the new displays compared to the other three repeated displays. Notably, significantly high similarities were observed in the fixation density map between recombined and fully repeated displays, as well as between rotated and fully repeated displays when the rotated display was back-rotated. Overall, this demonstrated a remarkably flexible use of the oculomotor system for search in partially repeated displays.

Study III explored the influence of egocentric and allocentric reference frames on contextual cueing. Participants learned various combinations of distractor-target configurations and external frame orientations during a training phase. In the subsequent testing phase, either the frame orientation or the configuration underwent rotation, disrupting either the allocentric or egocentric predictions for the target location. Despite these manipulations, contextual cueing persisted. However, when both reference frames were simultaneously invalidated for predicting target location, contextual cueing was eliminated. This highlights the role of both egocentric and allocentric reference frames in providing effective search guidance in repeated contexts, as long as they contain valid information about the search goal.

Collectively, the three studies presented in this thesis offer valuable insights into a nuanced understanding of contextual cueing, shedding light on the roles of global and local factors, as well as egocentric and allocentric reference frames in facilitating efficient visual search. The findings carry implications for theories of spatial attention and memory, enriching our comprehension of the cognitive mechanisms underlying the contextual cueing effect.

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List of Abbreviations

ANOVA ……………………….. analysis of variance

CCE……………………… ……. contextual cueing effect

IL ………………………………. initial saccade latency

TLF to BF………………………. time between the last fixation and button press

SPR ……………………………. scanpath ratio

FDM …………………………… fixation density map

1. General introduction

1.1. Motivation and structure of this thesis

Attention is a fundamental cognitive state that allows individuals to selectively allocate cognitive resources to relevant inputs while ignoring irrelevant ones. Although attention can be applied across various sensory modalities, visual search is a widely recognized modality for studying attention due to its ease of use and visualization. In the study of attentional selection, researchers have identified numerous factors influencing attention allocation, including bottom-up effects stemming from scene characteristics and top-down effects guided by individual goals or experience. Of particular interest in this thesis is the role of spatial memory in guiding attention allocation. Chapter 1.2 offers a detailed description of the impact of spatial memory on attentional selection.

To investigate the influence of spatial memory on attention selection, Chun and Jiang introduced the contextual cueing effect paradigm in 1998. This paradigm showcased a learning phenomenon wherein individuals displayed faster search speeds when encountering spatial displays composed of distractors and target items they had previously learned. Chapter 1.3 delves into the contextual cue effects paradigm, exploring the nature and mechanism of contextual cueing learning.

The motivation of this thesis is to explore how various spatial factors within displays contribute to contextual learning and influence attention allocation. In pursuit of this objective, Chapters 1.4 through 1.6 delve into three sub-themes related to contextual cueing effects in depth. These sub-themes encompass:

1) Understanding What is Learned in Contextual Cueing.
2) Analyzing Oculomotor Patterns in Contextual Cueing Search.
3) Exploring the Impact of Reference Frames in Contextual-Guided Visual Search.

Structured around these three sub-themes, the experiments presented in this dissertation address several questions: Chapter 2 investigates the contributions of spatial configuration and individual location to contextual cue effects. Chapter 3 examines how these two factors influence eye movements in partially repeated displays. Chapter 4 explores the roles of egocentric and allocentric references as contextual cues, as well as the validity of such cues.

In Chapter 5, the results of the experiments are interpreted and discussed about each other. Conclusions are drawn within a broader context, considering their implications in relation to current literature.

1.2. Attention and spatial memory in visual search

1.2.1. Attention in visual search

Attention is a fundamental cognitive-behavioral state that enables individuals to selectively allocate their cognitive resources to relevant inputs while disregarding the irrelevant ones (Chelazzi et al., 2019; Noonan et al., 2018; van Moorselaar & Slagter, 2020). Numerous examples illustrate the role of attention in daily life. For instance, when watching a movie in a theater, despite the constant movement of people around and the occasional sound of rustling popcorn bags or coughing, individuals are able to focus their attention on the screen and engage with the unfolding movie story. This is due to the ability to attention selection, which is a necessary feature of human perception, as our sensory receptors receive more information than our brains can handle in terms of both capacity and duration at any given moment (Buschman & Kastner., 2015; Driver, 2001; Simons & Rensink, 2005).

Although attention can be deployed across various types of sensory modalities, such as visual, auditory, olfactory, gustatory, and somatosensory modalities, it is commonly acknowledged that visual modality serves as the primary avenue for attention selection, offering a more approximation to attentional processes in real-world situations.

Visual search is considered a fundamental means by which individuals allocate attention to relevant stimuli, reflecting the complex mechanisms involved in object detection and identification in everyday situations (van der Heijden, 2003; Wolfe, 2020; Wolfe & Horowitz, 2004). Specifically, in typical visual search studies, participants are presented with an array of stimuli, one of which is the task-relevant target, while the others are task-irrelevant distractors. The primary objective of these studies is to uncover the underlying mechanisms that enable efficient selection and response to the target.

1.2.2. The role of spatial memory in guiding spatial attention

Spatial memory plays an important role in the process of selective attention (Chen & Hutchinson, 2019; Fischer et al., 2021; Hirschstein & Aly, 2022; Kasper et al., 2015; Le-Hoa Võ & Wolfe, 2015). By utilizing spatial memory, individuals are able to allocate their visual attention to a specific part of the visual field, allowing for more effective processing of the attended element and their surroundings (Chen & Hutchinson, 2019; Kasper, 2013).

While there are various ways to guide spatial attention using spatial memory, such as through an individual's accumulated life experiences or the use of scene previews

(Castelhano & Henderson, 2007; Hodsoll & Humphreys, 2005; Hollingworth, 2009; Watson & Inglis, 2007), one method that has sparked widespread discussion is the automatic extraction of statistical regularities by the individual's visual system to guide attention. (Wang & Theeuwes, 2018).

Statistical regularities refer to the systematic relationships or probabilistic dependencies between different elements or features in the environment. In the domain of visual perception, these regularities can be observed in the distribution of locations, colors, shapes, or textures within a scene. For example, certain items' locations may co-occur more frequently, while others may occur less frequently or rarely. By extracting the association between these items' locations regularity, the visual system can predict the likely target location and guide attention toward them (Baker et al., 2004; Seitz et al., 2023; Theeuwes et al., 2022; Turk-Browne et al., 2005).

The primary focus of this dissertation is the attentional guidance effect resulting from spatial statistical regularities in the context. Regarding this aim, the classical experimental paradigm of contextual cueing will be thoroughly discussed in the subsequent section.

1.3. Contextual-guided visual search

A strong cue for visual attention is contextual information that informs what and where the object should appear in a certain context. This contextual information can be acquired with spatial statistical regularities (Chun, 2000; Oliva & Torralba, 2007). As humans observe and interact with their surroundings, the visual system extracts information to construct an internal representation of scene after scene. The repetitive co-occurrence of objects or events can serve as these representations to predict the location of task-relevant items, enhancing the efficiency of visual processing (Chun & Jiang, 1998; Chun & Nakayama, 2000).

The occurrence of contextual cueing is dependent upon a certain level of stability within the spatial environment (Oliva & Torralba, 2007; Zang et al., 2018). It is only when the visual environment is relatively stable in its structure that the visual system can effectively exploit its predictability. This stability allows the observer to extract a schema of the visual input, capturing the statistical properties and co-occurrence frequencies of objects in the visual world (Baker et al., 2004; Fiser & Aslin, 2005). By retaining and utilizing these schemas, observers can optimize their behavior and increase their efficiency in visual processing (Chun & Turk-Browne, 2008; Henderson & Hollingworth, 1999).

The next section focuses on the contextual cueing paradigm which was initially introduced by Chun and Jiang (1998). This paradigm demonstrates a learning phenomenon wherein repeated exposure to a consistent arrangement of target and distractor configuration leads to progressively faster reaction times for target search. This phenomenon, known as contextual cueing, has been widely observed in numerous studies (Chun, 2000; Goujon et al., 2015; Jiang & Sisk, 2019; Jiang et al., 2019; Oliva & Torralba, 2007; Sisk et al., 2019). These findings provide evidence of the effectiveness of the contextual cueing paradigm in investigating and understanding the mechanisms underlying contextual-guided visual search.

1.3.1. Contextual cueing paradigm

1.3.1.1.Display design

In the contextual cueing paradigm, researchers have employed displays containing multiple objects arranged in specific configurations to simulate visual scenes. These constituent objects have featured either artificial simple letters/shapes (Chun & Jiang, 1999; Endo & Takeda, 2004) or naturalistic scenes (Brockmole et al., 2006; Summerfield et al., 2006). It is important to acknowledge that while naturalistic scenes offer ecological validity, their inclusion of accompanying semantic information presents challenges in terms of experimental control. In contrast, artificial letters have been extensively utilized in contextual cueing research due to their high level of experimental operability and ease of manipulation.

In the classic contextual cueing task, the search displays consisted of an array of items, including a T-shaped target and eleven L-shaped distractors, presented on a background. The target T was rotated by 90^{o} to the left or right, while the distractors were rotated by 0^{o}, 90^{o}, 180^{o}, or 270^{o}. The orientation of each letter was randomly chosen for each trial. To increase the search difficulty, there was an offset of the line junction of the distractor Ls. This made the distractors more similar to the target T (Jiang & Chun, 2001). In some studies, the items' eccentricity has been controlled, and the target locations were intentionally positioned away from the center of the screen to maintain a balanced level of search difficulty across different displays.

1.3.1.2. Task design

In the contextual cueing paradigm, participants are not informed about the experiment design. Two types of displays are presented randomly during the search task. Half of the search displays are repeated/old across time blocks, with the spatial configuration of the target and distractors remaining constant, although the orientation of the target and distractors vary randomly. The remaining half of the displays are novel/new, with the target location always presented alongside a random distractor configuration. Importantly, the target location in the new display generally remains constant across blocks, thereby equating the absolute target location probability between the two types of displays. The repeated target-distractors association in the repeated displays mimicked environmental regularities in a way that context could be used to predict target location, while the new displays serve as a control condition (refer to Figure 1.1 for a visual representation).

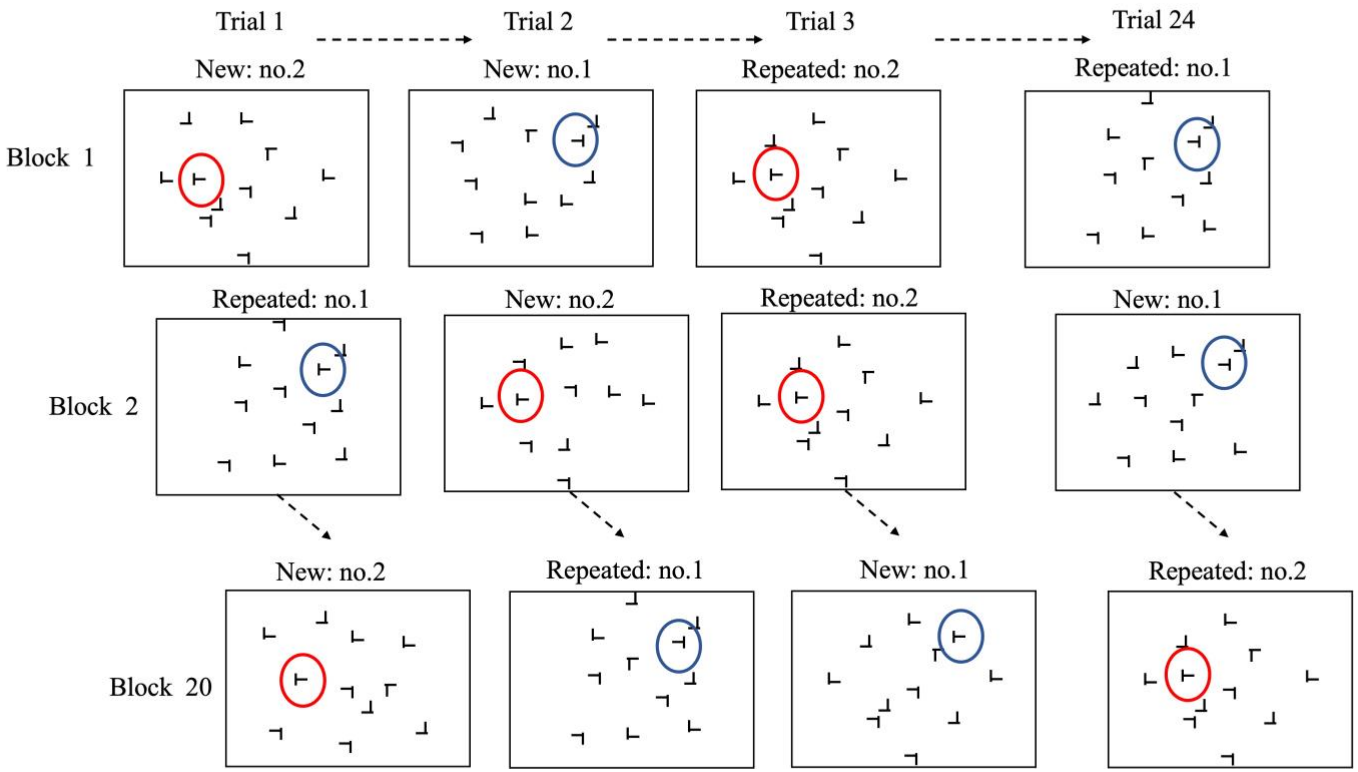

Figure 1.1. Typical design for the contextual cueing task. Participants are exposed to multiple blocks of trials (e.g., 30 blocks of 24 trials in Chun and Jiang, 1998), with 12 trials featuring repeated displays (or called old displays) and the other 12 trials featuring newly created displays (new displays). Those displays are presented in random order within each block. To prevent the contribution of target location probability to learning, both repeated and new display share the same set of targets.

A facilitation effect is commonly observed as participants engage in the task, leading to progressively faster search times for repeated displays compared to new displays. Importantly, this contextual cueing effect (CCE) tends to emerge early in the task, even after relatively few presentations of the Repeated displays (Chun & Jiang, 1998; Goujon et al., 2015; Jiang, Sigstad, et al., 2013; Jiang & Sisk, 2019; Jiang et al., 2019; Pollmann, 2019; Sisk et al., 2019). Figure 1.2 illustrates a classical response time (RT) pattern in contextual cueing tasks, depicting the gradual reduction in RT for new displays and a more pronounced decrease in RT for repeated displays over time.

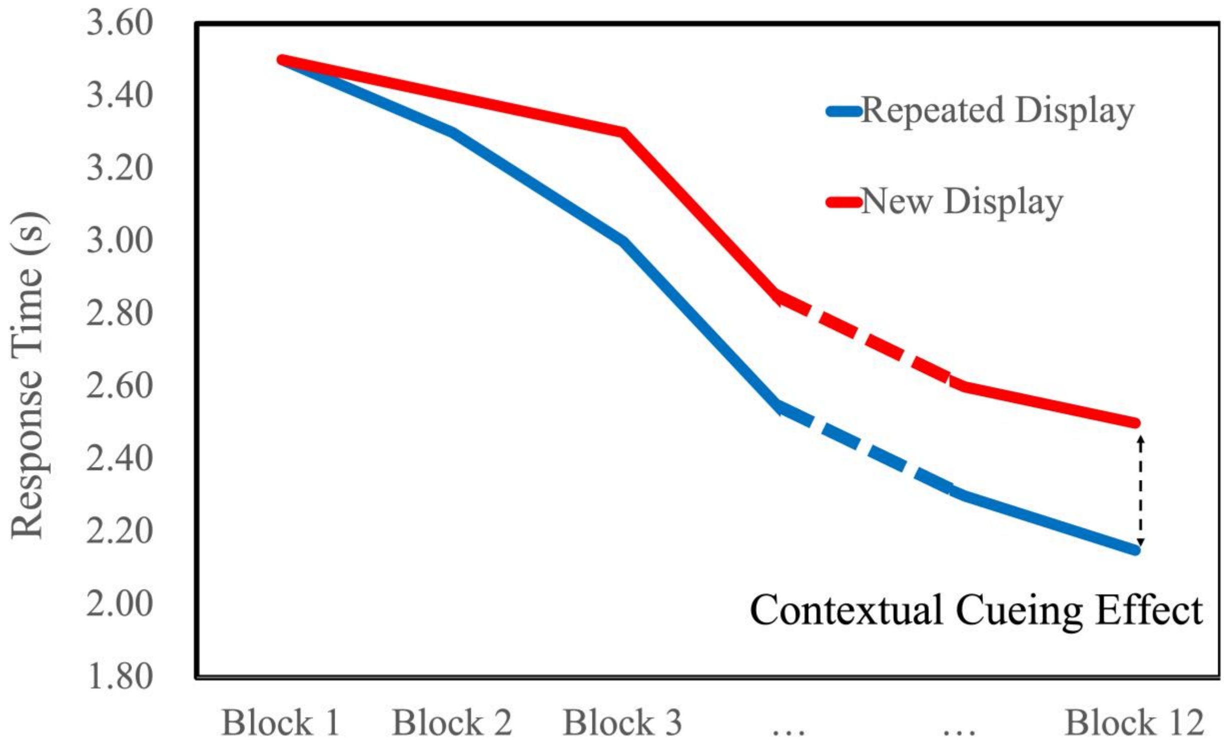

Figure 1.2. Typical response times for the contextual cueing task. Search performance improves over blocks, with faster responses for repeated displays compared to new displays. This advantage for repeated display compared to new display is termed contextual cueing effect.

1.3.1.3. The nature of contextual cueing learning

In the contextual cueing experiment, participants typically encounter an unexpected memory test at the end of the task. During the experiment, participants were sequentially shown multiple displays, that were either repeated or new. They were then required to respond with a ‘yes’ or ‘no’ to indicate whether they had previously encountered the displayed items during the search task.

In examining the outcomes of memory tests, the results generally indicated that observers were not able to distinguish between repeated and new displays accurately. Consequently, researchers have concluded that contextual cueing is acquired through implicit learning mechanisms (Chun & Jiang, 2003; Colagiuri & Livesey, 2016; Goujon, 2011). However, concerns have been raised regarding the potential influence of the limited number of repeated displays presented during the memory test compared to the learning phase (Vadillo et al., 2016). Furthermore, several studies have also explored the explicitness of contextual cueing memories, shedding light on the conscious awareness of participants regarding the learned associations (Smyth & Shanks, 2008; Westerberg et al., 2011).

The contextual cueing effect is a phenomenon that involves the acquisition of spatial information and its subsequent impact on enhancing the efficiency of search activity. Previous literature offered multiple theoretical propositions regarding the mechanisms underlying the contextual cueing effect, supported by empirical evidence at both behavioral and neurophysiological levels. The following section aims to elucidate significant issues in this regard, which will be discussed in detail to provide a comprehensive understanding of the contextual cueing phenomenon.

1.3.1.4. The mechanism that facilitates the search in contextual cueing task

Numerous studies have endeavored to explore the underlying mechanisms that facilitate the search in contextual cueing tasks. From these investigations, three distinct perspectives have emerged: the theory of attention guidance, the theory of response selection, and the theory of multiple stages. Each of these theoretical frameworks offers a unique insight into the processes that underpin contextual cueing. These perspectives offer different explanations and emphasize different aspects of the phenomenon, contributing to a more comprehensive understanding of the mechanisms that drive contextual cueing.

Attention-guided theory: The attention-guided theory posits that participants acquire contextual cueing and utilize attentional guidance towards the target location in subsequent encounters with the search display. This early deployment of attention to the target location facilitates faster detection of the target object and enhances search efficiency over time. This theory highlighted the role of attentional guidance in mediating the contextual cueing effect (Harris & Remington, 2017; Zhao & Ren, 2020).

Studies on contextual search with varying set sizes (the number of search items) have demonstrated that the search slopes, derived from the relationship between Response

Time and Set Size, decrease for repeated display, indicating a higher search efficiency when the display is repeated (Chun & Jiang, 1998). Moreover, in a contextual cueing task employing electrophysiological measures, researchers examined the amplitude of N2pc waves, a reliable indicator of attention focus. The results indicated that the amplitude of N2pc waves was significantly greater in repeated condition than in new condition (Johnson et al., 2007). The finding provides compelling evidence that the presence of contextual cues increases the efficiency of visual search by guiding visual attention toward the target location (Peterson & Kramer, 2001).

Response selection theory: The theory of response selection suggests that the contextual cueing effect arises from the acceleration of the processing related to the response in the later stages of visual search tasks. According to this theory, participants' confirmation response to the target item is sped up, increasing in search efficiency (Kunar et al., 2006; Kunar & Wolfe, 2008; Wang et al., 2019).

Kunar et al (2017) examined the set-size function and indicated that there is only a small difference in slope between repeated and new conditions, which emerged very early on, perhaps over the first few repetitions. Furthermore, in their experiment 3, they observed contextual cuing effect disappeared when added interference to the response selection process. These findings suggest that the facilitation effect of contextual cueing is not primarily attributed to early search guidance but rather to response selection acceleration (Kunar et al., 2007).

Another study using a variant of the contextual cueing paradigm revealed that under Repeated conditions, participants' judging standard (β value) became more relaxed, while the discrimination index (d') remained unaffected. Using event-related potential techniques, the researchers further demonstrated that the accelerated response time observed under repeated conditions was reflected in a late positive potential, indicative of a response-related process (Schankin et al., 2011). These findings provide further support for the theory of response selection in explaining the contextual cueing effect (Hout & Goldinger, 2012).

Multiple stages theory: The multiple-stage theory presents a comprehensive framework that synthesizes and reconciles prior accounts of visual search within the contextual cueing effect. This theory postulates that the visual search process can be conceptually divided into three discrete stages: 1) The early phase of processing corresponds to the initial latency and is likely associated with initial perceptual processing; 2) The late phase represents the duration from the time between last fixation (TLF) to button press (BP), which is likely related to response selection; 3) The middle phase, encompassing the remaining duration, plays a role in intermediate processing stages. The multiple stages theory suggests that the mechanisms of each stage can be investigated independently to provide a more detailed and nuanced understanding of how individuals perform visual search tasks in the presence of contextual cues.

Zhao et al. (2012) conducted a meticulous investigation using eye movement technology to examine the involvement of the middle and later stages in the contextual cueing task. Their findings revealed significant differences between repeated and new conditions in the both middle and late stages. Specifically, the difference in the middle stage was predominantly the result of a decrease in the number of eye saccades, while the difference in the late stage was due to the reduction in the time interval from the last fixation to the key response. These findings indicate that the impact of the spatial contextual cueing effect is attributable to the guiding role of the spatial context on attention and the impact of the response selection stage on the acceleration of target item confirmation (Ogawa & Watanabe, 2010; Schankin & Schubö, 2010; Zhao et al., 2012). Figure 1.3 illustrates the processing stages, acceleration mechanisms, and manifestations of visual search in the contextual cueing task.

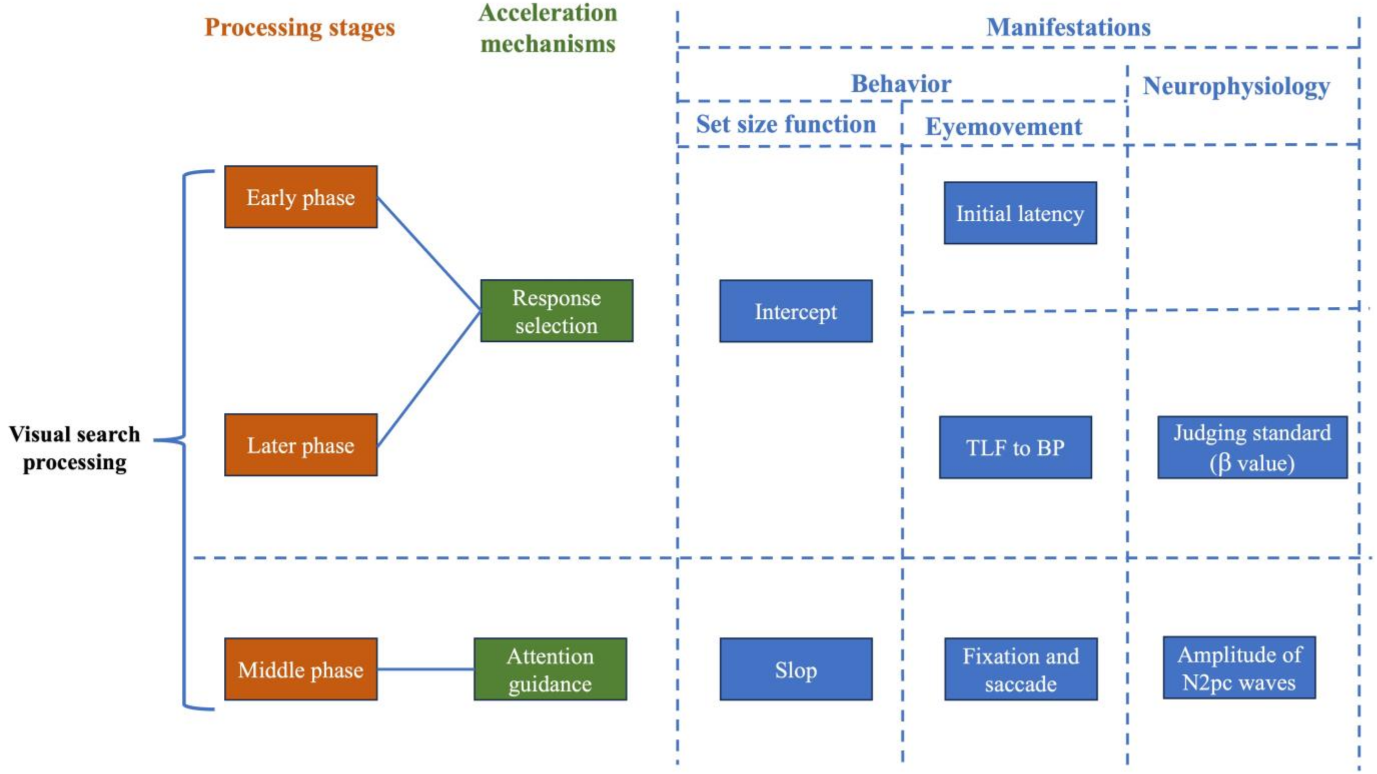

Figure 1.3. Mechanisms of the contextual cueing effect. Processing stages, acceleration mechanisms and manifestations of the visual search processing during contextual cueing task.

1.3.1.5. Exploring various aspects of the contextual cueing paradigm

Since its introduction, the contextual cueing paradigm has been the subject of numerous investigations. While the observation of search advantage has been replicated extensively, two aspects of the paradigm have been explored. The first aspect focuses on top-down control in the contextual cueing task, which includes attentional control (Jiang & Chun, 2001), coupling of attention and context memory (Annac et al., 2013; Giesbrecht et al., 2013), motivation and its influence on attention and contextual processing (Pollmann et al., 2016; Sharifian et al., 2017; Tseng & Lleras, 2013), neural mechanisms underlying attention and contextual processing (Goujon et al., 2015), search procedure reflected by oculomotor correlates (Tseng & Li, 2004; Zhao et al., 2012). In addition, the contextual feature is another important aspect that reveals what and how the spatial factors are processed and learned (Jiang & Wagner, 2004; Olson & Chun, 2002; Shi et al., 2013; Zang et al., 2016; Zellin, 2013; Zellin et al., 2014).

As noted earlier, the spatial contextual cueing paradigm has generated a great deal of interest in various fields of cognitive sciences, providing new insights into the comprehension of attention selection and spatial memory. A variety of accounts have attempted to explain how context influences object perception before behavioral responses are executed. Within this context and with the purpose of the present thesis, this thesis will provide an overview of the critical findings and debates and discuss of three aspects of contextual cueing: 1) What is Learned in Contextual Cueing? 2) oculomotor analysis in contextual cueing search; 3) The impact of the reference frame in contextual-guided visual search.

1.4. What is learned in contextual cueing?

The question of what is learned in spatial contextual cueing has been the subject of much research and debate in the field of the contextual cueing framework. On the one hand, a moderate body of research has been predicated on the assumption that the effect arises from global information (Brockmole et al., 2006; Brooks et al., 2010; Kunar et al., 2006). Specifically, participants extract the associative learning of the global configuration and the target location, thereby facilitating the search process. According to Chun and Jiang (1998), the global spatial layout formed by all items is extracted, which serves as an effective cue for identifying the target location. In experiment 4 of Brady and Chun (2007), the facilitation in search attributed to contextual cueing disappeared when the original configuration of distractor locations within the target quadrant was maintained, but the quadrants in the display were shuffled. This effect is attributable to the repetition of the global configuration, rather than specific perceptual details (Kunar et al., 2014; Makovski & Jiang, 2010).

On the other hand, various studies have demonstrated that observers do not perceive the entire visual display uniformly. Instead, local information near the target serves as a sufficient source of contextual cueing (Brady & Chun, 2007; Olson & Chun, 2002; Song & Jiang, 2005). For example, repeating three distractor locations could produce a robust contextual cueing effect (Song & Jiang, 2005). Similarly, in the study of Olson and Chun (2002), the visual display was divided into two regions: one half contained the repeated context, while the other half contained the new context. The two parts of the display were not explicitly delineated, and yet contextual cueing was observed only when the target was placed within the repeated region (see Figure 1.4). This finding suggests that observers were more sensitive to the local area surrounding the target (Olson & Chun, 2002). Similarly, other studies have shown that the range of repeated informative context can be further reduced to a quadrant (Brady & Chun, 2007) or to a more limited range where only 20-30% of the display matches the previous one (Jiang et al., 2005). These lines of evidence collectively suggest that, at the end of a successful visual search, the target is memorized along with its partial local predictive information in the vicinity of the target (Brady & Chun, 2007).

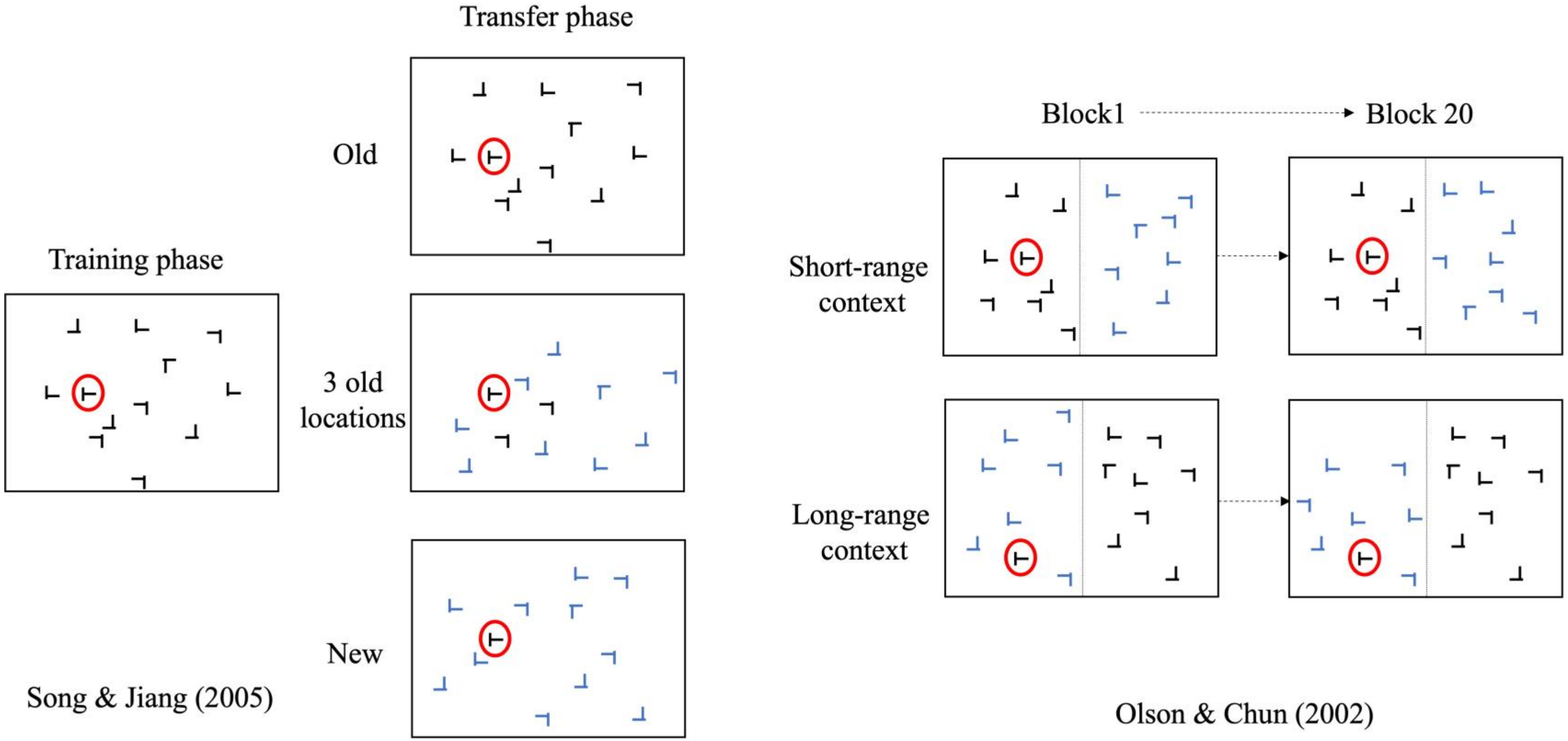

Figure 1.4. Schematic of the experiment design of Song and Jiang (2005) and Olson and Chun (2002).

Based on the above evidence, the arrangement of the environment as well as the information near the target appeared to have the ability to influence the search behavior of the participants in the pursuit of recurring patterns. In light of this repetitive scenario, what specific information was acquired by the participants? Jiang and Wagner (2004) conducted a study that investigated configuration and location in contextual guided search in two separate experiments. In one experiment, they generated search displays that comprised distractor locations from two previously explored repetitive displays that had the same target location but different display configurations. This arrangement ensured that all distractor locations were repeated but the display configuration was novel. In contrast, in another experiment, the search displays were rescaled and shifted previously explored displays, thereby altering the distractor locations while maintaining the relative configuration. The effect of contextual cueing was found in both experiments, indicating that both global configuration and individual locations play a role in contextual cueing (Jiang & Wagner, 2004).

Similar to Jiang and Wagner's study in 2004, the first study in this dissertation (Study I) aimed to investigate the roles of two factors: global configuration and individual locations in contextual cueing. However, Study I differed from Jiang and Wagner's work in two significant ways. Firstly, instead of adopting the two separate experiments used by Jiang and Wagner, Study I employed a within-subjects design to examine the contributions of both types of cues to the contextual cueing effect. This within-subjects design was chosen to reduce the possibility of participants adapting to a specific type of display change during the transfer phase. Secondly, Study I investigated configurational cueing by rotating displays, as opposed to the rescaled and displaced displays used by Jiang and Wagner in 2004. The use of rotation prevented the strategy of adapting a personal spatial reference frame to the stimulus-filled part of the monitor, which could have been employed when rescaled and shifted the displays.

Building upon the findings discussed in this chapter, our hypothesis posited that both global configuration and individual location could potentially contribute to contextual cueing. However, the inclusion of various display types within a single experiment might pose challenges to memory-guided search. Despite this, we hypothesized that retaining either one of these cues in a display, following comprehensive learning of both types of information, did not eliminate contextual cueing, as long as the other cue remained present.

1.5. Oculomotor analysis in contextual cueing

Previous research has shown that oculomotor behavior is closely linked to visual attention and learning (Annac et al., 2019; Salvucci, 2000). This link between oculomotor behavior and attention has been observed in a variety of tasks, indicating that where we look and how we move our eyes are directly related to how we attention to and perceive our environment (Itti & Koch, 2001; Schütz et al., 2011). Moreover, several studies have also demonstrated that oculomotor behavior can be modulated by learning processes, suggesting that the patterns of eye movements we exhibit are not only reflective of our current visual attentional state but also can be shaped and refined through experience and practice (Henderson et al., 2005; Tal et al., 2021). Thus, exploring oculomotor correlates of contextual cueing learning is of great interest as it can provide insights into the underlying mechanisms of how we learn and adapt to complex visual environments.

Contextual cueing leads not only to reduced search times for repeated displays but also to a changeable oculomotor behavior over the course of learning. As participants gain increased familiarity with the repeated display, their eye movement became more efficient and less exploratory (Brockmole & Henderson, 2006; Manginelli & Pollmann, 2009; Neider & Zelinsky, 2006; Peterson & Kramer, 2001; Tseng & Li, 2004; Zang et al., 2015). Peterson and Kramer (2001) discovered that a repeated stimulus configuration required fewer fixations to locate the target. Zang et al. (2015) observed slightly extended gaze durations, along with a reduced number of fixations and shortened scan paths for 'old' displays.

Using eye movement recording, contextual cueing can be better investigated separately for different processing stages, since the eye tracking system can be used to infer moment-to-moment cognitive processes in a fairly direct manner. Zhao et al., (2012) introduce a framework for analyzing the search process, dividing it into three distinct periods: *early, middle, and later phases*. The *early phase* encompasses initial saccade latency (IL), referred to the duration from the display onset to the initiation of the first saccade, which is influenced by perceptual recognition processes. The *later phase*, denoted as the time between the last eye fixation and the response via button press (TLF to BF), measures the reaction time required for participants to respond when their fixation is near to the target location (Tseng & Li, 2004). The remaining duration, termed the *middle phase*, represents the duration of this phase obtained by subtracting the initial latency and TLF to BP from the overall manual response time. The middle phase can be characterized by various factors such as scanpath ratio (SPR: dividing the total distances traveled by all eye movements before arriving at the target by the linear distance between the first fixation point and the target) and the number of fixation or saccades.

The findings revealed minimal impact of contextual cues on the initial latency and distance between the first fixation and the target location in the repeated display compared to the new display. However, a slight contextual cueing effect emerged during the middle phase, evident by fewer saccades and higher SPR for the Repeated display but no main effect of average fixation duration. Additionally, a reliable effect of configuration on TLF to BP was observed, indicating a shorter duration of TLF to BP or a quicker response to targets in repeated display. Overall, Zhao et al. (2012) demonstrates the utility of eye movement data in discerning distinct stages of information processing within the overall response. The results suggest that the contextual cueing effect involves a dual-state modulation, with attentional guidance playing a primary role and a smaller contribution from response selection facilitation (Zhao et al., 2012).

Table 1.1 presents the results of several studies on oculomotor correlates of contextual cueing learning. By synthesizing these results, the table offers a concise overview of the predominant pattern observed in the literature concerning the impact of contextual cueing on oculomotor.

Table 1.1. The oculomotor indicators correlate of contextual cueing learning. It encompasses various oculomotor indicators, such as initial saccade latency (IL), scan pattern ratio (SPR), and time from the last eye fixation to button-press (TLF to BP).

Oculomotor Parameter	**Description in contextual cueing learning**
The first saccade	In some trials of repeated configuration, eye went directly to the target (Brockmole & Henderson, 2006; Tseng & Li, 2004).
	The distance between first eye fixation and target did not change as a result of learning (Tseng and Li, 2004).
	Time from the start of the search display to the occurrence of the IL did not change as a result of learning (Tseng and Li, 2004; Zhao, 2012).
Number of fixations/saccades	The existing body of literature on oculomotor behavior in contextual learning consistently supports the observation that fewer fixations or saccades are required to locate the target in repeated displays.
saccades amplitude	The saccade amplitude did not differ during learning (Tseng and Li, 2004).
SPR	SPR is higher in repeated than in new configurations (Zhao, 2012).
Fixation duration	Shorter fixation duration associated with contextual cueing was observed in (van Asselen et al., 2011).
TLF to BP	The TLF to BP was found to be shorten during learning in Zhao et al., (2012), or not change in Tseng and Li (2004), Manelis & Reder (2012) and Harris and Remington (2017).

To delve deeper into the underlying processes of global configuration and individual location in contextual cueing, Study II of this thesis integrates the parallel design used in Study I with eye movement analysis methods. The primary objective of Study II is to investigate whether the pattern of eye movements made during search in a recombined or rotated display would resemble that of the original display encountered during the incidental learning phase of the experiment.

In addition to the conventional metrics of reaction time and the number of fixation points, a new metric—fixation density map (FDM) was introduced. FDM generated from eye-tracking experiments finds extensive application in image processing. When individuals conduct searches within a scene, the resulting gaze patterns can be post-processed into FDM, which are subsequently regarded as reliable representations of human visual attention (Engelke et al., 2012).

On the one hand, anticipation of a greater similarity in fixation density was projected for the comparison between fully repeated and recombined displays. This expectation is rooted in the assumption that the search process would continue to be guided by individually repeated item locations. On the other hand, anticipation was held that previously learned displays, when rotated, would yield fixation density comparable to the original displays after back-rotated, resulting in a high fixation density in the comparison between repeated and rotated displays.

1.6. Impact of reference frame in contextual-guided visual search

The reference frame of coding space is crucial because it determines the allocation of attention when observers move in the environment and impacts visual attention (Shelton & McNamara, 2001). For example, when a person trying to find their way to a friend's house in a new city. The person may use an egocentric reference frame, such as remembering the turns they have taken based on their perspective (e.g., 'I turn left at the gas station and right at the park'), or an allocentric reference frame, such as following a map that shows the layout of the city relative to north, south, east, and west (e.g., 'I need to head east on Mian Street and turn north when meeting a bridge'). In real-life situations, the environment can be viewed and approached from the egocentric and allocentric perspectives, understanding the difference between the two reference frames is important for effective navigation and orientation.

Several studies have explored the impact of reference frames on the search process. In a typical task involving target probability cueing, the target is more likely to appear in the 'rich' quadrant with higher probability (50%) than in the 'sparse' quadrant with lower probability (17% each). In a subsequent test session, the target appears with equal probability in all quadrants. Participants were asked to move 90° around a flat screen and perform the search task again. The results demonstrated that the attentional bias shifted with the participant, moving towards a previously 'sparse' quadrant, indicating a persistent egocentric spatial bias resulting from incidental learning of the target's likely locations (Jiang & Swallow, 2013b). However, evidence also suggested the operation of an external/allocentric reference frame in probability cueing, particularly when observers were explicitly informed of the likely quadrant to contain the target (Jiang et al., 2014) or when they tilted their body or head (Jiang & Swallow, 2013a).

The relationship between incidental learning of contextual cueing and viewpoint-dependent reference frame has been established through research. Specifically, Chua and Chun (2003) conducted a study where observers were trained in the contextual-cueing task, with 3-D displays constantly rotated at 0°, 15°, 30°, or 45° relative to the observer, which was manipulated between subjects. During the subsequent test session, displays were always presented at the 0° view angle. The study found that as the angular deviation between the training and test displays increased, contextual facilitation decreased significantly (Chua & Chun, 2003). It suggested that contextual cueing depends on the egocentric reference frame.

Study III of the dissertation investigated the influence of egocentric and allocentric reference frames on contextual cueing. These two reference frames were operationally defined in Study III. The allocentric reference frame was delineated by adding a box as a landmark outside the scene, manifesting the relationship between items and landmarks. Conversely, the egocentric reference frame was conceptualized as representing the relationship between items and observers within the environment.

The underlying assumption suggested that if reference frames played no role in contextual cueing, simultaneous changes to both reference frames would not diminish the search advantage in repeated conditions. However, if reference frames did indeed influence contextual cueing, altering the reference system would reduce the obtained contextual cue effect. Thus, if contextual cues rely on the interplay between these two reference systems, disrupting either reference system would weaken the contextual cue effect. Conversely, if reference frames could be flexibly adapted, the search advantage conferred by contextual cueing would persist even if one reference system is compromised while the other remains intact.

Furthermore, Study III explored whether changes in the predictive efficacy of the allocentric reference frame, as a factor predicting target location, could be utilized as contextual cues. In Experiment 1, the two kinds of reference frames were established with different levels of validity. For instance, the egocentric reference frame was helpful in predicting target location in 50% of trials, whereas the allocentric reference frame was beneficial in only 25% of trials. In Experiment 2, both types of reference frames had consistent validity, at 50% for each. Comparing Experiment 1 to Experiment 2, if the allocentric reference frame was not utilized to retrieve the memory trace of repeated displays due to its low predictability of target location, it would indicate that the efficacy of reference frames in predicting targets could influence the contextual cue effect.

1.7. Questions addressed by this thesis

As described in Section 1.2, progress has been made in understanding the contextual cueing effect, shedding light on how spatial information influences visual search processes from the bottom up via spatial memory. However, given the vastness of the topic of visual search, there remain several unresolved issues. The experiments proposed in this thesis aim to investigate a central theme: the contribution of spatial information to the contextual cueing effect. Sections 1.3 to 1.5 address three derived questions related to this theme: the contributions of global configuration and individual location to contextual cueing, whether these two factors can elicit scanpaths resembling those observed in the original displays, and the influence of egocentric and allocentric reference frames on contextual cueing.

As outlined in Section 1.3, previous studies have individually demonstrated the contributions of global and local information to the contextual cueing effect (Brady & Chun, 2007; Jiang & Wagner, 2004; Olson & Chun, 2002). However, a key concern arises regarding the potential adaptation of participants to specific types of display changes within a single experiment. To address this, Study I (chapter 2) employed a within-subject design, simultaneously varying global configuration and individual location information within the same experiment. Additionally, Study I investigated configurational cueing in rotated configurations, as opposed to the rescaled and displaced displays used by Jiang and Wagner (2004), to avoid potential confounds related to spatial reference frame adaptation strategies.

To have a deeper understanding of the underlying process related to the contribution of global configuration and individual location, Study II (chapter 3) sought to determine whether the pattern of eye movements made during search in a display containing disrupted individual locations but preserving the global configuration or vice versa would resemble that observed in the original display encountered during the incidental learning phase. Chapter 1.4 demonstrates the application of eye movement analysis methods in previous contextual cueing experiments. Notably, those experiments have primarily recorded eye movement data in fully repeated displays (Brockmole &

Henderson, 2006; Manginelli & Pollmann, 2009; Peterson & Kramer, 2001; Tseng & Li, 2004), making Study II the first to utilize eye-tracking methods to examine partially repeated displays in context-guided search.

As discussed in Chapter 1.5, research on spatial memory has provided support for the roles of both egocentric and allocentric reference frames in the search process (Jiang & Swallow, 2013a, 2013b; Jiang, Swallow, & Capistrano, 2013). Meanwhile, some studies have indirectly suggested that contextual cueing may be influenced by these two reference frames (Chua and Chun, 2003; Jiang and Wagner, 2004). In Study III (chapter 4), the primary aim was to systematically investigate whether the reference frame underlying contextual cueing is subject to top-down modulation. Additionally, Zang et al. (2018) demonstrated that the validity of display factors influences search guidance in repeated displays, as evidenced by the frequency of display repetition. Therefore, it raises the question: Does the reliability of reference frames also affect contextual cueing? Study III addressed this by manipulating the predictability of target locations based on reference frames in two experiments to investigate whether contextual cueing is influenced by the validity of the cue provided by the reference frame.

All experiments were conducted on young, healthy human participants. Specific research hypotheses and arguments will be elaborated upon in the respective experiments. These experiments contribute to a more comprehensive understanding of the underlying mechanisms and cognitive processes involved in contextual cueing, paving the way for further exploration in this field of study.

2. Study I: The contribution of spatial position and rotated global configuration to contextual cueing

The results of this experiment were first published in: Zheng, L., Pollmann, S. The contribution of spatial position and rotated global configuration to contextual cueing. *Atten Percept Psychophys* 81, 2590–2596 (2019). https://doi.org/10.3758/s13414-019-01871-9

2.1. Abstract

Spatial information can incidentally guide attention to the likely location of a target. This contextual cueing was even observed if only the relative configuration, but not the individual locations of distractor items were repeated or vice versa (Jiang & Wagner in Perception & Psychophysics, 66(3), 454-463, 2004). The present study investigated the contribution of global configuration and individual spatial location to contextual cueing. Participants repeatedly searched 12 visual search displays in a learning session. In a subsequent transfer session, there were four conditions: fully repeated configurations

(same as the displays in the learning session), recombined configurations from two learned configurations with the same target location (preserving distractor locations but not configuration), rotated configurations (preserving configuration but not distractor locations), and new configurations. We could show that contextual cueing occurred if only distractor locations or relative configuration, randomly intermixed, was preserved in a single experiment. Beyond replicating the results of Jiang and Wagner, we made an adjustment to a particular type of transformation – that may have occurred in separate experiments – unlikely. Moreover, contextual cueing in rotated configurations showed that repeated configurations can serve as context cues even without preserved azimuth.

2.2. Introduction

What regularities can be used as contextual cues to guide visual search in repeated displays? Chun and Jiang (1998) developed a well-defined paradigm to investigate this question. Participants were asked to search for the target T among some L-shaped distractors. There were two types of search displays: old and new displays. For the old displays, the layout of distractors presented in the first block was preserved across repetitions. For the new displays, the positions of distractors varied randomly across blocks. However, contextual cueing was observed even if only some aspects of the displays were repeated. Either repetition of global configuration or individual distractor locations alone sufficed to facilitate search speed (Jiang & Wagner, 2004). In their Experiment 1, Jiang and Wagner (2004) constructed search displays that consisted of half the distractor locations of one previously searched display and half of the distractor locations of another repeated display that both shared the same target location. In this way, all distractor locations were repeated, but the display configuration was new. In contrast, in their Experiment 2, they rescaled and displaced previously searched displays, in this way changing the distractor locations but keeping the relative configuration intact (Fig. 2.1). Contextual cueing was observed in both experiments, indicating that both location and configuration cues contribute to contextual cueing.

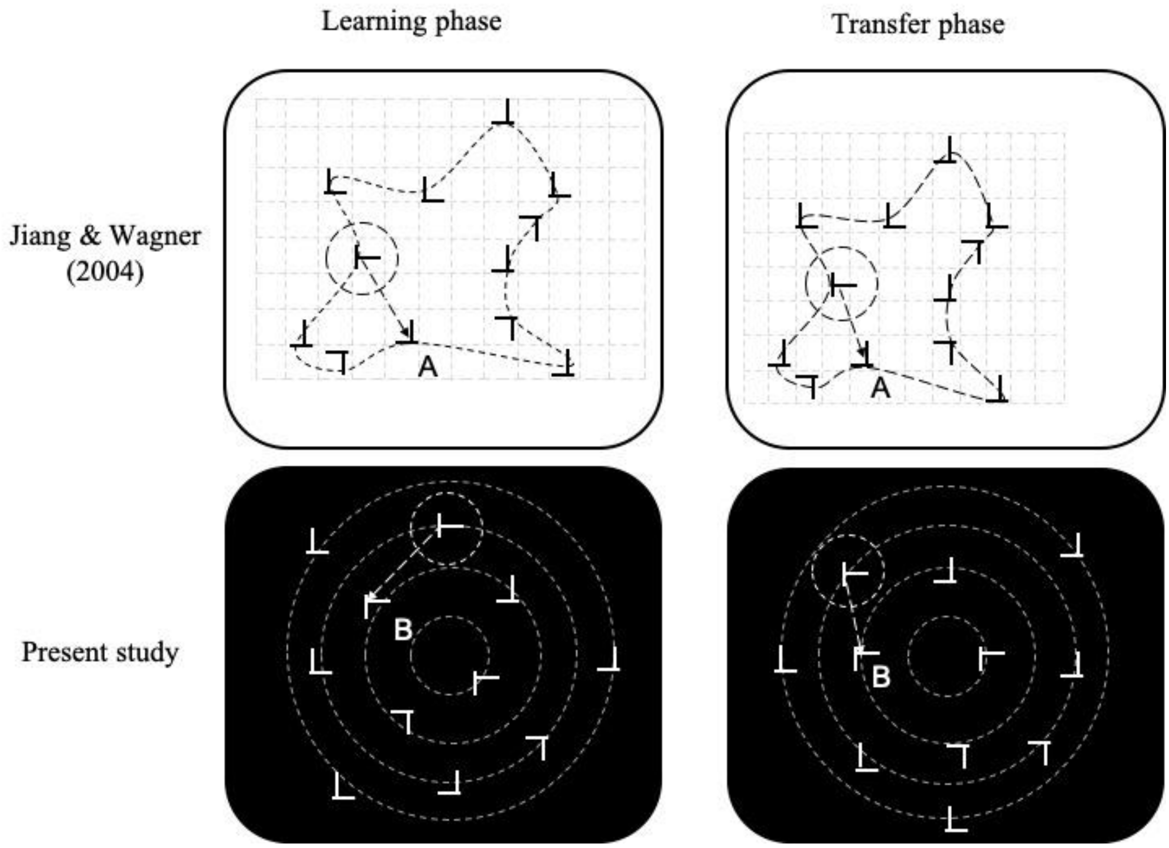

Figure 2.1. Illustration of display design in the learning phase of Study I. A schematic sample of the displays tested in Jiang and Wagner (2004, Experiment 2, redrawn after their original figure) and the present study (rotated configuration). All dotted parts and the letters A and B (see text for explanation) were not visible in the actual experiments.

In the present study, similar to that of Jiang and Wagner (2004), we also investigated the contribution of global configuration and individual spatial location to contextual cueing. However, the present study differs from Jiang and Wagner's work in two important aspects. First, Jiang and Wagner (2004) separately investigated the role of overall configuration and individual locations in two separate experiments. In contrast, we adopted a within-subjects design to investigate the contribution of the two kinds of cues to the contextual cueing effect. Second, we used a rotated configuration instead of the rescaling and displacing of configurations used in Jiang and Wagner (2004, Experiment 2). Jiang and Wagner had rescaled the search displays by a factor of 1.25 and additionally shifted the displays in one of the cardinal directions by 4.5º. These operations changed the item locations with reference to the computer screen but preserved the relative spatial relations within the configuration. For example, the upper half of Figure 2.1 is a sketch of Jiang and Wagner (2004). Distractor A appears at the lower right of the target in the learning phase (figure on the upper left), this kind of relationship repeated in the transfer phase (figure on the upper right). However, participants may be flexible in choosing their spatial reference. For instance, if item locations are defined relative to the stimulus-filled area rather than the computer screen, item locations may essentially be unchanged by rescaling and displacement. For the related effect of target location probability cueing, a persistent bias towards the target-rich quadrant of the display has been shown (Jiang, Swallow, Rosenbaum, et al., 2013) supporting the view that participants may flexibly adapt their reference frame to the actual stimulus-filled display borders rather than the screen borders. Therefore, we wanted to dissociate configuration and item locations in a more fundamental way by rotating the display by 45º. In the example in Figure 2.1, the relative position between distractor B and the target changed from the learning phase to the transfer phase from the lower left to the lower right of the target. In this way, a contextual cueing effect observed for the rotated displays would support the concept of contextual cueing by global configuration independent of item position more strongly than the original experiment by Jiang and Wagner (2004). Moreover, the random succession of four conditions – fully repeated, new, recombined and rotated displays - should make it much more difficult to adjust, perhaps implicitly, to one type of manipulation than in the experiments of Jiang and Wagner (2004).

To obtain contextual cueing from a rotated configuration is not trivial. In fact, Chua and Chun (2003) did not observe significant contextual cueing after rotation of a pseudo-3-D configuration for 30º or 45º in depth (Chua & Chun, 2003). Similarly, Tsuchiai, Matsumiya, Kuriki, and Shioiri (2012) observed contextual cueing for 3D configurations rotated in depth only when this rotation was caused by the motion of the observer to a new viewpoint (Tsuchiai et al., 2012). Similar restrictions were observed for target probability cueing (Jiang & Swallow, 2013b).

In contrast, intact contextual cueing was observed after 90° rotation of a 2D configuration – actually smartphone icons – in the image plane, although successful contextual cueing was influenced by the exact way of transformation. Contextual cueing was preserved when local arrangements of neighboring icon clusters in the display center or at its edges were preserved after rotation (Shi et al., 2013). However, smartphone icons had different shapes and colors and the grid of the smartphone display was fully occupied, different from a classic contextual cueing display. Thus, participants rather learned the spatial arrangement of specific features than a spatial configuration of similar distractors.

Since we were not interested in the question of viewpoint dependence that led to the 3D-rotation studies and because cueing appeared to survive 2D rotation better than 3D rotation, we chose 2D rotation to keep the configuration of search items intact while maximally altering the individual items' locations. Specifically, we manipulated global configuration and individual spatial location by using three repeated configurations: fully repeated, recombined, and rotated configurations. Fully repeated configurations were the same as the configurations shown in the learning session. Distractor locations in recombined configurations were randomly drawn from two fully repeated displays from the learning phase that shared the same target location (see Fig. 2.2). In this way, all distractor locations were repeated, but the configuration was destroyed. The displays of the rotated condition were formed by rotating fully repeated displays of the learning phase clockwise or counterclockwise by 45°. In this way, the configuration was preserved but the individual distractor locations were changed. In order to avoid a confound with the target probability effect, all four types of configurations (three repeated and one new) in the transfer session shared the same set of target locations.

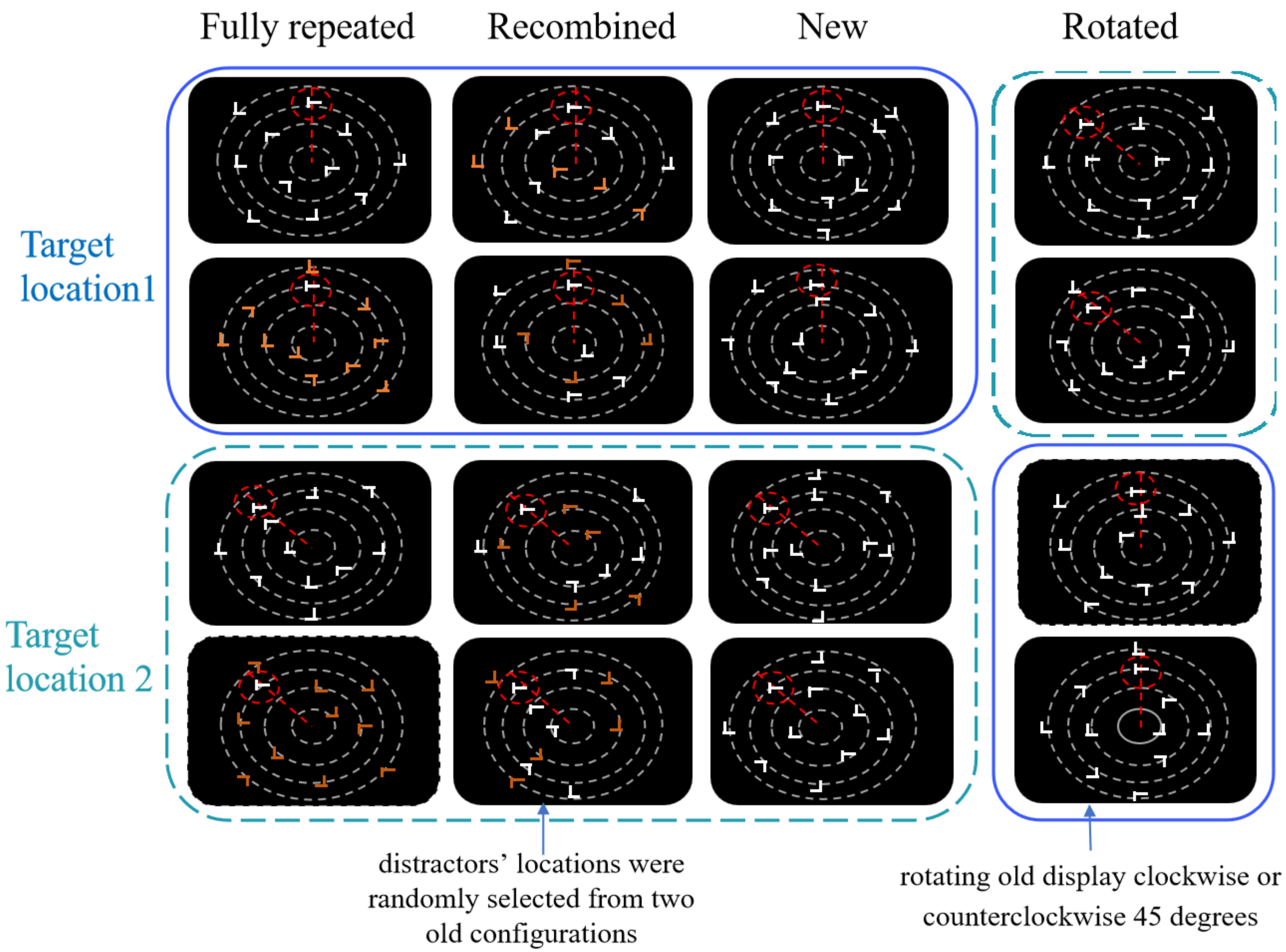

Fig 2.2. Illustration of display design in the transfer phase of Study I. In the actual experiment, the circle marking the target, the four concentric circles, and the straight line were all invisible. Configurations in the dotted line or in the solid line have the same target location.

Following the report by Jiang and Wagner (2004), we hypothesized that all three repeated conditions would lead to contextual cueing, even though the presence of several types of repeated displays and the new display in one experiment might increase the difficulty of the memory-guided search.

2.3. Methods

2.3.1. Participants

In order to determine the appropriate sample size, we first calculated the effect size for the contextual cueing effect of the recombined condition in the study by Jiang and Wagner (2004). Their t-test resulted in $t\,(14) = 2.32$ from which we calculated the effect size $\mathrm{dz} = t / \sqrt{n} = 0.599$. In turn, this effect size led to a required sample size of n = 26 for dependent means with $\alpha = 0.05$ and $1\text{-}\beta = 0.90$ (calculated with G-power, Faul et al., 2009).

Twenty-seven healthy young adults (eleven females) with a mean age of 25.3 years participated in this study. One participant's data was excluded because of an unexpected program crash. Participants were all right-handed and had normal or corrected-to-normal visual acuity. And they were naïve to the purpose of the present research. After the experiment, the participants received a fixed payment of €8 or a 1-h study credit.

2.3.2. Equipment and stimuli

Participants were tested individually in a sound-attenuated chamber. They viewed a computer screen from a fixed distance of 57 cm by using a chin rest, at which 1 cm of distance corresponds to 1^{o} of visual angle. The program was run by PsychoPy software and the experiment was conducted on a screen (resolution:1920 × 1080 pixels; refresh rate: 60 Hz).

The displays consisted of an array of eleven white items (one T-shaped target and ten L-shaped distractors) that were presented on a black background (Fig. 2.2). The target T was rotated by 90^{o} to the left or right and the distractors were rotated by 0^{o}, 90^{o}, 180^{o}, or 270^{o}, each individual letter's orientation was randomly chosen for each trial. In order to increase the search difficulty, there was an offset of the line junction of the distractor Ls. This made the distractors more similar to the target T (Jiang & Chun, 2001). To control item eccentricity, their positions were chosen on four imaginary concentric circles. Every circle comprised eight equidistant possible item locations. In order to ensure that the target was not immediately detected at display onset, target locations were chosen only on the three outer circles to obtain a minimum distance from central fixation.

2.3.3. Procedure

Participants were instructed to search the target T as fast as possible. They were asked to place the left index finger and the right index finger on the J and F keys of the keyboard, respectively and indicate the target's rotation (left or right) by pressing one of two buttons. Each trial started with a white fixation cross for 1s. Then a search display came on and remained visible until either a button was pressed to signal a judgment, or 10 s had elapsed. The search display was followed by 0.5 s of feedback with the word 'correct' or 'incorrect' shown on the screen.

The experiment consisted of a learning phase and a transfer phase. The learning phase consisted of 20 blocks of 12 trials and the transfer phase consisted of three blocks of 48 trials. Every 48 trials (four blocks in the learning phase, one block in the transfer phase), were followed by 10 s rest. The transfer phase was followed by an explicit recognition test. The whole experiment lasted about fifty minutes.

Learning phase: Six target locations were drawn from the three outer imaginary concentric circles so that the polar angle between the two target positions on each circle was 45 degrees. In this way, the two target positions could be exchanged with each other in the rotation condition of the transfer phase, keeping target location probability constant.

For each target location, 20 distractor locations were randomly selected from the 32 possible locations and randomly divided into two sets of ten locations. In this way, each target location was paired with two different sets of 10 distractor locations. Twelve displays (six target locations × two sets of distractor locations) in total were presented in random order in each block.

Transfer phase: The transfer phase consisted of three blocks, each block contained 12 displays of four configuration types (fully repeated, recombined, rotated, and new; Fig.

2.2). The displays of the four configurations were randomly interleaved in the transfer session. The 12 fully repeated displays were the same as those presented during the learning phase. The 12 recombined displays also contained the same six target locations as the fully repeated displays. However, half of the distractors were selected randomly from each of the two distractor sets that were initially paired with the same target location in the learning phase. Because of the random selection, the configurations of the learning phase were completely destroyed. New displays also contained the same six target locations from the learning phase, but each target location was paired with two sets of randomly selected distractor locations. To keep learning of repeated and new displays comparable during the transfer phase, new displays were also repeated across transfer blocks. The rotated displays were generated by 45° clockwise or counterclockwise respectively rotation of one half each of the displays from the learning phase so that the target location probabilities of the six target locations were kept constant by this manipulation.

Recognition phase: The recognition session consisted of a question section and an assessment section. First, participants answered the question: "Do you think that some items' configurations were repeated?". If the answer was "yes", the participant was asked the second question: "Did you deliberately try to memorize these configurations?".

Subsequently, the 12 fully repeated, 12 recombined, and 12 rotated displays of the transfer session and 12 new configurations were presented. The newly created configurations shared the same set of target locations with the three types of repeated configurations. Participants’ task was to indicate whether they had seen the display before or not by pressing one of two buttons.

2.4. Results

2.4.1. Learning phase

Error trials and search times longer than 3 standard deviations from the mean reaction times (outliers) were excluded from the analysis. Overall error rates and outliers were quite low, namely 1.3% for target localization errors and 0.27% for outliers. Error rates and outliers did not differ between blocks, as assessed by one-way analyses of variance (F (19, 500) = 1.40, p > .1, η_p^2 = 0.05 for target localization errors and F (19, 500) = 0.80, p > .1, η_p^2 = 0.03 for outliers).

For the mean reaction times (RTs) without error trials, data were aggregated into epochs consisting of four blocks each. We observed a significant main effect of epoch, analyzed by one-way analysis of variance (F (4, 125) = 6.23, p < .001, η_p^2 =0.13) due to decreasing reaction times over epochs.

2.4.2. Transfer phase

Error rates (%) and outlier rates (%) based on means and SDs from each configuration and participant as a function of configuration are shown in Table 2.1. We calculated a

Bayesian repeated-measures ANOVA of the error rates of the four configurations (fully repeated, recombined, rotated, and new configuration) that yielded a $BF_{01} = 9.197$ for the main effect of configuration. The same calculation method for the outlier rates yielded a $BF_{01} = 7.523$. The results thus provided substantial evidence for the equality of the four configurations in both error and outlier rates.

Table 2.1 Mean error rates and outliers as a function of configuration in the transfer phase of Study II.

	configuration			
	Fully repeated	Recombined	Rotated	New
Mean Error Rates (%)	1.4	2.2	2.4	1.6
Outliers (%)	1.0	1.0	0.6	0.6

Trials with errors or outliers were excluded from the analysis of RTs. A one-way analysis of variance showed that the main effect of configuration was significant (F (3, 100) = 3.46, $p < .05$, $\eta_p^2 = 0.07$).

We hypothesized that all three kinds of repeated displays (fully repeated, recombined, and rotated displays) would lead to a search time advantage compared with new displays. To test this hypothesis, we tested the linear contrast $3 * RT_{new} - RT_{fully\ repeated} - RT_{recombined} - RT_{rotated}$ versus zero that yielded t (25) = 7.367, $p < 0.001$, $d = 2.04$, confirming the hypothesis.

To further analyze if each repeated condition led to shorter reaction times compared with new displays, we used one-tailed paired-samples t-tests. After Bonferroni correction (Armstrong, 2014) for three comparisons ($\alpha = 0.05 / 3 = 0.017$), as shown in Table 2.2, RTs in the new configuration were significantly longer than all of the three repeated configurations (fully repeated, recombined, rotated). Another family of three tests was calculated between the repetition conditions, to investigate potential differences in the amount of contextual cueing due to full or partial display repetition. These two-tailed paired-samples t-tests were not significant.

Table 2.2. Reaction times comparisons between configurations in the transfer phase of Study II. Note that comparisons between new and repeated conditions (upper half of table) were one-tailed t-tests, while comparisons between repeated configurations (lower half of table) were two-tailed t-tests (see text for explanation).

		df	*t*	*p*	*d*
New	Fully repeated	25	8.339	<.001	0.80
	Recombined	25	4.521	<.001	0.58
	Rotated	25	6.286	<.001	0.65
Fully Repeated	Recombed	25	-1.482	.151	0.21
	Rotated	25	-1.256	.221	0.14
Recombined	Rotated	25	0.680	.503	0.07

In order to test for equality of reaction times between the repeated conditions, we calculated Bayes factors for the fully repeated, recombined and rotated configuration. $BF_{01} = 3.908$ between recombined and rotated yielded substantial evidence for equality. $BF_{01} = 1.830$ between fully repeated and recombined and $BF_{01} = 2.384$ between fully repeated and rotated yielded anecdotal evidence for equality (Wetzels et al., 2011).

The mean RTs, separately for the last three blocks of the learning phase and the three blocks and four configurations (fully repeated, recombined, rotated and new) of the transfer phase, are presented in Fig. 2.3.

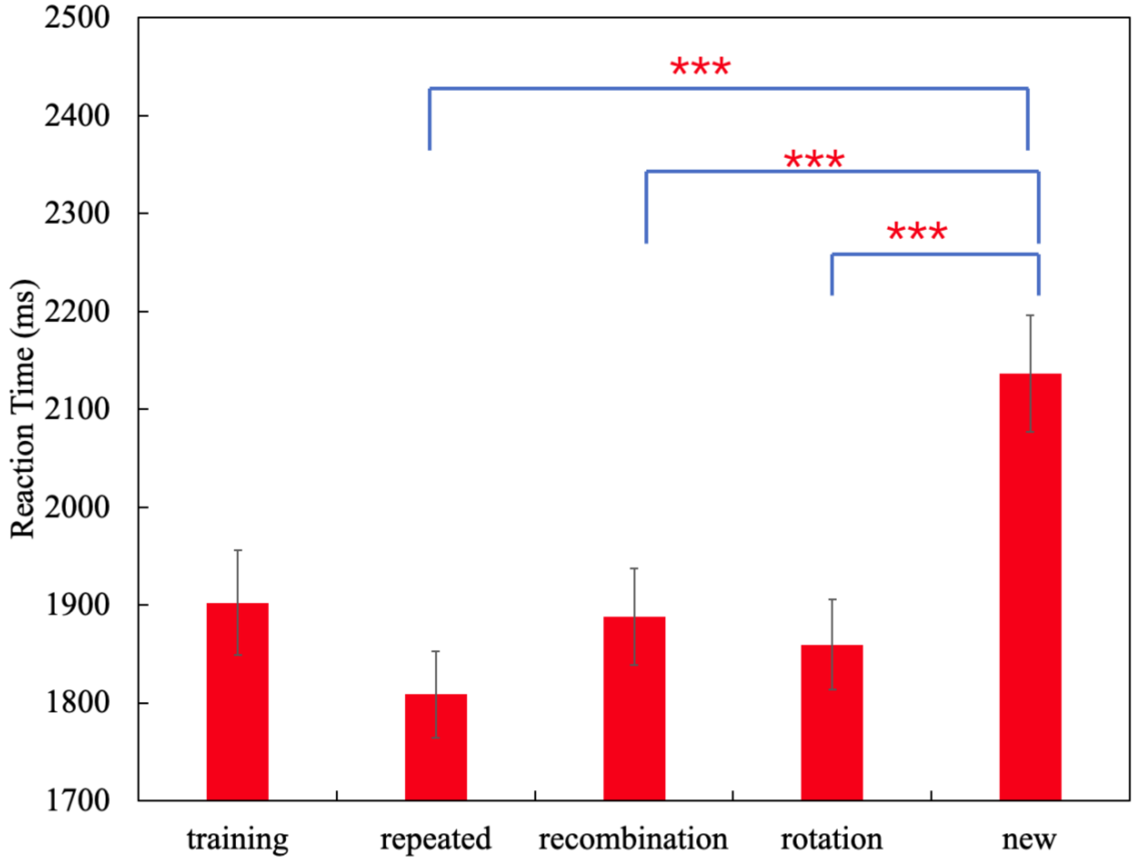

Figure 2.3. Results of mean response times in Study I. Mean response time in the last three blocks of the learning phase and four configurations (repeated, recombination, rotation and new) of the transfer phase. Error bars represent standard error of the mean. The statistical results can be seen in Table 2.2.

2.4.3. Recognition phase

Overall accuracy was 48.5%. Mean accuracy for fully repeated configurations was 51.6%, for recombined configurations 48.4%, for rotated configurations 49.4%, and for new configurations 55.6%. Two-tailed paired sample t-tests indicated no significant deviations from chance level (50%), either for repeated configuration (t (25) = 0.467, p = 0.644, d = 0.13), or for recombination configuration (t (25) = -0.385, p = 0.703, d = 0.11), or rotation configuration (t (25) = -0.167, p = 0.869, d = 0.05), or new configuration (t (25) = -1.668, p = 0.108, d = 0.47).

For fully repeated configurations, the hit rates were 26% for fully repeated configurations, 25% for recombined configurations, and 25% for rotated configurations. The false-alarm rate for new configurations was 22%. To rule out that the lack of significant differences was due to a lack of power, we also conducted Bayesian t-tests assessing whether the alarm rate was comparable to the hit rate in the three repeated configurations. BF_{01} = 2.376 in the recombined configuration and BF_{01} = 2.759 in the rotated configuration yielded anecdotal evidence for equality. In the fully repeated configuration, BF_{01} = 3.752 yielded substantial evidence for equality.

2.5. Discussion

The present study confirmed that the presence of global configuration or individual distractor locations alone can produce contextual cueing. Participants learned and flexibly used both global configuration or individual distractor location cues within the same experiment. Disrupting either the global configuration (recombination condition) or the individual distractor locations (rotation condition) did not remove contextual cueing, as long as the other cue was present.

Beyond previous work (Jiang & Wagner, 2004), we observed configuration and location cueing in the same experiment instead of two separate experiments, reducing the chance that participants could adjust to one particular type of display change (recombination or rotation) in the transfer phase. Moreover, the present study investigated configurational cueing in rotated configurations instead of the rescaled and displaced displays of Jiang and Wagner (2004). Rotation prevents the use of a strategy to adapt the personal spatial reference frame to the stimulus-filled part of the monitor that could have been used in Experiment 2 of Jiang and Wagner (2004). Taken together, the results of both studies show high flexibility of configurational cueing.

While recombined and rotated displays led to significantly shorter reaction times than new displays, recombined and rotated reaction times were still numerically higher than for fully repeated displays. Bayes factors yielded only anecdotal evidence for equality of reaction times between fully repeated and either recombined or rotated displays. Thus, we cannot say that contextual cueing by recombined or rotated displays is as efficient as contextual cueing by fully repeated displays. It should be noted that the efficiency of contextual cueing may depend on parameters like the rotation angle for rotated displays or the number of items in recombined displays; therefore, we cannot make a generalizable statement of the relative impact of location and configuration information in the present study. In future studies, it might be worth investigating the impact of rotation or recombination by varying the rotation angle and the proportion of item number.

Could it be that the use of two manipulations in a single experiment led to carry-over effect in learning between conditions? We find it difficult to imagine that this created systematic dependencies between conditions. The similarity of our results with the results from separate experimental tests of contextual cueing by individual locations and global configuration reported by Jiang and Wagner (2004) rather suggested that contextual cueing by individual locations or global configuration occurred rather independently from each other.

Beesley, Vadillo, Pearson, and Shanks (2015) have noted that the recombination condition of Jiang and Wagner (2004), again used in our study, may still have contained partial configurational information in addition to the repeated distractor locations (Beesley et al., 2015). However, in the present study (and likely also in Jiang and Wagner's experiment), the random recombination of distractor locations destroyed the original configurations of the two original displays quite severely, as illustrated in Figure 2.2.

The preserved contextual cueing effect for rotated configurations is in agreement with a previous study by Shi et al. (2013) that also found preserved contextual cueing after rotation - although in quite dissimilar displays (smartphone display icons) and with a more complex rearrangement of rotated display parts (Shi et al., 2013). Rotations in the depth plane of three-dimensional displays, however, appear to be more detrimental to contextual cueing.

A post-experimental recognition test yielded no evidence for the explicit recognition of the fully repeated displays. There has been a debate about the validity of recognition tests for the contextual cueing paradigm (Colagiuri & Livesey, 2016; Vadillo et al., 2016). The main point of critique is the necessarily limited number of repeated displays and the associated limited power of recognition tests. In the present experiment, we tried to evaluate the likelihood of a "true" similarity of hit and false-alarm rates, supporting implicit learning, by calculating Bayes factor analyses between hits and false alarms for the repeated conditions. These analyses yielded moderate support for equality of hits and false alarms for the fully repeated displays and somewhat weaker support for the recombined and rotated displays. In any case, the analysis yielded more support for implicit than for explicit learning.

2.6. Conclusion

Our findings show that both global configuration and individual locations can be used as contextual cues. This is true even when displays contain only configuration or location cues in random succession, making adjustment to one category of cues difficult. Moreover, configurational cues were effective after 45° rotation, demonstrating a high flexibility of cueing by configurations

3. Study II: Contextual cueing - eye movements in rotated and recombined displays

The results of this experiment were first published in: Zheng L, Marek N, Melnik N and Pollmann S (2024) Contextual cueing—Eye movements in rotated and recombined displays. *Front. Cognit.* 3:1403749. doi: 10.3389/fcogn.2024.1403749

3.1. Abstract

Contextual cueing leads to improved efficiency in visual search resulting from the extraction of spatial regularities in repeated visual stimuli. Previous research has demonstrated the independent contributions of global configuration and spatial position to contextual cueing. The present study aimed to investigate whether learned spatial configuration or individual locations would elicit fixation patterns resembling those

observed in the original displays. We found that search guidance based on either local or global spatial context, by combining distractor locations from two learned displays or rotating displays, kept not only search time facilitation intact, in agreement with previous studies, but also enabled search with less fixations and more direct scan paths to the target. Fixation distribution maps of recombined or rotated displays were more similar to the original displays than random new displays. However, for rotated displays this was only true when the rotation angle was taken into account. Overall, this shows an astonishingly flexible use of the oculomotor system for search in incompletely repeated displays.

3.2. Introduction

Contextual cueing is a phenomenon characterized by the extraction of spatial regularities from repeated visual stimulus patterns, leading to enhanced efficiency of visual search. Numerous studies have consistently demonstrated the facilitation effect associated with contextual cueing, wherein participants exhibit faster search times for displays with repeated configurations (Goujon et al., 2015; Jiang & Sisk, 2020; Jiang et al., 2019; Sisk et al., 2019). Notably, previous studies have highlighted the independent contribution of spatial position and global configuration to contextual cueing (Jiang & Wagner, 2004; Zheng & Pollmann, 2019). This was achieved by the design of two types of displays: the first type of display recombined distractors from two learned configurations with the same target location, thereby preserving individual target-distractor relations but destroying the global spatial configuration of distractors.

The second type of display was obtained by changing display size (Jiang & Wagner, 2004) or rotating the entire display around its center (Zheng & Pollmann, 2019), thereby preserving the spatial configuration but changing all distractor locations. Contextual cueing was observed in both types of displays, which suggests that both the spatial position of individual items and the overall arrangement of the display contribute to guiding attention and facilitating efficient search processes.

However, these studies only analyzed search times, as a summary measure of the underlying processes. Thus, although the search time benefits for recombined and rotated (or enlarged) displays demonstrated that search was more efficient in these partially repeated displays, they yielded no further information about the underlying processes. One way to learn more about these processes is to measure eye movements.

Contextual cueing not only leads to reduced search times for repeated displays but also to fewer fixations and more efficient fixation patterns (Brockmole & Henderson, 2006; Manginelli & Pollmann, 2009; Peterson & Kramer, 2001; Tseng & Li, 2004). However, in these previous studies, eye movement data were recorded in fully repeated displays. In contrast, in the present study, we explored eye movements in rotated displays - that selectively contained only the previously learned spatial configuration of items but not the learned item locations - or in recombined displays - in which all distractor locations were predictive of the target location, but the overall configuration of distractor locations was not.

There is evidence that both the individual spatial target-distractor relations and the overall spatial configuration contribute to contextual cueing. On the one hand, it was observed that repeating only distractor locations in the vicinity of the target led to search facilitation of about the same magnitude as repeating all locations of a display (Brady & Chun, 2007; Olson & Chun, 2002). On the other hand, in the same studies, effects of global context on contextual cueing were observed, e.g., the search facilitation due to contextual cueing was lost if all distractor locations in the target quadrant were preserved, but the quadrants of a display were shuffled (Brady & Chun, 2007, Exp. 4). Thus, the evidence gained from search times suggests that both the local distractor position and the global target-distractor configuration of a display are vital information sources that help predict the target location.

Here, we asked if the pattern of eye movements made during search in a recombined or rotated display would be similar to the original display that was encountered during the - incidental - learning phase of the experiment. Regarding the recombined displays, the question was, would the eye movement pattern for searching a display in which 100% of distractor locations were predictive of the target, but 50% each stemmed from two different trained displays, thus destroying the overall target-distractor configuration, still be more similar to the eye movement pattern in the original display(s), compared to an eye movement pattern recorded during viewing a new display? Regarding the rotated displays, we asked if a display that is repeated but rotated by 45° elicits a fixation pattern that is similar to the one elicited by the original display, but likewise rotated by 45°. Alternatively, it might be assumed that a rotation angle of 45° is sufficiently small that the fixation pattern from the original display need not be rotated, perhaps using larger attentional foci (indicated by fewer fixations and larger saccade amplitudes) for an efficient search.

It may be argued that higher similarity of fixation patterns for a trained display and its recombined or rotated versions, rather than a new display, is trivial, because it may simply be achieved by fixating the display items one by one. However, fixation patterns are typically not identical when a scene is repeatedly presented. Rather, the number of fixations tends to be reduced for repeated presentations (Damiano & Walther, 2019; Smith et al., 2006). We expected the same here, a fixation pattern that is similar - though perhaps rotated - to the fixation pattern during initial presentation, but reduced in the number of fixations and with a more efficient scan path, yielding a reduced search time.

3.3. Methods

3.3.1. Participants

Twenty-four young adults (13 females and 11 males) with an average age of 23.7 years participated in the experiment, having self-reported normal or corrected-to-normal vision, and provided written informed consent for taking part in this study. Data from two participants were excluded because of unexpected program crashes, resulting in a final sample size of twenty-two participants. After they completed the experiment, participants were compensated with an 8-euro payment or a 1-hour study credit.

3.3.2. Equipment

Participants were individually tested in a sound-attenuated chamber, to ensure minimal external distractions. During the experiment, participants viewed a computer screen from a fixed distance of 57 cm by using a chin rest. Stimuli were presented on a screen with a resolution of 1920×1080 pixels and a refresh rate of 60 Hz.

The PsychoPy software was used to generate stimuli, control the timing of experimental events, and record participants' responses. Eye movements were recorded with an EyeLink 1000 desktop mount eye-tracking system (SR Research, Missisauga, Ontario, Canada), with 1000 Hz temporal resolution.

3.3.3. Stimuli

The displays consisted of an arrangement of eleven white items (one T-shaped target and ten L-shaped distractors) that were presented against a black background (Fig. 1). The target T was rotated by 90o to the left or right and the distractors were rotated by 0o, 90o, 180o, or 270o. Each letter's orientation was randomly determined for each trial. To increase the search difficulty, there was an offset (7 pixels) of the line junction of the distractor Ls, making the distractors more similar to the target T (Jiang & Chun, 2001).

3.3.4. Procedure

The eye tracker was calibrated with the standard nine-point calibration procedure at the start of each block. Throughout the block, recalibration was performed throughout the block as required to account for any potential measurement errors or variability arising from subtle shifts in pupil position across different trials.

Each trial began with a drift correction procedure to check whether the calibration model is still accurate. Following successful drift correction, participants were presented with the search display, during which they were allowed to freely move their eyes. The task was to identify the orientation of the T target (either rotated to left or rotated to right) by pressing the corresponding left or right key on a keyboard. The search display remained visible until the participants responded, or until a maximum duration of 6 seconds had elapsed. Participants were given feedback after each response. This feedback provided participants with information regarding the accuracy of their responses in the preceding trial, allowing for real-time performance evaluation. The experimental procedure is illustrated in Figure 3.1.

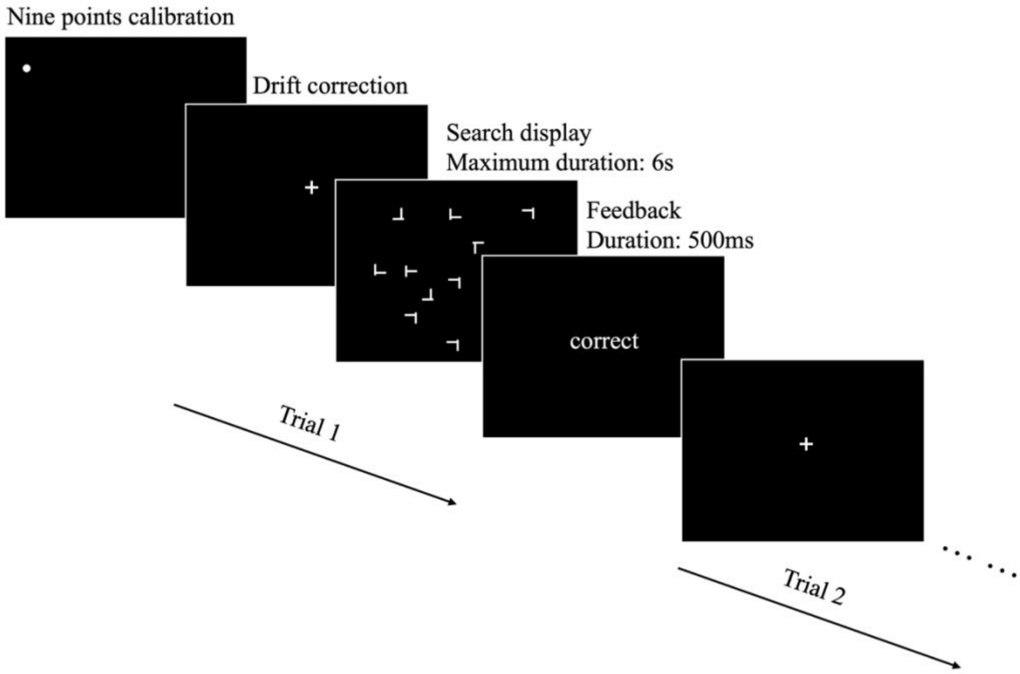

Figure 3.1. Experimental procedure employed in Study II. The procedure employed in the present experiment. Prior to the start of each block, a nine-point calibration was conducted to ensure the accuracy of the eye-tracking system. Throughout the block, ongoing calibration checks were performed and adjustments were made when necessary to maintain optimal tracking accuracy. Each trial began with a white fixation cross at the center of the screen, serving as an initial point of visual focus for participants. Following this, a search display was presented, where participants were required to indicate the target's rotation by pressing respective buttons. The search display remained visible until either the button was pressed or a maximum duration of 6s had elapsed. At the end of each trial, feedback was presented for 500ms.

3.3.5. Design

The experiment consisted of a learning phase and a transfer phase. The learning phase consisted of 20 blocks of 12 trials (240 trials in total), and the transfer phase consisted of 4 blocks of 48 trials (192 trials in total). To mitigate participant fatigue and allow for periodic breaks, every set of 48 trials (four blocks in the learning phase, and one block in the transfer phase) was followed by a rest period of 10 seconds. The whole experiment took about 50 mins to complete.

3.3.5.1. Learning phase

The positioning of the items in the experiment followed a specific arrangement of four concentric circles with radii of 2.04°, 3.99°, 6.28°, and 8.76°. Within each circle, there were eight equidistant possible item locations. To ensure that the target was not readily detectable at display onset, target locations were chosen only on the three outer circles.

The displays were generated individually for each participant, with the following procedure. Six target positions were randomly chosen on each of the three outer circles. Next, the second target position, following a 45-degree shift, was selected for each target. Overall, for 6 initial target locations, 6 rotated target locations were selected. By employing this design, this selection of target positions allowed for the systematic exchange of two target locations in the rotated condition of the transfer phase while maintaining a consistent probability distribution of the target location.

Each target position was paired with two sets of distractors in different positions. Specifically, for each target position, 20 distractor positions were randomly selected from the pool of items. These selected distractor positions were then randomly divided into two sets of ten positions. Each set of ten positions was matched with the target to form a display configuration. In this way, a total of twelve displays (six target locations × two sets of distractor locations) were generated and presented in random order in each block.

3.3.5.2.Transfer phase

The transfer phase consisted of four blocks. Each block consists of 12 displays encompassing four randomly interleaved configuration types: Fully Repeated, Recombined, Rotated, and New, following the design of the prior study by Zheng and Pollmann (2019). Fully Repeated displays were identical to those presented during the learning phase. This configuration served as a baseline for evaluating the retention and transfer of learned spatial associations. In the Recombined displays, the six target locations were consistent with those of the Fully Repeated displays. However, one half of the distractors each was selected randomly from each of the two distractor sets that were initially paired with the same target location in the learning phase (Figure 3.2a). To create the Rotated displays, half of the Fully Repeated displays were rotated 45o clockwise, while the other half was rotated 45^{o} counterclockwise. As the polar angle between the two target positions on each circle was 45°, the target location probabilities of the six target locations were kept constant by this manipulation (Figure 3.2b). Finally, New displays contained again the same learned six target locations as the other display types, but each target location was paired with two sets of randomly selected distractor locations. To keep learning of repeated and new displays comparable during the transfer phase, New displays were also repeated across transfer blocks.

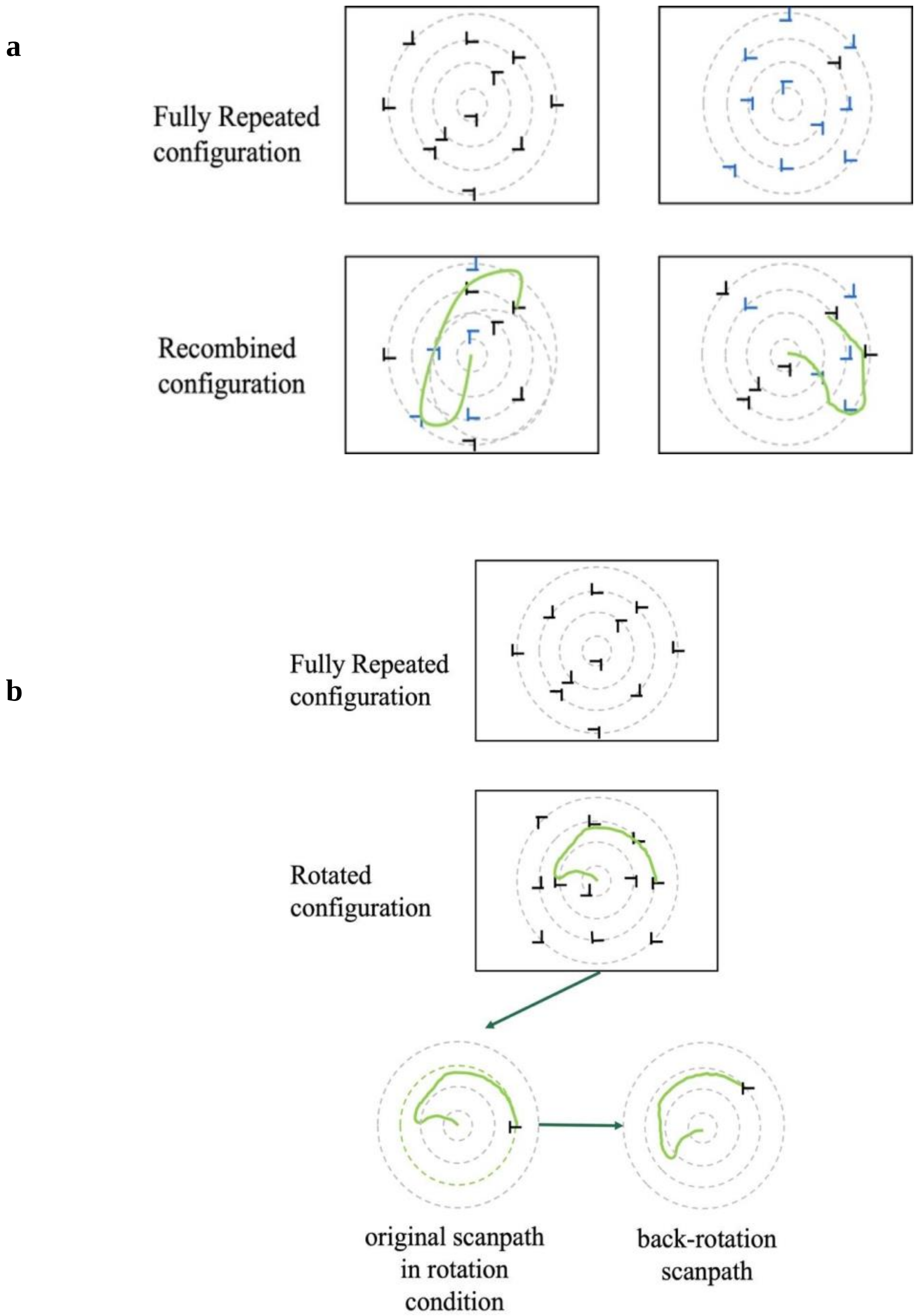

Figure 3.2. Example of recombined and rotated displays in Study II. (a) Examples of two recombined displays with the same target location but different (symbolized by black and blue) distractors. In the actual experiment, all distractors were black. The green lines represent possible eye movement trajectories. (b) The illustration of scanpath in rotated display and back-rotated scanpath in the transfer phase.

3.3.6. Data analysis

3.3.6.1. Accuracy and reaction Time (RT)

Our main focus was the analysis of search times, defined as the time from display onset to the response. However, we also analyzed the rate of incorrect responses to rule out speed-accuracy trade-offs. To this end, we conducted one-way analyses of variance to analyze the proportion of trials in which participants either provided incorrect responses or failed to respond within the designated time frame (6 seconds). Incorrect and slow response trials were excluded from the dataset for search time analyses.

To assess whether the reduction in search time reached a plateau towards the end of the learning phase, indicating that most of the learning had occurred and little additional learning was expected in the transfer phase, a Bayesian ANOVA was conducted on blocks 16-20.

During the transfer phase, we further explored the influence of different configurations on search performance. To analyze the proportion of incorrect trials, we conducted one-way analyses of variance, with the configuration considered as fixed factor. Regarding the analysis of search time, since the main effect across blocks was of particular interest, we performed a repeated measures ANOVA, using search time as dependent variable, and block and configuration as within-subject factors. If the main or interaction effect was significant, we utilized post-hoc tests to investigate specific contrasts.

Equality of search times across the partially and fully repeated conditions was assessed by calculating Bayes factors for the Fully Repeated, Recombined, and Rotated configurations.

3.3.6.2.Basic oculomotor indicators

We also conducted an examination of fundamental oculomotor metrics, specifically focusing on the number of fixations, saccade amplitude (average per participant), and scan pattern ratio (SPR, calculated by dividing the sum of saccade amplitudes by the straight-line distance from the scene center (initial fixation) to the target location; Brockmole and Henderson, 2006). Employing a repeated-measures analysis of variance (ANOVA) with the configurations and blocks as main factor, we aimed to ascertain potential dissimilarities in these indicators within distinct configurations and across distinct time blocks. Subsequent paired-sample t-tests were conducted to further elucidate the significance of specific pairwise comparisons.

3.3.6.3.Fixation density maps (FDM)

For each trial, the spatial distribution of the eye movement data was plotted as an FDM with the same limits as the original presentation screen (1920 x 1080 pixel). To correct for possible inaccuracies during recording, each FDM was spatially smoothed using a Gaussian filter with sigma of 30. All FDM were saved for visual inspection, transformed into greyscale matrices using the Open Computer Vision Library and subsequently vectorized with Numpy (Harris et al., 2020). Pairwise correlation distances (1 - correlation) were calculated between all vectors. Correlation distance coefficients were then transformed into Pearson coefficients. In order to achieve an approximately normal distribution, Fisher's z-transformation was applied. Figure 3.3 illustrates representative examples of relatively similar and dissimilar fixation density maps.

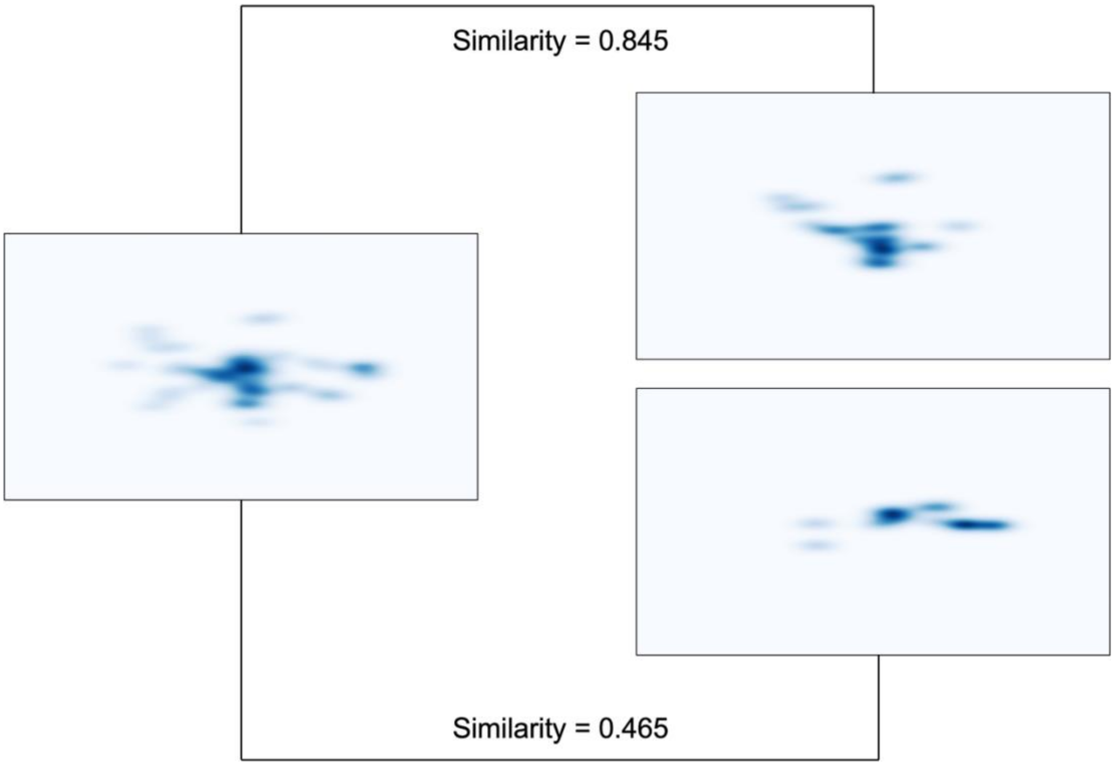

Figure 3.3. *Representative examples of fixation density maps with varying degrees of similarity.* The map on the left shares a higher similarity with the one on the top right (0.845), while it exhibits lower similarity with the one on the bottom right (0.465). These examples are taken from three displays belonging to one participant. The three displays share the same target location but are from different conditions: fully repeated condition (left), back-rotated condition (top right), and new condition (bottom right).

The similarity in FDM was assessed using paired t-tests, comparing fully repeated with the other two partially repeated conditions. In addition, we tested the hypothesis that participants were able to mentally rotate a learned display configuration to adapt it to a rotated display. In this case, the fixation pattern may also be rotated to adapt to the display rotation. Consequently, a back-rotated version of the fixation pattern should fit the fixation pattern of the same displays fully repeated (i.e. unrotated) version better than the fixation pattern before back-rotation. The back-rotated condition was created by rotating the fixations from the rotated displays in the direction opposite to display rotation by 45 degrees, as depicted in Figure 3.2b. Overall, this FDM analysis involved comparisons between fully repeated and recombined displays, rotated and back-rotated displays, as well as fully repeated and back-rotated displays.

3.4. Results

3.4.1. Learning phase

The participants exhibited high performance, with an error plus slow response rate of only 2.88% throughout the learning phase. The rate of error plus slow response trial decreased as the experiment progressed (Figure 3.4), confirmed by a significant block main effect in a one-way analysis of variance (F (19, 420) = 2.798, $p < .001$, η_p^2 = 0.112).

Importantly, search times exhibited a significant decrease over the course of the experiment as well (Figure 3.4). A one-way ANOVA showed a main effect of Block (F (19, 420) = 6.052, $p < .001$, η_p^2 = 0.215).

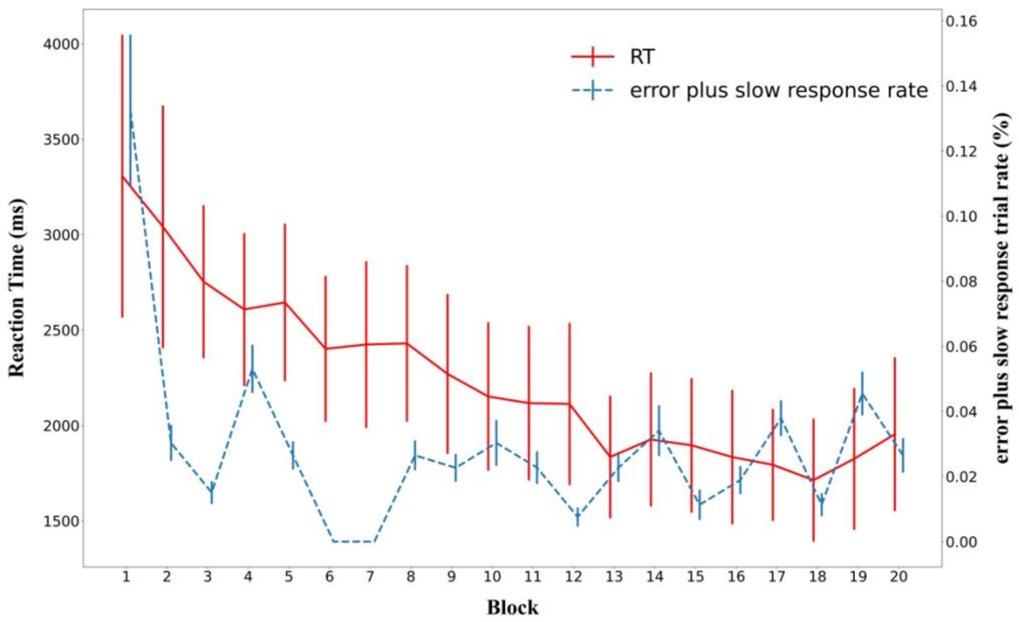

Figure 3.4. Results of the learning phase in Study II. Mean response time, error plus slow response trial rate during the learning phase across blocks. Error bars represent standard errors of the mean.

However, Figure 3.4 suggests that search times plateaued towards the end of the learning phase. This was strongly supported by a Bayesian ANOVA over the last five blocks (BF_{01} = 18.7).

3.4.2. Transfer phase

3.4.2.1. Error (including slow response) trials rate

In the transfer phase, the incorrect (error + slow response) trial rate was measured across four conditions, namely Fully Repeated, Recombined, Rotated, and New. The incorrect response rates in each condition were low overall (3.21% for Fully Repeated, 3.23% for Recombined, 3.79% for Rotated, and 5.11% for New) and a one-way ANOVA did not yield a significant main effect of condition (F (3, 84) = 1.056, p = 0.372).

3.4.2.2. Search times

The repeated measures ANOVA with the configuration and block as factors revealed significant main effects of Configuration (F (3, 63) = 7.875, p < .001, η_p^2 = 0.273) and Block (F (3, 63) = 4.925, p = 0.004, η_p^2 = 0.190) with RT decreasing over blocks. The interaction between Configuration and Block was not significant (F (9, 189) = 0.292, p = 0.976, η_p^2 = 0.014).

The post-hoc analysis showed that the RT in the New configuration were significantly higher than in the Fully Repeated configuration (t (21) = 4.509, p < .001, d = 0.376), the Recombined configuration (t (21) = 3.827, p = 0.002, d = 0.319), and the Rotated configuration (t (21) = 2.764, p = 0.045, d = 0.231), indicative of contextual cueing in the three (partially) repeated configurations. No other comparisons yielded significant results (Figure 3.5).

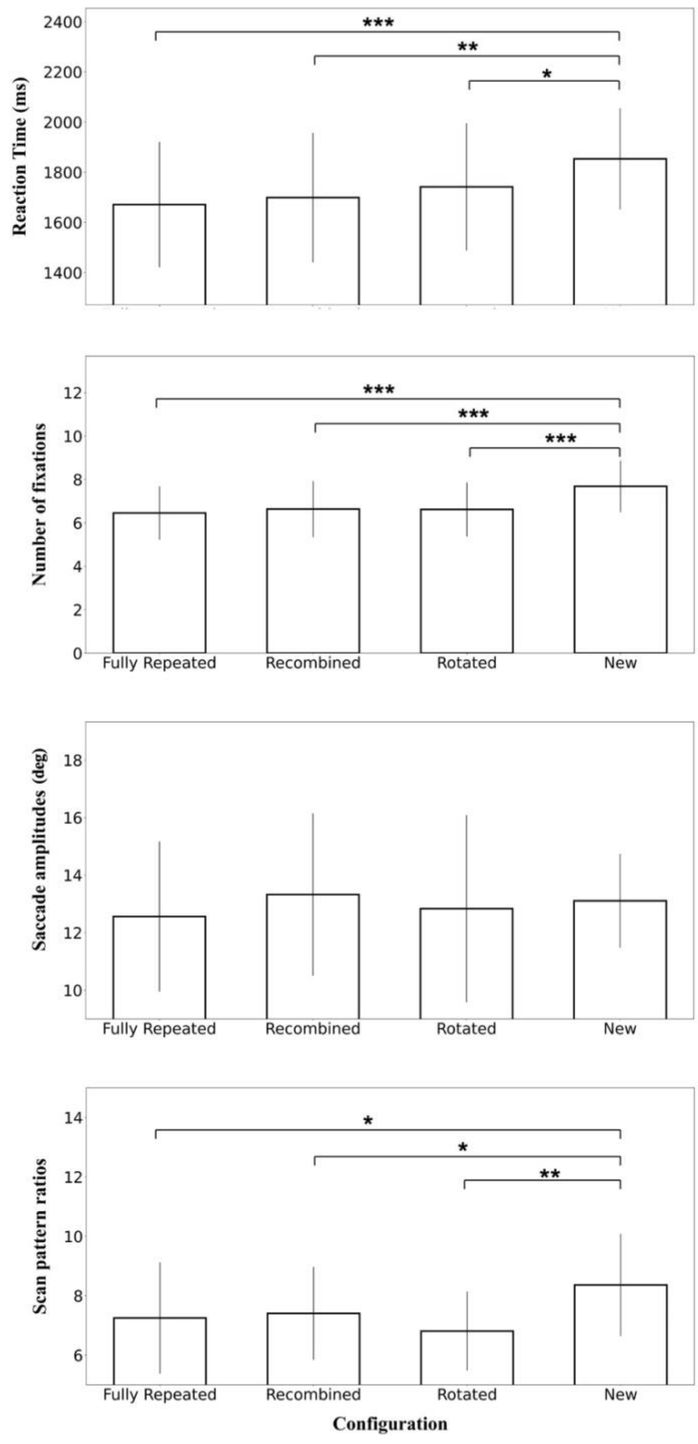

Figure 3.5. Results of the transfer phase in Study II. Mean response time, the number of fixations, saccade amplitudes, and scan pattern ratios in the four configurations (Fully Repeated, Recombined, Rotated, and New) of the transfer phase. Error bars represent standard errors of the mean. Significance levels are denoted by asterisks, with * indicating p <.05; ** indicating p < .01, *** indicating p < .001.

To test for equality of search times between the repeated conditions, Bayes factors were calculated for the Fully Repeated, Recombined, and Rotated configurations. The Bayes factor (BF_{01}) of 1.996 between Recombined and Rotated and 1.081 between Fully Repeated and Rotated yielded anecdotal evidence for equality. Additionally, the Bayes factor of 3.574 between Fully Repeated and Recombined yielded substantial evidence for equality (Wetzels et al., 2011).

3.4.2.3. Basic oculomotor indicators

Number of fixations

The repeated measures ANOVA with the configuration and block as main effect on the number of fixations revealed significant main effects of Configuration (F (3, 63) = 17.903, $p < .001$, $\eta_p^2 = 0.460$) and Block (F (3, 63) = 3.284, $p = 0.026$, $\eta_p^2 = 0.135$) with fewer fixations over blocks. The interaction between Configuration and Block was not significant (F (9, 189) = 1.229, $p = 0.279$, $\eta_p^2 = 0.055$).

The post-hoc analysis showed that the number of fixations in the new configuration was significantly higher than in the fully repeated configuration (t (21) = 5.516, $p < .001$, d = 1.176), the recombined configuration (t (21) = 5.534, $p < .001$, d = 1.180), and the rotated configuration (t (21) = 6.060, $p < .001$, d = 1.292). No other comparisons yielded significant results (Figure 3.5).

Saccade amplitudes

The repeated measures ANOVA on saccade amplitude did not indicate significant main effects of configuration (F (3, 63) = 0.513, p = 0.675, η_p^2 = 0.024) or block (F (3, 63) = 1.543, p = 0.212, η_p^2 = 0.068). The interaction between configuration and block (F (9, 189) = 0.340, p = 0.960, η_p^2 = 0.010) was also not significant (Figure 3.5).

Scan pattern ratios

The repeated measures ANOVA on scan pattern ratios revealed a significant main effect of configuration (F (3, 63) = 4.397, p = 0.007, η_p^2 = 0.173). The main effect of block (F (3, 63) = 2.160, p = 0.102, η_p^2 = 0.093) and the interaction between Configuration and Block were not significant (F (9, 189) = 1.606, p = 0.116, η_p^2 = 0.071).

The post-hoc analysis showed that the scan pattern ratios in the new configuration were significantly higher than in the fully repeated configuration (t (21) = 1.835, p = 0.040, d = 0.391), the recombined configuration (t (21) = 2.199, p = 0.020, d = 0.469), and the rotated configuration (t (21) = 3.025, p = 0.003, d = 0.645). No other comparisons yielded significant results (Figure 3.5).

3.4.2.4. Spatial fixation density maps (FDM)

We compared FDMs to analyze the similarity of the spatial fixation distribution between conditions. Figure 3.6 shows the similarity matrix of 12 displays and 5 conditions.

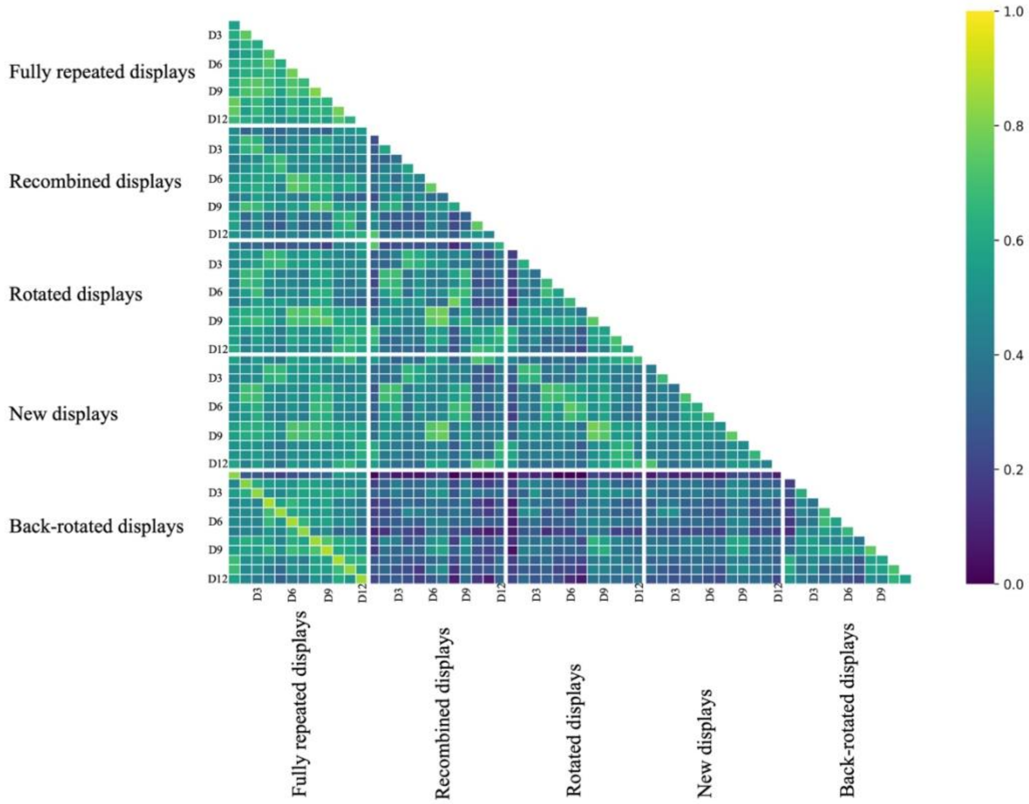

Figure 3.6. Similarity matrix. The figure depicts the similarity matrix of 12 displays across 5 conditions, with distinctive white lines marking the boundaries between different conditions. In the horizontal and vertical axes, 'D' represents 'display'. Each correlation coefficient in the matrix was converted back from the distance correlation (1-r) and then transformed using the Fisher Z-transformation.

What can be seen in the matrix is that similarity was high in the lines parallel to the main diagonal, indicating that displays sharing the same target location and parts of the distractor locations (i.e., fully repeated and recombined displays) had more similar FDMs than displays not sharing these locations. This was most obvious for the similarity of back-rotated FDMs and fully repeated FDMs, where an individual display and its back-rotated version shared the target and all distractor locations.

In particular, we expected recombined displays to elicit FDMs similar to those of the fully repeated displays they received one half of the distractors from. Consequently, we anticipated that the FDMs of the fully repeated displays were more similar to the FDMs of the respective recombined displays than to those of the new displays sharing the same distractor location. This was confirmed by a t-test comparison, indicating the similarity between repeated and recombined displays was higher than that between the fully repeated and new displays (t (21) = 6.276, p < .001, d = 1.338).

We further expected that a rotated display would prompt FDM similar to those of the original display, albeit rotated by the angle of display rotation. Thus, we expected the back-rotated FDMs to be more similar to the FDM for the fully repeated presentation of the same display than the rotated FDM. A t-test comparison revealed that the similarity between repeated and back-rotated displays was higher than that between the repeated and rotated displays (t (21) = 15.490, p < .001, d = 3.302).

In addition, in order to confirm that the similarity of back-rotated FDMs of rotated displays and the FDMs of fully repeated displays are not just driven by shared (though rotated) target location, they should be more similar to fully repeated displays than new displays with the same target location. Again, this was confirmed through a t-test, revealing that the similarity between repeated and back-rotated displays was higher than that between the repeated and new displays (t (21) = 10.200, p < .001, d = 2.175).

The results of paired t-tests are visually presented in Figure 3.7, with specific values detailed earlier in the text.

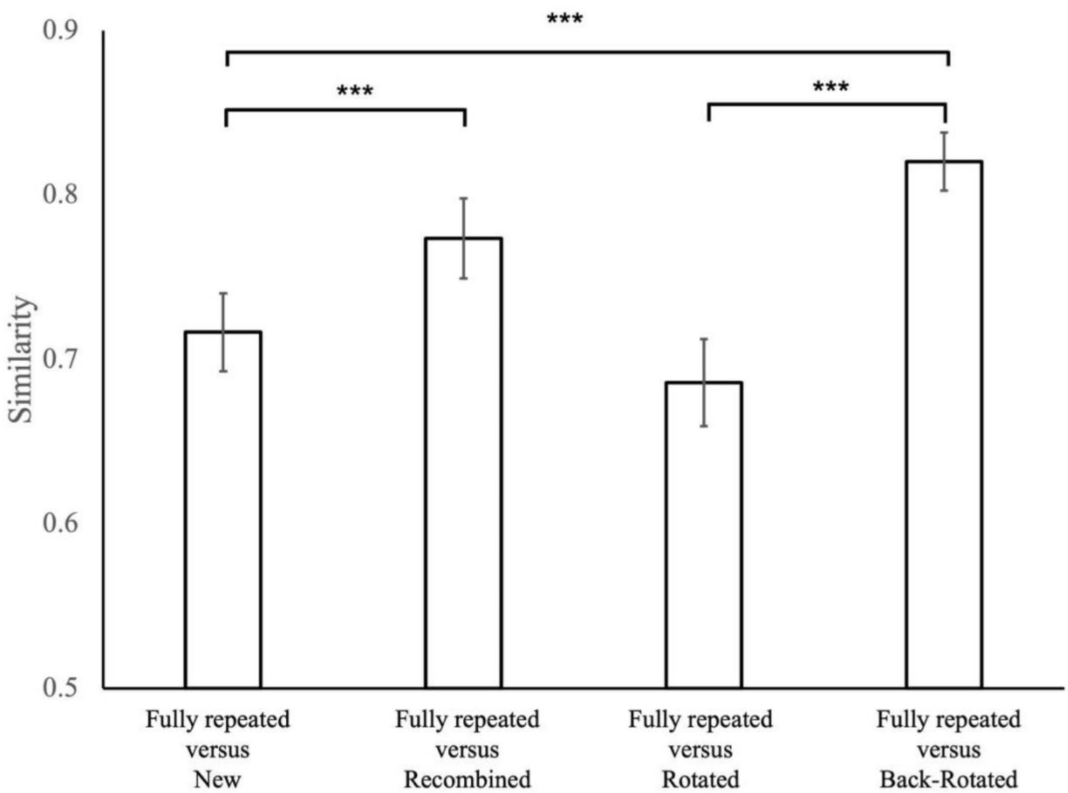

Fig 3.7. The similarity values for condition comparisons. Error bars represent standard errors of the mean. The significance level in result of t-tests is denoted by asterisks, with *** indicating p < .001.

Looking at the similarity matrix (Figure 3.7), it appears that fixation patterns between different fully repeated displays are more similar than between different new displays.

This is puzzling because using learnt distractor configurations for search guidance might be expected to lead to more distinct fixation patterns for repeated displays. Recently, however, it has been proposed that the search time benefits of repeated displays in the contextual cueing paradigm come about not (only) due to search guidance enabled by the learnt configurations of individual displays, but by a common search path that is optimized for all repeatedly presented displays (Seitz et al., 2023). This common scanpath hypothesis predicts that search paths - and consequently fixation patterns - of different repeated displays should be more similar than between different new displays. We indeed found that the similarity of fixation patterns was significantly higher between different fully repeated displays than between different new displays ($t_{one\text{-}sided}(21) = 14.667$, $p < .001$, $d = 3.127$). Thus, the fixation patterns might support the 'common scanpath' hypothesis. However, the similarity of fixation patterns between rotated displays were not significantly higher than between new displays, (rotated: ($t_{two\text{-}sided}(21) = -1.843$, $p = 0.079$), and, the similarity between recombined displays was significantly lower than between new displays ($t_{two\text{-}sided}(21) = -4.081$, $p < .001$, $d = -0.870$).

3.5. Discussion

Search in repeated displays can not only lead to reduced search times, but also to more efficient scan paths during visual search (Brockmole & Henderson, 2006; Manginelli & Pollmann, 2009; Peterson & Kramer, 2001; Tseng & Li, 2004). Here, we investigated if that is also the case if only partial spatial constellations are repeated in recombined displays or the display is rotated. We found that recombined displays, containing repeated target and distractor positions, but lacking a repeated global configuration, were searched with less fixations and an improved scan pattern ratio than new displays. Furthermore, spatial fixation heat maps in these displays were more similar to those of fully repeated displays than to novel displays.

Likewise, search in rotated displays, in which the global configuration was preserved, but local target and distractor positions were changed, were also searched with less fixations and an improved scan pattern ratio. Spatial fixation heatmaps showed that this was achieved by rotating the fixation pattern along with the display rotation.

Visual search benefits from repeated spatial patterns, even if they are incomplete. For instance, previous work had already shown that repetition of three items out of a previously learned display were sufficient to elicit a search advantage, as an indicator of contextual cueing (Bergmann & Schubö; Song & Jiang, 2005). Likewise, displays that conserved only spatial relations between individual distractor and target locations - by recombining distractor locations from two learned displays with the same target location) on the one hand or only global target-distractor configurations on the other hand (by magnification or rotation) elicited contextual cueing (Jiang and Wagner, 2004; Zheng and Pollmann, 2019). The reduced search times found in the latter studies, indicating the use of learned spatial relations for efficient search guidance, were replicated in the present study. In addition, analysis of eye movements showed that the increased search efficiency in both recombined and rotated displays was achieved by making fewer fixations that led more straightforward to the target - indicated by improved scan pattern ratio. This extends previous reports of more efficient eye movement patterns in fully repeated displays (Brockmole & Henderson, 2006; Manginelli & Pollmann, 2009; Peterson & Kramer, 2001; Tseng & Li, 2004) to displays that repeat only local or global spatial context. Note that all four conditions - fully repeated, recombined, rotated, and new - shared the same target locations, so that differences in search efficiency between these conditions cannot be due to target location probability cueing (Geng & Behrmann, 2005; Golan & Lamy, 2023; Jiang & Swallow, 2013b).

Fixation heatmaps of recombined displays were more similar to those of fully repeated displays than those of new displays. It might be argued that this is trivial, because recombined and fully repeated displays share half of the distractor locations, whereas fully repeated and new displays share only a few randomly drawn distractor locations, if any. Although fixation need not fall on items, but rather on points that allow to judge item relations important for the task at hand, the partially joint structure may well explain the similarity of fixation heatmaps for fully repeated and recombined displays. However, in combination with the reduced number of fixations and the improved scan pattern ratio, the similarity of fixation heatmaps for recombined and fully repeated displays shows that during search of recombined displays, participants do not just follow the items on the screen, but extract useful information from the previously encountered spatial target-distractor relations to guide search efficiently. Importantly, however, the spatial relation of individual distractors and the target appears to be only useful for contextual cueing if no random distractors lie in between repeated target-distractor pairs (Olson & Chun, 2002).

Concerning the rotated displays, analysis of fixation heatmaps yielded an important information that would not have been available by investigating fixation counts and scan pattern ratios alone. We found that the spatial fixation heatmaps of rotated displays were comparably dissimilar to the fixation heatmaps of the identical, but unrotated (fully repeated) displays as new displays. However, when we back-rotated the heatmaps of the rotated displays, they became significantly more similar to the non-rotated displays than the new displays, indicating that our participants appeared to rotate their learned scan patterns to efficiently search in rotated displays.

Unexpectedly, we found that fixation patterns were more similar between different fully repeated displays than between different new displays. If fixations patterns followed incidentally learnt display configurations, one might expect the opposite, namely distinctive fixation patterns for individual repeated displays. Recently, an alternative explanation has been proposed to account for the search time advantage of repeated displays. Seitz and colleagues (2023) proposed that a common search path is learned that is optimal for all repeated displays, rather than different search paths for individual displays. Our finding of increased fixation pattern similarity between fully repeated displays may support this assumption. However, fixation pattern similarity was not increased between recombined displays or rotated displays. Thus, the search time reductions observed for these displays could not be explained by the concept of a common search path. It seems likely that if learning a common search path contributes to the contextual cueing effect, it may not be the only contributing mechanism. As this was a post hoc finding, it should be regarded with caution. However, we find it intriguing enough to warrant further research.

Neither for rotated nor recombined displays did we observe altered saccade amplitudes. Increased saccade amplitudes, together with a reduced number of fixations, might have been a sign of a search with an enlarged focus of attention (Geringswald & Pollmann, 2015). This might have been a way to capture the global configuration in altered displays. In contrast, a reduced focus of attention might have been a possible reaction to the conserved spatial relations of individual target-distractor locations in the absence of a preserved global configuration. However, as noted, we observed no indication of such adjustments. Note, that fully repeated, recombined and rotated displays were presented in random sequence, so that a deliberate advance selection of an attentional focus size to focus on more global or local spatial contexts would have been impossible.

We did not see significant differences in the search times to fully repeated, recombined or rotated displays. However, we do not know if a 50% repetition of distractor locations in the recombined displays and a 45-degree rotation of the configuration in the rotated displays equate to the same degree of disruption of the global configuration and individual locations. A more nuanced exploration of these aspects could contribute to a comprehensive understanding of the observed phenomena and guide future research in this domain.

In summary, we found that eliminating either local or global spatial context from repeated search displays kept not only search time facilitation intact, but was also accompanied by less fixations and a more direct scan path to the target. Fixation distribution maps of recombined or rotated displays were more similar to the original displays than random new displays. However, for rotated displays this was only true when the rotation angle was taken into account. Overall, this shows an astonishingly flexible use of the oculomotor system for search in incompletely repeated displays.

4. Study III: Egocentric and allocentric reference frames can flexibly support contextual cueing

The results of this experiment were first published in: Zheng L, Dobroschke J-G and Pollmann S (2021) Egocentric and Allocentric Reference Frames Can Flexibly Support Contextual Cueing. *Front. Psychol.* 12:711890. doi: 10.3389/fpsyg.2021.711890

4.1. Abstract

We investigated if contextual cueing can be guided by egocentric and allocentric reference frames. Combinations of search configurations and external frame orientations were learned during a training phase. In Experiment 1, either the frame orientation or the configuration was rotated, thereby disrupting either the allocentric or egocentric and allocentric predictions of the target location. Contextual cueing survived both of these manipulations, suggesting that it can overcome interference from both reference frames. In contrast, when changed orientations of the external frame became valid predictors of the target location in Experiment 2, we observed contextual cueing

as long as one reference frame was predictive of the target location, but contextual cueing was eliminated when both reference frames were invalid. Thus, search guidance in repeated contexts can be supported by both egocentric and allocentric reference frames as long as they contain valid information about the search goal.

4.2. Introduction

Objects are often spatially arranged in certain regularities. The human visual system has the ability to extract the regularities from sensory input in an incidental way and use them to guide visual attention. In the lab, scientists typically investigate human search behavior by asking participants to find a predefined target item among competing distractor items. Chun and Jiang (1998) designed an experiment that presented a target T among a set of distractors Ls. Importantly, and unbeknownst to their participants, in half of the trials, displays ('Repeated Display') presented in the first block were repeated in subsequent blocks, maintaining a consistent target-distractor configuration. In the other half of the trials, newly generated displays were presented ('New Display'). Within a few blocks, the reaction time (RT) for repeated displays became significantly lower than for new displays. This search advantage, guided by invariant spatial target-distractor configurations, is indicative of contextual cueing (Chun, 2000; Goujon et al., 2015; Jiang & Sisk, 2019; Sisk et al., 2019).

Here, we put forward that spatial reference frames (RFs) modulate contextual cueing. RFs can affect where visual attention is allocated based on spatial memory when observers encounter a familiar scene (McNamara, 2002). One common framework divides RFs into egocentric and allocentric RFs (Klatzky, 1998; Miniaci & De Leonibus, 2018). The egocentric RF presents visual objects with respect to the observer's particular perspective, including but not limited to retinotopic, head-centered, and trunk-centered RFs. The allocentric RF, independent of the observer's perspective, presents visual objects in relation to environmental features. In a nutshell, we can distinguish the two RFs by describing their reference. For example, defining the location of an object to myself (the food shop is in front of me) uses the egocentric RF, whereas describing the shop's location relative to a landmark (the shop is to the left of a park) uses the allocentric RF.

What kind of reference frame does contextual cueing depend on? Previous work on contextual cueing has found that preserving the absolute locations of distractors in the display, but destroying the relative relations between distractors (by combining distractors from two repeated displays) suffices for contextual cueing to occur (Jiang & Wagner, 2004; Zheng & Pollmann, 2019). This could be seen as an example of an egocentric reference frame. Likewise, contextual cueing was observed when the absolute distractor locations were changed by rescaling or rotation, but their relative spatial locations were preserved (Jiang and Wagner, 2004; Zheng and Pollmann, 2019). Moreover, it has been argued that contextual cuing can be based on pairwise associations between the locations of the target and the distractors near the target (Brady & Chun, 2007). This could be argued to be an instance of an allocentric reference frame guiding contextual cueing.

While these examples concern the relations within items of a search display, in the present experiments, we added an external reference frame in order to investigate if contextual cueing will be modulated by it. In addition, we investigated if the reference frame underlying contextual cueing is top-down modulable. In Experiment 1, participants were repeatedly exposed to search displays within an external frame through the learning phase, enabling target-distractor configuration learning of the display but also learning to associate the display with the external frame of a certain orientation. In the subsequent test phase, by rotating the outer frame around an unchanged repeated display, we invalidated the allocentric reference frame but kept the egocentric RF intact (Figure 4.1). In contrast, by rotating the repeated display but keeping the external frame unchanged, we invalidated both the egocentric and allocentric reference frames. In Experiment 1a, rotation of the search display led to unequal target location probabilities, which might have confounded the measurement of contextual cueing. Therefore, Experiment 1b used displays with equal target location probability to investigate the potential contribution of target location probability cueing to Experiment 1a.

In Experiment 1, the contribution of the reference frames to contextual cueing was investigated by means of interference caused by changed - thereby invalid - reference frames. In contrast, in Experiment 2, we asked if a rotated allocentric reference frame may support search guidance when it was a valid predictor of the target location in an equally rotated display.

4.3. Experiment 1a

Methods

Participants

Twenty-six young adults (fifteen females and eleven males; mean age 24.12 ± 3.55 years) participated in Experiment 1a. Two participants' data were lost because of unexpected program crashes. Participants remained naive to the purpose of the research during the experiments. They had self-reported normal or corrected-to-normal vision. After the experiment, they received an €8 payment or a one-hour study credit. Participants provided written informed consent before testing. All experiments of this study were approved by the Ethics Board of the Medical Faculty of the Otto-von-Guericke University, Magdeburg.

Stimuli

The experiment was conducted on a screen (resolution:1920 × 1080 pixels; refresh rate: 120 Hz). A black cardboard with a round opening in the middle (radius = 27.2cm) covered the screen's frame, to remove it as a potential reference frame. The stimuli were created and presented with PsychoPy3 (v3.0.0b11). Participants viewed the screen from a fixed distance of 57 cm by using a chin rest.

Each search display comprised eleven L distractor letters and one target letter T (0.4° × 0.4°). The distractors had four possible directions: 0°, 90°, 180°, and 270°, while the target was rotated by 90º or 270º. The distractor L-shapes had an offset (of approximately 17%) to make them more similar to the target T (Jiang & Chun, 2001). The items were arranged on imaginary circles around central fixation with a 1.5º, 3.5º, 5.5º, and 7.2º radius with eight possible locations for each eccentricity. The eccentricities of items were balanced across each display, and the eccentricities of the target were balanced across the four configurations. Participants were asked to discriminate the target's orientation and press a corresponding key on a standard keyboard.

Design

After 12 practice trials that were not further analyzed, the experiment included a learning phase and a test phase. In the learning phase, participants searched twelve repeated displays for twenty blocks. These repeated displays were generated individually for each participant and presented in random sequence in each block.

The test phase consisted of four blocks. Each block contained twelve displays of each of four experimental conditions (see Figure 4.1), Displays were presented in random order. The four conditions varied with respect to the validity of the egocentric and allocentric cues, as follows:

Ego+/Allo+: Unchanged repeated displays from the learning phase. The plus signs indicate that both egocentric and allocentric reference frames were valid predictors of the target location.

Ego+/Allo-: Unchanged search display from the learning phase with rotated outer frame. The plus sign after Ego indicates that the egocentric reference frame was a valid predictor of the target location, while the minus sign after Allo indicates that the allocentric reference frame was an invalid predictor of the target location.

Ego-/Allo-: The outer frames did not rotate along with the rotated search displays. The minus signs indicate that both egocentric and allocentric reference frames were invalid predictors of the target location.

New: newly generated displays that shared the same set of target locations with the Ego+/Allo+ condition.

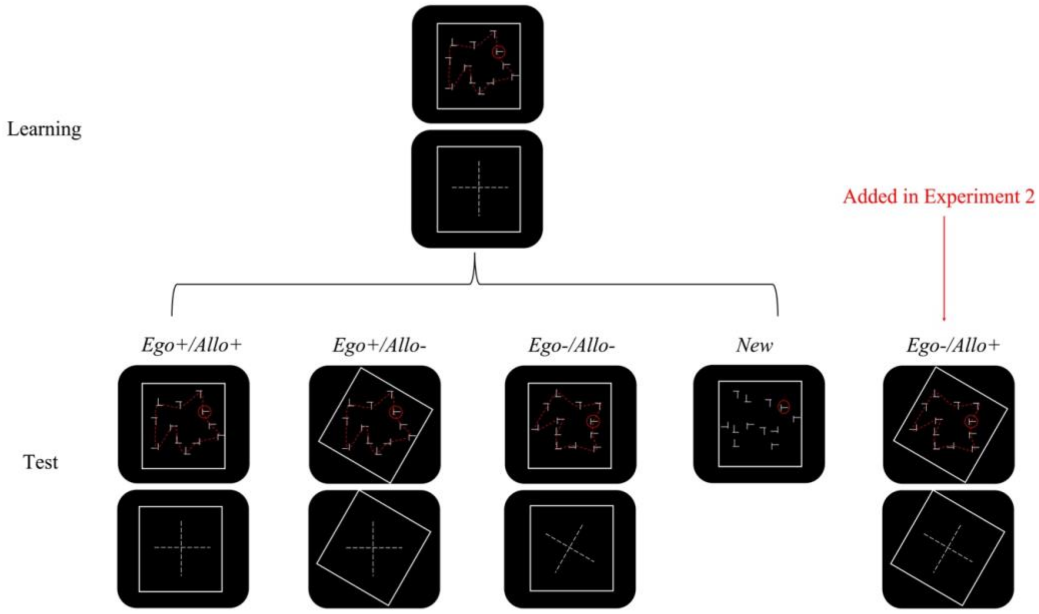

Figure 4.1. Schematic drawing of the configurations in Study III. A schematic drawing panel briefly describes the displays (the cross in the middle represents the search display's configuration relative to the learning phase). Configurations in the new condition were newly generated, so there is no schematic drawing for it. The rightmost column represents one condition newly added in Experiment 2. In the actual experiment, all dash lines and the schematic drawings were not visible. For details see the methods section.

Results

Learning phase

Although reaction times were the primary variable of interest, we first analyzed error rates and outlier rates (reaction times longer than three standard deviations above average and lower than 300 ms) to investigate potential speed-accuracy trade-offs. To increase statistical power, we aggregated every four consecutive blocks into a single epoch, resulting in five epochs overall. The alpha level was set at 0.05. If the main effect became significant, we ran additional post-hoc tests, the least significant differences (LSD), to compared data between each epoch. The mean error rate was 5.47 ± 2.44%. The one-way ANOVA showed that the error rate did not differ between epochs [F (4, 119) = 1.069, p = 0.375]. The outliers rate was 3.23 ± 2.49%, with a significant main effect of epoch [F (4, 119) = 4.160, p = 0.03]. Post-hoc LSD test showed that the outlier rate in the first epoch was significantly higher than outlier rates in the other four epochs (all ps < 0.003).

Error and outlier trials were excluded from the reaction times analysis. For reaction times, again, four blocks were aggregated into one epoch and the analysis procedure was identical to that for error rates and outlier rates. The one-way ANOVA yielded a significant main effect of epoch [F (4, 119) = 4.439, p = 0.02] due to reduced reaction times over epochs (RT_{epoch1} = 2899 ms, RT_{epoch5} = 2531 ms). Post-hoc LSD showed that the reaction times in the epoch1 was significantly higher than in the other four epochs (all ps < 0.05, except for p = 0.107 between epoch1 and epoch2).

Test Phase

One-way ANOVAs with configuration (*Ego+/Allo+*, *Ego+/Allo-*, *Ego-/Allo-*, *New*) were applied to error rates and outlier rates in test phase to rule out speed-accuracy trade-offs. The mean error rate was 2.86 ± 0.37%, and the outlier rate was 2.63 ± 0.48%. The one-way ANOVA revealed both measures did not differ between configurations [F (3, 92) = 0.97, p = 0.41 and F (3, 92) = 0.49, p = 0.69].

Error and outlier trials were excluded from the reaction time analysis. The repeated-measures ANOVA with configurations (*Ego+/Allo+*, *Ego+/Allo-*, *Ego-/Allo-*, *New*) and blocks (1-4) as factors was performed to investigate mean reaction times. The significant main effect of configuration [F (3, 69) = 9.5, p < .001, n_p^2 = 0.29] indicated reaction time differences between the four configurations, which will be further analyzed below. The significant main effect of block [F (3, 69) = 3.10, p = 0.032, n_p^2 = 0.12] reflected general learning in the test phase. The interaction between configuration and block was not significant [F (9, 207) = 0.73, p = 0.678].

To analyze the contextual cueing effect separately for the three repeated configurations (*Ego+/Allo+; Ego+/Allo-; Ego-/Allo-),* we respectively tested the difference between new and repeated displays (RT_{New} - $RT_{Repeated}$) versus zero by one-tailed paired samples T-tests. As shown in Table 4.1, contextual cueing effects were significant in all three repeated configuration conditions (see Figure 4.2).

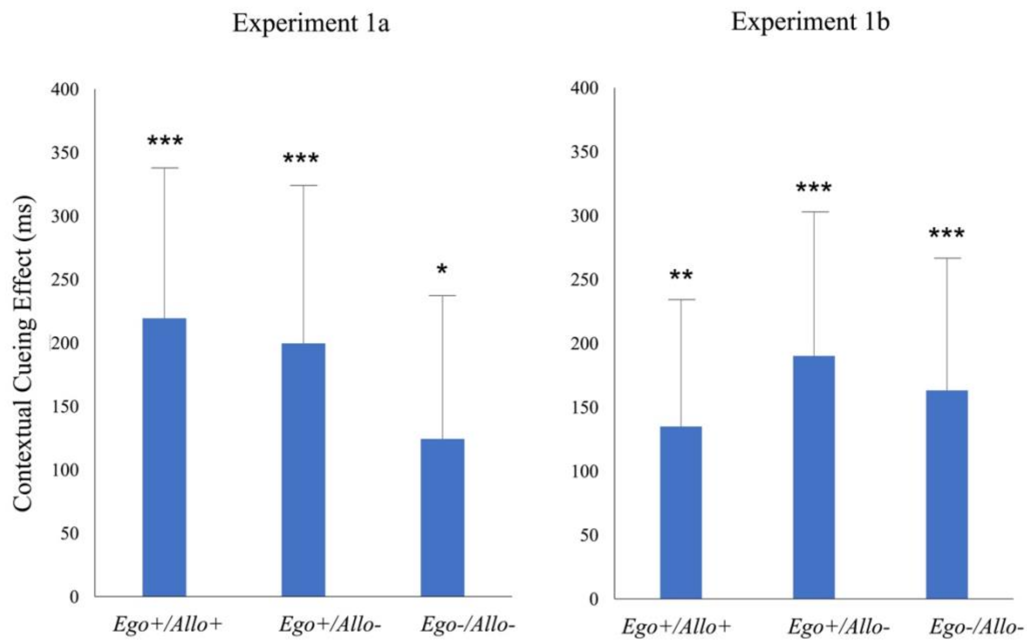

Figure 4.2. Contextual cueing in Experiment 1a and 1b of Study III. Significant differences revealed by pairwise comparisons of RT_{New} - $RT_{Repeated}$ versus zero are indicated by asterisks. Error bars represent SE of the mean. The statistical results are listed in Table 4.1.

Table 4.1. Comparisons between RT_{New} - $RT_{Repeated}$ versus zero in each configuration by one-tailed paired samples T-test.

	Configuration	*CCE(ms)*	*df*	*t*	*p*	*d*
EXP 1a	*Ego+/Allo+*	219	23	4.462	<.001	1.23
	Ego+/Allo-	199	23	4.262	<.001	1.29
	Ego-/Allo-	124	23	2.403	0.025	0.69
EXP 1b	*Ego+/Allo+*	134	24	3.331	0.003	0.95
	Ego+/Allo-	190	24	4.135	<.001	1.17
	Ego-/Allo-	163	24	3.867	<.001	1.10
EXP 2	*Ego+/Allo+*	150	28	4.384	<.001	1.15
	Ego+/Allo-	109	28	2.346	0.013	0.61
	Ego-/Allo-	12	28	0.226	0.416	0.05
	Ego-/Allo+	112	28	1.701	0.017	0.50

Reaction times were compared by two-tailed paired samples T-tests to investigate significant RT-differences. The T-tests showed no significant difference between the three repeated configuration conditions (Table 4.2). Furthermore, Bayesian paired samples T-tests were calculated for not significant contrasts to investigate equality of RTs between conditions. These tests yielded moderate evidence for the equality of *Ego+/Allo+* and *Ego+/Allo-*, i.e. the conditions that differed only in the validity of the allocentric cue, whereas they were close to 1 (equal probability of H0 and H1) for *Ego+/Allo+* and *Ego-/Allo-*, i.e. fully valid vs. invalid cues, and for *Ego+/Allo-* and *Ego-/Allo-*, i.e. conditions differing in the validity of the egocentric cue (Table 4.2).

Table 4.2. Reaction times comparisons (two-tailed paired samples T-test and Bayesian paired samples T-test) between configurations in the test phases of Experiment 1a, Experiment 1b, and Experiment 2.

	Configurations		***df***	***t***	***p***	***d***	**BF_{01}**
EXP 1a	*Ego+/Allo+*	*Ego+/Allo-*	23	0.528	0.603	0.03	4.104
		Ego-/Allo-	23	2.015	0.056	0.06	0.837
	Ego+/Allo-	*Ego-/Allo-*	23	1.923	0.067	0.26	0.966
EXP 1b	*Ego+/Allo+*	*Ego+/Allo-*	24	-1.505	0.145	0.14	1.753
		Ego-/Allo-	24	-0.675	0.506	0.66	3.855
	Ego+/Allo-	*Ego-/Allo-*	24	-0.621	0.54	0.07	3.978
EXP 2	*Ego+/Allo+*	*Ego+/Allo-*	28	1.168	0.253	0.11	2.733
		Ego-/Allo+	28	1.061	0.431	0.16	3.781
	Ego+/Allo -	*Ego-/Allo+*	28	-0.206	0.968	0.04	5.062
	Ego-/Allo-	*Ego-/Allo+*	28	1.537	0.051	0.22	4.948

4.4. Experiment 1b

In the 'Ego-/Allo-' configuration of Experiment 1a, the targets' absolute positions changed with the configuration's rotation, moving to a location where the target had not appeared during learning. Thus, this condition may have been more difficult than the other conditions in which target location probability may have contributed to learning. To address this issue, in Experiment 1b, we employed the same design as in Experiment

1a but with equal target location probability between locations (Geng & Behrmann, 2005; Jiang, Swallow, & Capistrano, 2013; Kabata & Matsumoto, 2012). Specifically, six target locations were drawn from the three outer imaginary concentric circles in the learning phase so that the polar angle between the two target positions on each circle was 30°. To keep the target location probabilities equal in the test phase, the rotated search displays were generated by 30° clockwise or counterclockwise rotation of one half each of the displays from the learning phase, see Figure 4.3 as an example.

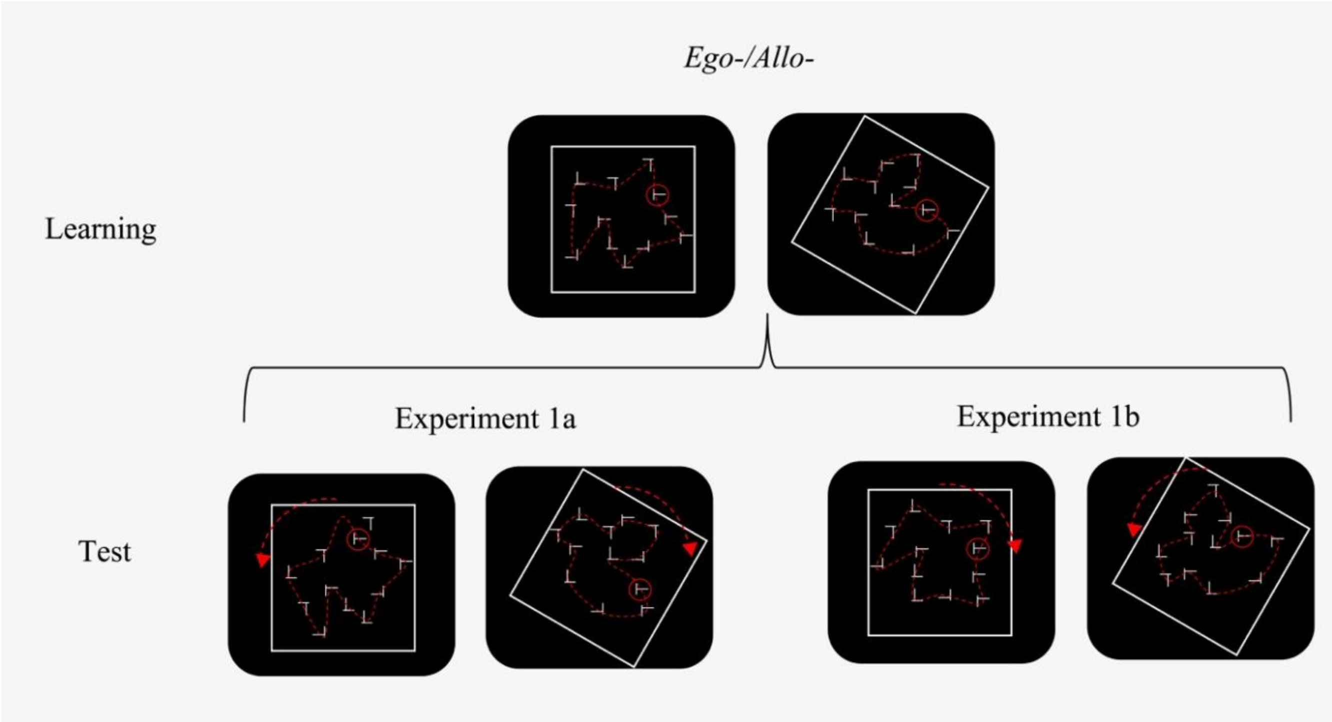

Figure 4.3. Difference between Experiment 1a and Experiment 1b in the 'Ego-/Allo-' condition of Study IIII. Experiment 1b, half of the target positions from the learning phase coincided with the other half of the target positions after rotation to remove the confound of unequal target location probabilities. In the actual experiment, the circle marking the target and the imaginary layout were not visible

Methods

Participants

Twenty-five young adults (sixteen females and nine males; mean age 20.3 ± 2.00 years) participated in Experiment 1b. All the participants had self-reported normal or corrected-to-normal vision. None of them had been tested in Experiment 1a. After they finished the experiment, they received a €7 payment or a one-hour study credit.

Stimuli

The apparatus and stimuli were identical to Experiment 1a.

Design

We employed the same design as in Experiment 1a, except that, in learning phase, twelve target locations were drawn from the three outer imaginary concentric circles and six of them coincided with the other half of the six target positions after rotation in the test phase, keeping target location probability constant (see Figure 4.3).

Results

Learning phase

Again, four blocks were aggregated into one epoch. The mean error rate was 5.00 ± 3.34%. The one-way ANOVA for the error rate showed a significant main effect of epoch [F (4, 120) = 5.393, p < .001]. The outlier rate was 3.67 ± 3.47%. The one-way ANOVA on outliers showed a significant main effect of epoch [F (4, 120) = 2.247, p < .001]. The post-hoc LSD tests showed that the outlier rates and error rates in epochs 1 and 2 were significantly higher than outlier rates and error rates in epochs 4 and 5 (all ps < 0.05, except for p = 0.058 for comparisons between error rates in epoch 2 and epoch 4).

Error and outlier trials were excluded from the reaction time analysis. The one-way ANOVA on reaction times yielded a significant main effect of epoch [F (4, 120) = 3.652, p = 0.008] due to the reduced reaction times over epochs (RT_{epoch1} = 2873 ms, RT_{epoch5} = 2391 ms). The post-hoc LSD showed that the reaction time in epoch 1 was significantly higher than in epochs 4 and 5 (ps < 0.05) but not significantly higher than epoch 2 (p = 0.333) and epoch 3 (p = 0.082).

Test phase

The mean error rate was 3.37 ± 0.24%. The one-way ANOVA revealed that it did not differ between configurations [F (3, 99) = 0.931, p = 0.43]. The outlier rate was 4.06 ±

1.49%. The significant main effect of configuration [F (3, 99) = 3.577, p = 0.02] indicated different outlier rates between the configurations. The post-hoc LSD showed the outlier rate in the New configuration was significantly higher than the three repeated configurations (all ps < 0.05). Error and outlier trials were excluded from the subsequent analysis for reaction times.

Again, a repeated-measures ANOVA with configurations (*Ego+/Allo+*, *Ego+/Allo-*, *Ego-/Allo-*, *New*) and blocks (1-4) as factors was performed to investigate mean reaction times. The significant main effect of configuration [F (3, 72) = 8.132, p < .001, n_p^2 = 0.253] indicated reaction time differences between the four configurations, which will be further analyzed below. The significant main effect of block [F (3, 72) = 4.486, p = 0.006, n_p^2 = 0.157] reflected general learning. The interaction between configuration and block was not significant [F (9, 216) = 0.825, p = 0.593].

The RTNew- RTRepeated differences in the three repeated configurations (*Ego+/Allo+; Ego+/Allo-; Ego-/Allo-*) were significantly higher than zero (Table 4.1), indicating significant contextual cueing in the three repeated configuration conditions (Figure 4.2).

We compared the potential difference of reaction times between the three configurations (*Ego+/Allo+; Ego+/Allo-; Ego-/Allo-*) with two-tailed paired samples T-tests. There were no significant differences. To further test for equality of reaction times between configurations, we calculated Bayesian paired samples T-tests. These tests yielded moderate evidence for the equality of *Ego+/Allo+* and *Ego-/Allo-*, differing in the validity of both cue types, of *Ego+/Allo-* and *Ego-/Allo-*, differing in the validity of the egocentric cue, and anecdotal evidence for the equality of *Ego+/Allo+* and *Ego+/Allo-*, differing in the validity of the allocentric cue (Table 4.2).

Interim discussion

The contribution of target location probability to search performance

Although the amount of contextual cueing effect in *Ego-/Allo-* configuration did not differ significantly between Experiment 1a and Experiment 1b (independent samples T-test: t (47) = 0.59, p = 0.56), we observed a numerically stronger contextual cueing effect in Experiment 1b (163ms) compared to Experiment 1a (124ms). We inferred that the weaker contextual cueing effect in Experiment 1a might have been due to the target appearing in low-probability locations after rotation. However, the weaker but still significant contextual cueing effect in the *Ego-/Allo-* condition of Experiment 1a indicated that a potential target location probability cueing effect was not sufficient to eliminate the contextual cueing effect.

Summary of the results of Experiment 1

Across Experiment 1a and Experiment 1b, we found that disrupting the allocentric and egocentric reference frames could not eliminate the search advantage for repeated displays. Specifically, we found that contextual cueing is preserved when a rotated external frame suggests that the search display is likewise rotated, but it is not (*Ego+/Allo-*). We even found contextual cueing when the learned display was rotated within the unchanged external frame, so that both configuration (*Ego-/Allo-*) and rotating only the frame (*Ego+/Allo-*) led to an imbalance of the validity of the egocentric and allocentric reference frames, in that the egocentric reference frame was valid in 50% of trials (two out of four conditions: *Ego+/Allo+* and *Ego+/Allo-*) whereas the allocentric reference frame was valid only in 25% of trials (the *Ego+/Allo+* condition). This may have led participants (incidentally) to ignore the frame orientation during the test phase. Instead, they may have used the display orientation itself as the allocentric reference, which would explain the intact contextual cueing effect in the *Ego-/Allo-* condition.

4.5. Experiment 2

The design of Experiment 1 was based on an interference logic - would invalid allocentric and egocentric reference frames eliminate contextual cueing? In contrast, Experiment 2 included a new condition in which the external frame and the display were rotated by the same angle, so that the changed allocentric RF was a valid predictor of the target location. This design change also removed a potential weakness of Experiment 1, namely the unequal validity between the egocentric and allocentric reference frames.

Methods

Participants

Thirty young adults (eighteen females and twelve males; mean age 21.46 ± 3.21 years) participated in Experiment 2. One participant's data were excluded because the error rate (16.88%) was higher than three deviations above the average (3.90%). None of them had participated in Experiment 1. All the participants had self-reported normal or corrected-to-normal vision. All of them provided written, informed consent to take part in the experiment. After they finished the task, they received an €8 payment or a 1-h study credit.

Stimuli

The apparatus, stimuli, and trial sequence were identical to those in Experiment 1b, except that the items' (T and Ls) were rotated along with the configuration, forming orientations of 30º, 120º, 210º, and 300º, in addition to the non-rotated orientations of 0º, 90º, 180º, and 270º.

Design

The design was identical to those in Experiment 1b, except that the *Ego-/Allo+* condition was newly added and the number of trials per condition was reduced to eight per block. In the *Ego-/Allo+* condition, the outer frames rotated along with the rotated search displays, making the changed allocentric reference frame a valid predictor of the target location (see Figure 4.1).

Results

Learning phase

The mean error rate was 3.32 ± 3.03%, and the mean outlier rate was 3.38 ± 4.36%. The one-way ANOVA yielded a significant main effect for both measures [error rate: F (4, 144) = 2.528, p = 0.043; outlier rate: F (4, 44) = 3.373, p = 0.011]. The post-hoc LSD tests showed that the error rate in the fifth epoch was significantly lower than error rates in the previous four epochs (all *ps* < 0.05), and the outlier rate in the first epoch was significantly higher than error rates in the other four epochs (all *ps* < 0.01).

Error and outlier trials were excluded from the reaction time analysis. The one-way ANOVA on reaction times yielded a significant main effect of epoch [F (4, 144) = 15.729, p < .001] due to the reduced reaction times over epochs (RT_{epoch1} = 2725ms, RT_{epoch5} = 1970ms). LSD showed that the reaction time in epoch 1 was significantly higher than in the other four epochs (all *ps* < 0.05).

Test phase

The mean error rate was 1.68 ± 0.76% and the mean outlier rate was 2.56 ± 0.84%. Both measures did not differ between configurations [F (4, 144) = 1.428, p = 0.228 and F (4, 144) = 2.325, p = 0.06, respectively].

The repeated-measures ANOVA with configurations (*Ego+/Allo+*, *Ego+/Allo-*, *Ego-/Allo-*, *Ego-/Allo+*, *New*) and blocks (1-4) as factors was performed to investigate mean reaction times. The significant main effect of configuration [F (3, 72) = 8.132, p < .001, n_p^2 = 0.253] indicated reaction times differences between the configurations, which will be further analyzed below. The significant main effect of block [F (3, 72) = 4.486, p = 0.006, n_p^2 = 0.157] reflected general learning. The interaction between configuration and block was not significant [F (9, 216) = 0.825, p = 0.593].

To analyze the contextual cueing effect separately for the four repeated configurations (*Ego+/Allo+; Ego+/Allo-; Ego-/Allo-; Ego-/Allo+*) yielded contextual cueing, we respectively compared the RT_{New} - $RT_{Repeated}$ versus zero contrast for the four repeated conditions. As the results of the one-tailed paired samples T-test (shown in Table 4.1), contextual cueing effects in the *Ego+/Allo+*, *Ego+/Allo-*, and *Ego-/Allo+* configurations were significant, but no significant contextual cueing was observed in the *Ego-/Allo-* configuration, i.e. the condition with both invalid egocentric and allocentric cues (see Figure 4.4).

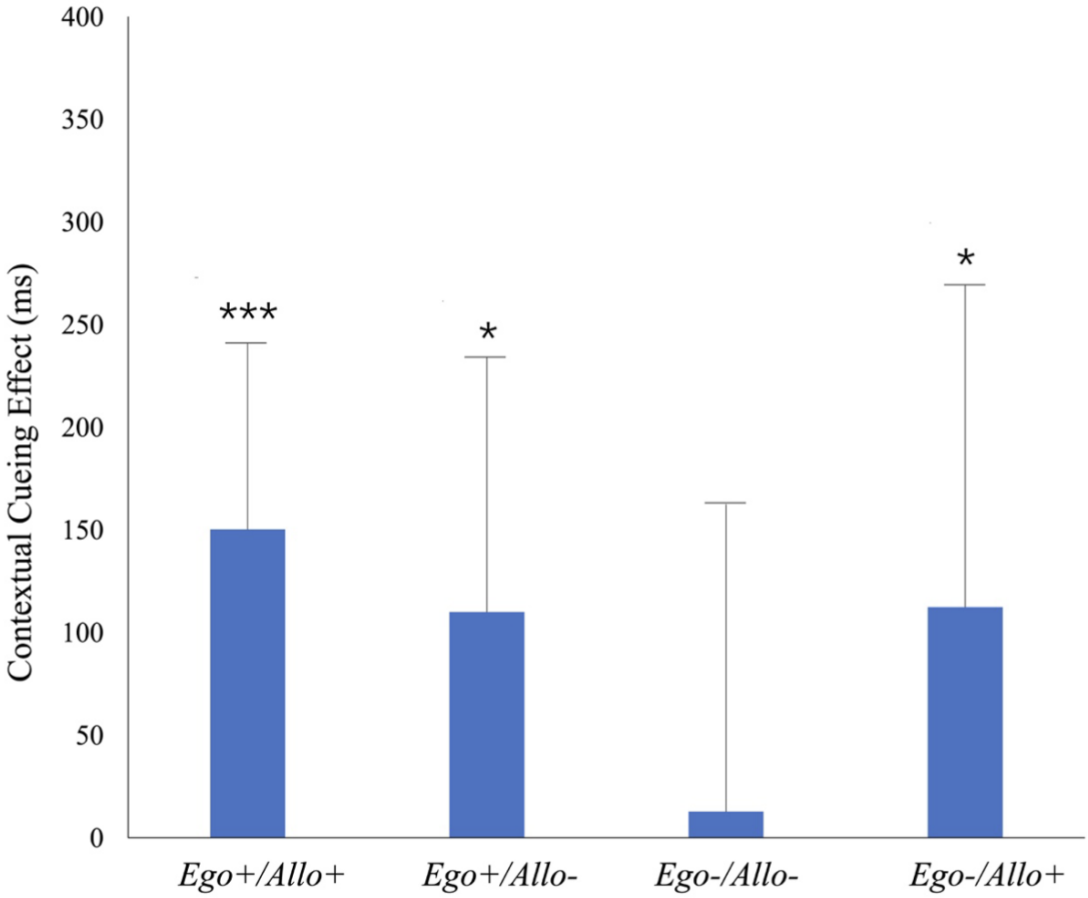

Figure 4.4 Contextual cueing in the test phase in Experiment 2 of Study III. Significant differences revealed by pairwise comparisons of RTNew - RTRepeated and zero are indicated by black asterisks. Error bars represent SE of the mean. The statistical results can be seen in Table 3.1.

We compared the reaction times between the four repeated conditions (*Ego+/Allo+; Ego+/Allo-; Ego-/Allo-; Ego-/Allo+*) by two-tailed paired samples T-tests (Table 4.2). Whereas the results indicated no significant difference between *Ego+/Allo+*, *Ego+/Allo-* and *Ego-/Allo+*, the search advantage for Ego-/Allo- was significantly lower than for *Ego+/Allo+* and *Ego+/Allo-*, and marginally lower than for *Ego-/Allo+*. Bayesian paired samples T-tests again investigated the equality of RTs in non-significant contrasts. Moderate evidence was yielded for the equalities of *Ego+/Allo+* and *Ego-/Allo+*, conditions differing in the egocentric cue validity, *Ego-/Allo-* and of *Ego-/Allo+*, differing in the validity of the allocentric cue, and of *Ego+/Allo-* and *Ego-/Allo+*, conditions with one valid and one invalid cue type. Anecdotal evidence for RT equality was observed for the *Ego+/Allo+* and *Ego+/Allo-* conditions, with valid egocentric cue, but differing in the validity of the allocentric cue.

Interim discussion

Again, we observed contextual cueing if at least one of the reference frames was preserved from training to test. However, in contrast to Experiment 1, no contextual cueing was observed when both reference frames yielded invalid predictions (*Ego-/Allo-*). This was expected if participants relied more on the external reference frame (and less on allocentric information from the search display itself) because of the frame's higher overall validity (Zang et al., 2018).

4.6. Discussion

The present study provides an initial exploration of the dependence of contextual cueing on egocentric and allocentric reference frames. In Experiment 1, we invalidated either the validity of an external reference frame alone or together with an additional invalidation of the egocentric reference frame. Both manipulations did not lead to significant reductions in the size of contextual cueing, compared with fully repeated display / frame combinations.

Experiment 1a might have been affected by a potential confound between contextual cueing and target location probability cueing (Geng & Behrmann, 2005; Jiang, Swallow, & Capistrano, 2013; Kabata & Matsumoto, 2012; Sisk et al., 2019), leading to potentially lower contextual cueing scores when the display was rotated (*Ego-/Allo-* condition, marginal difference between *Ego-/Allo-* and *Ego+/Allo+* conditions). However, when this confound was removed in Experiment 1b, no significant difference between the contextual cueing scores of *Ego-/Allo-* and *Ego+/Allo+* was observed, indicating that contextual cueing was obtained in spite of both reference frames being invalid predictors of the target location.

Experiment 1 investigated the contribution of egocentric and allocentric reference frames with an interference logic. We investigated if contextual cueing was reduced when either the external frame or the display itself was rotated, relative to fully repeated displays. However, this procedure may have led participants to ignore the external frame's orientation and focus on the display itself. This view is supported by similar results in previous experiments where only the search displays were repeated without an external frame and contextual cueing was observed in spite of display rotation (Jiang and Wagner, 2014; Zheng and Pollmann, 2019).

In Experiment 2, we introduced trials with a rotated external frame that validly predicted the target location, because we wanted to know if changes of the allocentric reference frame that were valid predictors of the target location could be used for contextual cueing. We observed comparable contextual cueing scores when either the allocentric or egocentric reference frame was valid, but the other was not, suggesting that both egocentric and allocentric reference frames could support contextual cueing. Of note, if only one reference frame was valid (*Ego+/Allo-* and *Ego-/Allo+*), numerically lower contextual cueing effects were observed than for fully repeated display (40ms and 37ms, respectively). It might be tempting to speculate if both RFs contribute jointly to contextual cueing. However, besides that these differences were not significant, to test this further, one would need to systematically vary the magnitude of rotation of the display and the external frame in order to see if this affects the size of the contextual cueing effect (Chua & Chun, 2003).

Strikingly, contextual cueing was abolished when both reference frames were invalid in Experiment 2 (*Ego-/Allo-*). Not surprisingly, the Bayesian paired samples T-tests provided moderate or anecdotal evidence for longer reaction times in the *Ego-/Allo-* condition than the other three repeated conditions (Rouder et al., 2009). This contrasted with a significant contextual cueing effect in the *Ego-/Allo-* condition in Experiment 1, which was of equal size with the *Ego+/Allo+* and *Ego+/Allo-* conditions. As mentioned, in Experiment 1, the allocentric reference frame had a low predictiveness of the target location and therefore might not have been used to retrieve memory traces of repeated displays. Apparently, the increased validity of the external reference frame prompted its use for search guidance in repeated displays (Zang et al., 2018). Note, this difference cannot be due to learning because the learning phases of Experiments 1 and 2 did not differ in validity. The different validities of the reference frames occurred only in the test phase. Therefore, the presence versus absence of contextual cueing when both reference frames were invalid must have been due to memory retrieval or search guidance processes rather than due to configuration learning. This emphasizes the importance to distinguish between learning and expression of learning in contextual cueing (Frensch et al., 1998; Manginelli, Baumgartner, et al., 2013; Manginelli, Langer, et al., 2013).

The term 'egocentric' or 'allocentric' has assumed a very general meaning (Klatzky, 1998; Wang, 2017) and was used here to manifest the relationship between items and observers and between items and landmarks (Andersen & Enriquez, 2006). Further research might specify the contribution of retinotopic or head-centered reference frames (Jiang and Swallow, 2013). In related work, the importance of a body-centered reference frame has been demonstrated in spatial priming (Ball et al., 2010) and of an anatomical reference frame in tactile contextual cuing (Assumpção et al., 2018). Future studies might also investigate three-dimensional reference frames (Issartel et al., 2016). Chua and Chun (2003) trained participants on a virtual 3-D display viewed from a single viewpoint but tested at various rotations away from the training viewpoint. The results showed search advantages for trained repeated displays decreased as the rotation angular from training viewpoint to testing viewpoint increased. It might be worthwhile to investigate if a valid external 3-dimensional reference frame could prevent this view-point dependent reduction of contextual cueing.

It might be argued that in contextual cueing, the display itself contains allocentric information, i.e., the spatial relations between search items (Ball et al., 2009). As mentioned, this may have contributed to the intact contextual cueing effect in the *Ego-/Allo-* condition of Experiment 1. However, we believe that we have shown in Experiment 2 that an external reference frame can influence contextual cueing independent of the spatial information that can be gained from the display itself. One difference between Experiment 1 and Experiment 2 was that in the latter, the search items orientations were rotated along with the whole display, which may have supported the coding of the relative spatial positions of display items, i.e., allocentric information. However, this seems not to have affected contextual cueing in any major way because these items' rotations occurred in the *Ego-/Allo-* and the *Ego-/Allo+* conditions, where we observed no contextual cueing in the former, but in the latter. Thus, the difference in contextual cueing between these conditions can only be due to the external frame validity.

It may also seem puzzling that the Ego+/Allo- condition led to solid contextual cueing in Experiment 1 and Experiment 2 alike. One could argue that contextual cueing should be reduced in Experiment 2 because the allocentric cue is overall more valid than in Experiment 1, so that if it is invalid, as in the *Ego+/Allo-* condition, it should interfere with efficient search guidance. Obviously, this was not the case, suggesting that either valid egocentric or allocentric cues alone are sufficient to guide search in repeated displays. Note that the size of contextual cueing was numerically smaller and more variable in the *Ego+/Allo-* and *Ego-/Allo+* conditions than in the fully repeated (*Ego+/Allo+*) displays. While these differences failed to be significant, they also failed to yield robust evidence for equal size of contextual cueing in the Bayes tests, particularly between the *Ego+/Allo+* and *Ego+/Allo-* conditions. Thus, there is tentative evidence for an interfering effect of misleading egocentric and allocentric cues. However, it remains a worthwhile question for future research why the interference of misleading cues is smaller than the benefit of valid cues.

Egocentric and allocentric processes have also been discussed in the larger domain of spatial memory. Some research indicates that the two reference frames act simultaneously in spatial memory (Avraamides & Kelly, 2008; McNamara, 2002; Mou et al., 2004; Waller & Hodgson, 2006). In other cases, knowledge for one reference frame is developed in the relative absence of the other (Issartel et al., 2016; Jiang & Swallow, 2013a; Jiang, Swallow, & Capistrano, 2013; Wang & Spelke, 2000). Our study contributes to this discussion in two ways: First, it provides evidence that the reference frames in spatial memory can be top-down modulated, implying the adoption of reference frames influenced by intent of the participants. That gives a possible explanation why Jiang et al. (2013) found that participants showed probability cueing, another form of incidental spatial learning, with the egocentric reference frame, but with the allocentric reference frame when they were explicitly told about the regularity of search displays. Second, our findings highlight the need for consideration of cue validity when investigating reference frames in spatial memory.

4.7. Conclusion

We investigated the contribution of egocentric and allocentric reference frames to contextual cueing. Learned combinations of display configurations and orientations of an external frame could be used flexibly, depending on their probability to predict the target location.

5. Summary and general conclusion

Existing literature indicates that the contextual cuing effect, marked by enhanced visual search performance resulting from the learned association between target locations and their visual context, is influenced by various factors, such as implicit learning, working memory, global repetition statistics, distractor properties, spatial factors, and human development (Goujon et al., 2015; Jiang & Sisk, 2019; Jiang et al., 2019; Sisk et al., 2019).

Building upon this foundation, this thesis undertakes a series of studies designed to systematically investigate and compare the impact of four distinct forms of information on contextual cueing. These include an examination of the global configuration of the search display, the specific individual locations of search items within the display, and the reference frames representing egocentric and allocentric perspectives. Through a rigorous exploration of these factors, this thesis aims to contribute valuable insights into the nuanced mechanisms underlying contextual cueing effect and their implications for our understanding of visual search processes.

5.1. Main findings of the experiments presented in this thesis

Study I demonstrated that the contextual cueing effect persisted when only the global configuration of the display, rather than the individual locations of the distractor items, was repeated. Meanwhile, the results revealed the persistence of contextual cueing when solely the individual locations of the distractor items were repeated, without replicating the exact configuration.

Study I provided the first evidence that these two spatial factors simultaneously contribute to contextual cueing. Previous research, using various experimental designs, underscored the significant role of spatial target-distractor relations and overall spatial configuration in contextual cueing respectively (Brady & Chun, 2007; Jiang & Wagner, 2004; Olson & Chun, 2002). However, a potential concern in drawing conclusions from previous studies is that participants might habituate to a specific type of display change, as observed in separate experiments. Therefore, in Study I, a within-subject design was implemented to introduce different variations in display configurations within the same experiment, where some displays retained the overall layout, while others preserved the individual locations. It concluded that both global configuration and individual locations can independently contribute to the facilitation of visual search through learned associations, and participants exhibited flexible utilization of these two types of information when simultaneously exposed to both changes.

In Study II, the experimental design from Study I was combined with eye-tracking analysis, revealing that fewer fixations and a lower scan pattern ratio were observed not only in fully repeated displays but also in partially repeated displays, where repeating the individual locations but disrupting the global configuration, or vice versa.

Consistent with previous studies, replicating partial display information provided a similar search advantage as fully repeated displays (Bergmann & Schubö, 2021; Song & Jiang, 2005; Jiang & Wagner, 2004; Zheng & Pollmann, 2019). However, in previous research, this search advantage was mainly reflected in participants' ability to find the target with fewer search response times. In Study II, eye movement analysis revealed that the increased search efficiency in both recombined and rotated displays was achieved by fewer fixations and the improved scan pattern ratio. This finding extends previous reports of more efficient eye movement patterns in fully repeated displays to displays that repeat only local or global spatial context (Brockmole & Henderson, 2006; Manginelli & Pollmann, 2009; Peterson & Kramer, 2001; Tseng & Li, 2004).

Furthermore, fixation density maps analysis revealed that fixation heatmaps of recombined and rotated displays were more similar to those of fully repeated displays than those of new displays. Notably, the high similarity in fixation density maps was absent between fully repeated displays and rotated displays but became evident when the rotated displays were back-rotated. This intriguing revelation underscores the presence of comparable scanpath patterns in both fully and partially repeated displays, implying a degree of adaptability in the oculomotor system to contextual cues of global configuration and individual locations.

Study III represents an initial exploration of the influence of reference frames on contextual cueing. Three experiments delved into two classic spatial reference frames: egocentric and allocentric reference frames (Forster et al., 2023; Mou & McNamara, 2002; Volcic & Kappers, 2008). The findings demonstrate contextual cueing effect was eliminated when both reference frames were invalid. This aligns with the concept that reference frames play a crucial role in determining where visual attention is allocated based on spatial memory when observers encounter a familiar scene (Kelly & McNamara, 2010; Shelton & McNamara, 2001; Wang, 2012). However, the observed contextual cueing effect persisted as long as one reference frame was predictive of the target location. This demonstrated that egocentric and allocentric reference frames can flexibly support contextual cueing as long as they contain valid information about the search goal.

The efficacy of reference frames in influencing search performance is contingent upon their validity. In the first experiment of Study III, there was an imbalance in the validity of egocentric and allocentric reference frames. Specifically, the egocentric reference frame was valid in 50% of trials, while the allocentric reference frame was valid in only 25% of trials. This discrepancy might have inadvertently caused participants to disregard the allocentric reference frame we established, potentially resorting to alternative references such as the display orientation itself. Consequently, when both the allocentric and egocentric reference frames were simultaneously diminished, the contextual cueing effect persisted, as observed in Experiment 1. This finding aligns with our previous research, where contextual cueing was observed despite display rotation when only the search displays were repeated without an external frame (Jiang and Wagner, 2004; Zheng and Pollmann, 2019), but it is inconsistent with the results of Chua and Chun (2003), who rotated the virtual 3-D display. However, in the second experiment, we established equal validity between the egocentric and allocentric reference frames. Here, we found that contextual cueing was eradicated when both egocentric and allocentric reference frames were invalid. The validity of display factors in influencing search guidance in repeated displays was also evidenced by the frequency of display repetition (Zang et al., 2018).

The probability of target T appearing at various locations was rigorously controlled in all experiments of the thesis, with the exception of experiment 1a in Study III. This was evident not only in maintaining the equidistance of target locations within the display across conditions but also in ensuring consistent probability probabilities of target locations between different conditions (Geng & Behrmann, 2005; Golan & Lamy, 2023; Jiang & Swallow, 2013a). To exclude the target probability cueing effect between conditions is not trivial. However, in Experiment 1a of Study 3, an imbalance in target locations between conditions introduced a confounding effect. Specifically, when the display was rotated, the target moved to a new location not belonging to the original target set, thereby leading to a reduction in the contextual cueing effect in this condition. However, in Experiment 1b, when this confound was eliminated, the contextual cueing effect in this condition showed a significant enhancement.

5.2. Conclusions

Extensive endeavors have been undertaken to expand our understanding of the diverse factors influencing spatial memory. Investigating these factors is crucial as it aids in elucidating the complex interplay of elements that shape spatial memory processes (Broadbent et al., 2004; Burgess, 2006; Burgess, 2008). The studies outlined in this thesis contribute to the exploration of the roles of four display features—namely, global and local information, as well as egocentric and allocentric reference frames—within a framework of a classic visual search task known as the contextual cueing paradigm.

Specifically, the elimination of either local or global spatial context from repeated search displays not only preserves search time facilitation but also results in fewer fixations and a more direct scan path to the target. Additionally, fixation distribution maps of recombined or rotated displays closely resemble the original displays compared to random new displays. However, this similarity in rotated displays is contingent on considering the rotation angle. Overall, the findings highlight the remarkably flexible utilization of the oculomotor system for efficient search in incompletely repeated displays.

Additionally, the investigation into the contribution of egocentric and allocentric reference frames to contextual cueing reveals that learned combinations of display configurations and orientations of an external frame can be flexibly employed. This adaptability is contingent on their probability of predicting the target location, showcasing the nuanced interplay between reference frames and contextual cueing effect.

6. References

Andersen, G. J., & Enriquez, A. (2006). Use of landmarks and allocentric reference frames for the control of locomotion. *Visual Cognition*, *13*, 119–128.

Annac, E., Manginelli, A. A., Pollmann, S., Shi, Z., Müller, H. J., & Geyer, T. (2013). Memory under pressure: Secondary-task effects on contextual cueing of visual search. *Journal of Vision*, *13*(13), 1-15.

Annac, E., Pointner, M., K., P. H., Müller, H. J., Zang, X., & Geyer, T. (2019). Recognition of incidentally learned visual search arrays is supported by fixational eye movements. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, *45*(12), 2147.

Armstrong, R. A. (2014). When to use the Bonferroni correction. *Ophthalmic and Physiological Optics*, *34*(5).

Assumpção, L., Shi, Z., Zang, X., Müller, H. J., & Geyer, T. (2018). Contextual cueing of tactile search is coded in an anatomical reference frame. *Journal of Experimental Psychology: Human Perception and Performance*, *44*(4), 566.

6. References

Avraamides, M. N., & Kelly, J. W. (2008). Multiple systems of spatial memory and action. *Cognitive processing*, *9*, 93–106.

Baker, C. I., Olson, C. R., & Behrmann, M. (2004). Role of attention and perceptual grouping in visual statistical learning. *Psychological Science*, *15*(7), 460-466.

Ball, K., Smith, D., Ellison, A., & Schenk, T. (2009). Both egocentric and allocentric cues support spatial priming in visual search. *Neuropsychologia*, *47*(6), 1585–1591.

Ball, K., Smith, D., Ellison, A., & Schenk, T. (2010). A body-centred frame of reference drives spatial priming in visual search. *Experimental Brain Research*, *204*, 585–594.

Beesley, T., Vadillo, M. A., Pearson, D., & Shanks, D. R. (2015). Pre-exposure of repeated search configurations facilitates subsequent contextual cuing of visual search. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, *41*(2), 348-362.

Bergmann, N., & Schubö, A. (2021). Local and global context repetitions in contextual cueing. *Journal of Vision*, *21*(10), 9-9.

Brady, T. F., & Chun, M. M. (2007). Spatial constraints on learning in visual search: modeling contextual cuing. *Journal of Experimental Psychology: Human Perception and Performance*, *33*(4), 798.

Broadbent, N., Squire, L. R., & Clark, R. E. (2004). Spatial memory, recognition memory, and the hippocampus. *Proceedings of the National Academy of Sciences*, *101*(40), 14515-14520.

Brockmole, J. R., Castelhano, M. S., & Henderson, J. M. (2006). Contextual cueing in naturalistic scenes: Global and local contexts. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, *32*(4), 699.

6. References

Brockmole, J. R., & Henderson, J. M. (2006). Recognition and attention guidance during contextual cueing in real-world scenes: Evidence from eye movements. *Quarterly journal of experimental psychology*, *59*(7), 1177-1187.

Brooks, D. I., Rasmussen, I. P., & Hollingworth, A. (2010). The nesting of search contexts within natural scenes: evidence from contextual cuing. *Journal of Experimental Psychology: Human Perception and Performance*, *36*(6), 1046-1048.

Burgess, N. (2006). Spatial memory: how egocentric and allocentric combine. *TRENDS in Cognitive Sciences*, *10*(12), 551-557.

Burgess, N. (2008). Spatial cognition and the brain. *Annals of the New York Academy of Sciences*, *1124*(1), 77-97.

Buschman, T. J., & Kastner., S. (2015). From behavior to neural dynamics: an integrated theory of attention. *Neuron*, *88*, 127–144.

Castelhano, M. S., & Henderson, J. M. (2007). Initial scene representations facilitate eye movement guidance in visual search. *Journal of Experimental Psychology: Human Perception and Performance*, *33*(4), 753.

Chelazzi, L., F. Marini, Pascucci, D., & Turatto., M. (2019). Getting rid of visual distractors: the why, when, how and where. *Current opinion in psychology*, *29*, 135–147.

Chen, D., & Hutchinson, J. B. (2019). What is memory-guided attention? How past experiences shape selective visuospatial attention in the present. *Processes of visuospatial attention and working memory*, *41*, 185-212.

6. References

Chua, K. P., & Chun, M. M. (2003). Implicit scene learning is viewpoint dependent. *Perception and psychophysics*, *65*, 72–80.

Chun, M. M. (2000). Contextual cueing of visual attention. *TRENDS in Cognitive Sciences*, *4*(5), 170-178.

Chun, M. M., & Jiang, Y. (1998). Contextual Cueing: Implicit Learning and Memory of Visual Context Guides Spatial Attention. *Visual Cognition*, *36*(1), 28-71.

Chun, M. M., & Jiang, Y. (1999). Top-down attentional guidance based on implicit learning of visual covariation. *Psychological Science*, *10*(4), 360-365.

Chun, M. M., & Jiang, Y. (2003). Implicit, long-term spatial contextual memory. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, *29*(2), 224.

Chun, M. M., & Nakayama, K. (2000). On the functional role of implicit visual memory for the adaptive deployment of attention across scenes. *Visual Cognition*, *7*(1-3), 65-81.

Chun, M. M., & Turk-Browne, N. B. (2008). Associative learning mechanisms in vision. *Visual memory*, 209-245.

Colagiuri, B., & Livesey, E. J. (2016). Contextual cuing as a form of nonconscious learning: Theoretical and empirical analysis in large and very large samples. *Psychonomic Bulletin and Review*, *23*(6), 1996-2009.

Damiano, C., & Walther, D. B. (2019). Distinct roles of eye movements during memory encoding and retrieval. *Cognition*, *184*, 119-129.

6. References

Driver, J. (2001). A selective review of selective attention research from the past century. *British Journal of Psychology*, *92*(1), 53-78.

Endo, N., & Takeda, Y. (2004). Selective learning of spatial configuration and object identity in visual search. *Perception and psychophysics*, *66*(2), 293-302.

Engelke, U., Liu, H., Wang, J., Le Callet, P., Heynderickx, I., Zepernick, H. J., & Maeder, A. (2012). Comparative study of fixation density maps. *IEEE Transactions on Image Processing*, *22*(3), 1121-1133.

Fischer, M., Moscovitch, M., & Alain, C. (2021). A systematic review and meta-analysis of memory-guided attention: Frontal and parietal activation suggests involvement of fronto-parietal networks. *Wiley Interdisciplinary Reviews: Cognitive Science*, *12*(1), e1546.

Fiser, J., & Aslin, R. N. (2005). Encoding multielement scenes: statistical learning of visual feature hierarchies. *Journal of Experimental Psychology: General*, *134*(4), 521-537.

Forster, P., Fiehler, K., & Karimpur, H. (2023). Egocentric cues influence the spatial memory of landmark configurations for memory-guided actions. *bioRxiv*, 2023:2023-2004.

Frensch, P. A., Lin, J., & Buchner, A. (1998). Learning vs. behavioral expression of the learned: the effects of a secondary tone-counting task on implicit learning in the serial reaction task. *Psychological Research*, *61*, 83–98.

Geng, J. J., & Behrmann, M. (2005). Spatial probability as an attentional cue in visual search. *Perception and psychophysics*, *67*, 1252–1268.

6. References

Geringswald, F., & Pollmann, S. (2015). Central and peripheral vision loss differentially affects contextual cueing in visual search. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, *41*(5), 1485.

Giesbrecht, B., Sy, J. L., & Guerin, S. A. (2013). Both memory and attention systems contribute to visual search for targets cued by implicitly learned context. *Vision research*, *85*, 80-89.

Golan, A., & Lamy, D. (2023). Attentional guidance by target-location probability cueing is largely inflexible, long-lasting, and distinct from inter-trial priming. *Journal of Experimental Psychology Learning Memory and Cognition*(x).

Goujon, A. (2011). Categorical implicit learning in real-world scenes: Evidence from contextual cueing. *Quarterly journal of experimental psychology*, *64*(5), 920-941.

Goujon, A., Didierjean, A., & Thorpe, S. (2015). Investigating implicit statistical learning mechanisms through contextual cueing. *TRENDS in Cognitive Sciences*, *19*(9), 524-533.

Harris, A. M., & Remington, R. W. (2017). Contextual cueing improves attentional guidance, even when guidance is supposedly optimal. *Journal of Experimental Psychology: Human Perception and Performance*, *43*(5), 926.

Harris, C. R., Millman, K. J., Van Der Walt, S. J., Gommers, R., Virtanen, P., Cournapeau, D., Wieser, E., Taylor, J., Berg, S., & Smith, N. J. (2020). Array programming with NumPy. *Nature*, *585*(7825), 357-362.

Henderson, J. M., & Hollingworth, A. (1999). High-level scene perception. *Annual review of psychology*, *50*(1).

6. References

Henderson, J. M., Williams, C. C., & Falk, R. J. (2005). Eye movements are functional during face learning. *Memory and cognition, 33*(1), 98-106.

Hirschstein, Z., & Aly, M. (2022). Long-term memory and working memory compete and cooperate to guide attention. *Attention, perception, and psychophysics*, 1-33.

Hodsoll, J. P., & Humphreys, G. W. (2005). Preview search and contextual cuing. *Journal of Experimental Psychology: Human Perception and Performance*, *31*(6), 1346.

Hollingworth, A. (2009). Two forms of scene memory guide visual search: Memory for scene context and memory for the binding of target object to scene location. *Visual Cognition*, *17*(1-2), 273-291.

Hout, M. C., & Goldinger, S. D. (2012). Incidental learning speeds visual search by lowering response thresholds, not by improving efficiency: evidence from eye movements. *Journal of Experimental Psychology: Human Perception and Performance*, *38*(1), 90.

Issartel, P., Besançon, L., Guéniat, F., Isenberg, T., & Ammi, M. (2016). Preference between allocentric and egocentric 3D manipulation in a locally coupled configuration. *in Proceedings of the 4th Symposium on Spatial User Interaction*, 79–88.

Itti, L., & Koch, C. (2001). Computational modelling of visual attention. *Nature reviews neuroscience*, *2*, 194–203.

Jiang, Y., & Chun, M. M. (2001). Selective attention modulates implicit learning. *The Quarterly Journal of Experimental Psychology: Section A*, *54*(4), 1105-1124.

Jiang, Y., Song, J. H., & Rigas, A. (2005). High-capacity spatial contextual memory. *Psychonomic Bulletin and Review*, *12*(3), 524-529.

6. References

Jiang, Y., & Wagner, L. C. (2004). What is learned in spatial contextual cuing—configuration or individual locations? *Perception and psychophysics*, *66*(3), 454-463.

Jiang, Y. V., Sigstad, H. M., & Swallow, K. M. (2013). The time course of attentional deployment in contextual cueing. *Psychonomic Bulletin and Review*, *20*, 282-288.

Jiang, Y.V., Sisk, C.A. (2019). Contextual Cueing. In: Pollmann, S. (ed) *Spatial Learning and Attention Guidance*. Neuromethods, vol 151. Humana, New York, NY. https://doi.org/10.1007/7657_2019_19

Jiang, Y. V., Sisk, C. A., & Toh, Y. N. (2019). Implicit guidance of attention in contextual cueing: Neuropsychological and developmental evidence. *Neuroscience and biobehavioral reviews*, *105*, 115-125.

Jiang, Y. V., & Swallow, K. M. (2013a). Body and head tilt reveals multiple frames of reference for spatial attention. *Journal of Vision*, *13*(13), 9-9.

Jiang, Y. V., & Swallow, K. M. (2013b). Spatial reference frame of incidentally learned attention. *Cognition*, *126*(3), 378-390.

Jiang, Y. V., Swallow, K. M., & Capistrano, C. G. (2013). Visual search and location probability learning from variable perspectives. *Journal of Vision*, *13*, 13-13.

Jiang, Y. V., Swallow, K. M., Rosenbaum, G. M., & Herzig, C. (2013). Rapid acquisition but slow extinction of an attentional bias in space. *Journal of Experimental Psychology: Human Perception and Performance*, *39*(1), 87-99.

Jiang, Y. V., Swallow, K. M., & Sun, L. (2014). Egocentric coding of space for incidentally learned attention: Effects of scene context and task instructions. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, *40*(1), 233.

Johnson, J. S., Woodman, G. F., Braun, E., & Luck, S. J. (2007). Implicit memory influences the allocation of attention in visual cortex. *Psychonomic Bulletin and Review*, *14*(5), 834-839.

Kabata, T., & Matsumoto, E. (2012). Cueing effects of target location probability and repetition. *Vision research*, *73*, 23–29.

Kasper, R. W. (2013). *Knowing where to look: The role of memory, attention, and response processes when implicitly learned context facilitates visual search.* [Doctoral dissertation, University of California].

Kasper, R. W., Grafton, S. T., Eckstein, M. P., & Giesbrecht, B. (2015). Multimodal neuroimaging evidence linking memory and attention systems during visual search cued by context. *Annals of the New York Academy of Sciences,*, *1339*(1), 176-189.

Kelly, J. W., & McNamara, T. P. (2010). Reference frames during the acquisition and development of spatial memories. *Cognition*, *116*(3), 409-420.

Klatzky, R. L. (1998). Allocentric and egocentric spatial representations: definitions, distinctions, and interconnections. *in Spatial Cognition (Berlin; Heidelberg: Springer)*, 1–17.

Kunar, M. A., Flusberg, S., Horowitz, T. S., & Wolfe, J. M. (2007). Does contextual cuing guide the deployment of attention? *Journal of Experimental Psychology: Human Perception and Performance*, *33*(4), 816-828.

6. References

Kunar, M. A., Flusberg, S. J., & Wolfe, J. M. (2006). Contextual cueing by global features. *Perception and psychophysics*, *68*(7), 1204-1216.

Kunar, M. A., John, R., & Sweetman, H. (2014). A configural dominant account of contextual cueing: Configural cues are stronger than colour cues. *Quarterly journal of experimental psychology*, *67*(7), 1366-1382.

Kunar, M. A., & Wolfe, J. M. (2008). Time to guide: Evidence for delayed attentional guidance in contextual cueing. *Visual Cognition*, *16*, 804–825.

Le-Hoa Võ, M., & Wolfe, J. M. (2015). The role of memory for visual search in scenes. *Annals of the New York Academy of Sciences*, *1339*(1), 72-81.

Makovski, T., & Jiang, Y. V. (2010). Contextual cost: When a visualsearch target is not where it should be. *The Quarterly journal of experimental psychology*, *63*, 216–225.

Manginelli, A. A., Baumgartner, F., & Pollmann, S. (2013). Dorsal and ventral working memory-related brain areas support distinct processes in contextual cueing. *Neuroimage*, *67*, 363-374.

Manginelli, A. A., Langer, N., Klose, D., & Pollmann, S. (2013). Contextual cueing under working memory load: Selective interference of visuospatial load with expression of learning. *Attention, perception, and psychophysics*, *75*, 1103-1117.

Manginelli, A. A., & Pollmann, S. (2009). Misleading contextual cues: How do they affect visual search? *Psychological Research*, *73*, 212–221.

McNamara, T. P. (2002). How are the locations of objects in the environment represented in memory? *in International Conference on Spatial Cognition (Berlin; Heidelberg: Springer)*, 174–191.

6. References

Miniaci, M. C., & De Leonibus, E. (2018). Missing the egocentric spatial reference: a blank on the map. *F1000 Res*.

Mou, W., & McNamara, T. P. (2002). Intrinsic frames of reference in spatial memory. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, *28*(1), 162-170.

Mou, W., McNamara, T. P., Valiquette, C. M., & Rump, B. (2004). Allocentric and egocentric updating of spatial memories. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, 30:142.

Neider, M. B., & Zelinsky, G. J. (2006). Scene context guides eye movements during visual search. *Vision research*, *46*(5), 614-621.

Noonan, M. P., Crittenden, B. M., Jensen, O., & Stokes, M. G. (2018). Selective inhibition of distracting input. *Behavioural Brain Research*, *355*, 36–47.

Ogawa, H., & Watanabe, K. (2010). Time to learn: Evidence for two types of attentional guidance in contextual cueing. *Perception*, *39*(1), 72-80.

Oliva, A., & Torralba, A. (2007). The role of context in object recognition. *TRENDS in Cognitive Sciences*, *11*(12), 520-527.

Olson, I. R., & Chun, M. M. (2002). Perceptual constraints on implicit learning of spatial context. *Visual Cognition*, *9*(3), 273-302.

Peterson, M. S., & Kramer, A. F. (2001). Attentional guidance of the eyes by contextual information and abrupt onsets. *Perception and psychophysics*, *63*(7), 1239-1249.

Pollmann, S. (2019). Working memory dependence of spatial contextual cueing for visual search. *British Journal of Psychology*, *110*(2), 372-380.

6. References

Pollmann, S., Eštočinová, J., Sommer, S., Chelazzi, L., & Zinke, W. (2016). Neural structures involved in visual search guidance by reward-enhanced contextual cueing of the target location. *Neuroimage*, *124*, 887-897.

Rouder, J. N., Speckman, P. L., Sun, D., Morey, R. D., & Iverson, G. (2009). Bayesian t-tests for accepting and rejecting the null hypothesis. *Psychonomic Bulletin and Review*, *16*, 225–237.

Salvucci, D. D. (2000). A model of eye movements and visual attention. *In Proceedings of the International Conference on Cognitive Modeling* (No. S 252, p. 259).

Schankin, A., Hagemann, D., & Schubö, A. (2011). Is contextual cueing more than the guidance of visual–spatial attention? *Biological Psychology*, *87*(1), 58-65.

Schankin, A., & Schubö, A. (2010). Contextual cueing effects despite spatially cued target locations. *Psychophysiology*, *47*(4), 717-727.

Schütz, A. C., Braun, D. I., & Gegenfurtner, K. R. (2011). Eye movements and perception: A selective review. *Journal of Vision*, *11*(5), 9-9.

Seitz, W., Zinchenko, A., Müller, H., & Geyer, T. (2023). Statistical learning in visual search:‘contextual cueing’reflects the acquisition of an optimal,‘one-for-all’oculomotor scanning strategy.

Sharifian, F., Contier, O., Preuschhof, C., & Pollmann, S. (2017). Reward modulation of contextual cueing: Repeated context overshadows repeated target location. *Attention, perception, and psychophysics*, *79*(7), 1871-1877.

Shelton, A. L., & McNamara, T. P. (2001). Visual memories from nonvisual experiences. *Psychological Science*, *12*(4), 343-347.

6. References

Shi, Z., Zang, X., Jia, L., Geyer, T., & üller, H. J. (2013). Transfer of contextual cueing in full-icon display remapping. *Journal of Vision*, *13*(3), 2-2.

Simons, D. J., & Rensink, R. A. (2005). Change blindness: past, present, and future. *TRENDS in Cognitive Sciences*, *9*(1), 16-20.

Sisk, C. A., Remington, R. W., & Jiang, Y. V. (2019). Mechanisms of contextual cueing: A tutorial review. *Attention, perception, and psychophysics*, *81*, 2571-2589.

Smith, C., Hopkins, R. O., & Squire, L. R. (2006). Experience-dependent eye movements, awareness, and hippocampus-dependent memory. *The Journal of Neuroscience*, 26(44), 11304-11312.

Smyth, A. C., & Shanks, D. R. (2008). Awareness in contextual cuing with extended and concurrent explicit tests. *Memory and cognition*, *36*(2), 403-415.

Song, J. H., & Jiang, Y. (2005). Connecting the past with the present: how do humans match an incoming visual display with visual memory? . *Journal of Vision*, *5*, 322-330.

Summerfield, J. J., Lepsien, J., Gitelman, D. R., Mesulam, M. M., & Nobre, A. C. (2006). Orienting attention based on long-term memory experience. *Neuron*, *49*(6), 905-916.

Tal, A., Bloch, A., Cohen-Dallal, H., Aviv, O., Schwizer Ashkenazi, S., Bar, M., & Vakil, E. (2021). Oculomotor anticipation reveals a multitude of learning processes underlying the serial reaction time task. *Scientific Reports*, *11*(1), 1-12.

Theeuwes, J., Bogaerts, L., & van Moorselaar, D. (2022). What to expect where and when: how statistical learning drives visual selection. *TRENDS in Cognitive Sciences*.

Tseng, Y. C., & Li, C. S. R. (2004). Oculomotor correlates of context-guided learning in visual search. *Perception and psychophysics*, *66*(8), 1363-1378.

Tseng, Y. C., & Lleras, A. (2013). Rewarding context accelerates implicit guidance in visual search. *Attention, perception, and psychophysics*, *75*(2), 287-298.

Tsuchiai, T., Matsumiya, K., Kuriki, I., & Shioiri, S. (2012). Implicit learning of viewpoint-independent spatial layouts *Frontiers in Psychology*, *3*, 207.

Turk-Browne, N. B., Junge, J., & Scholl, B. J. (2005). The automaticity of visual statistical learning. *Journal of Experimental Psychology: General*, *134*(4), 552-564.

Vadillo, M. A., Konstantinidis, E., & Shanks, D. R. (2016). Underpowered samples, false negatives, and unconscious learning. *Psychonomic Bulletin and Review*, *23*(1), 87-102.

van Asselen, M., Sampaio, J., Pina, A., & Castelo-Branco, M. (2011). Object based implicit contextual learning: A study of eye movements. *Attention, perception, and psychophysics*, *73*.

van der Heijden, A. H. (2003). Selective attention in vision. *Routledge*.

van Moorselaar, D., & Slagter, H. A. (2020). Inhibition in selective attention. *Annals of the New York Academy of Sciences*, *1464*(1), 204-221.

Volcic, R., & Kappers, A. M. L. (2008). Allocentric and egocentric reference frames in the processing of three-dimensional haptic space. *Experimental Brain Research*, *188*(2), 199-213.

Waller, D., & Hodgson, E. (2006). Transient and enduring spatial representations under disorientation and self-rotation. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, 32:867.

Wang, B., & Theeuwes, J. (2018). Statistical regularities modulate attentional capture. *Journal of Experimental Psychology: Human Perception and Performance*, *44*(1), 13.

6. References

Wang, C., Haponenko, H., Liu, X., Sun, H., & Zhao, G. (2019). How Attentional Guidance and Response Selection Boost Contextual Learning: Evidence from Eye Movement. *Advances in Cognitive Psychology*, *15*(4), 265.

Wang, R. F. (2012). Theories of spatial representations and reference frames: what can configuration errors tell us? *Psychonomic Bulletin and Review*, *19*(4), 575-587.

Wang, R. F. (2017). Spatial updating and common misinterpretations of spatial reference frames. *Spatial cognition and computation*, *17*, 222–249.

Wang, R. F., & Spelke, E. S. (2000). Updating egocentric representations in human navigation. *Cognition*, *77*, 215–250.

Watson, D. G., & Inglis, M. (2007). Eye movements and time-based selection: Where do the eyes go in preview search? *Psychonomic Bulletin and Review*, *14*(5), 852-857.

Westerberg, C. E., Miller, B. B., Reber, P. J., Cohen, N. J., & Paller, K. A. (2011). Neural correlates of contextual cueing are modulated by explicit learning. *Neuropsychologia*, *49*(12), 3439-3447.

Wetzels, R., Matzke, D., Lee, M. D., Rouder, J. N., Iverson, G. J., & Wagenmakers, E. J. (2011). Statistical evidence in experimental psychology: An empirical comparison using 855 t tests. *Perspectives on psychological science*, *6*(3), 291-298.

Wolfe, J. M. (2020). Visual search: How do we find what we are looking for? *Annual review of vision science*, *6*, 539-562.

Wolfe, J. M., & Horowitz, T. S. (2004). What attributes guide the deployment of visual attention and how do they do it? *Nature reviews neuroscience*, *5*(6), 495-501.

Zang, X., Geyer, T., Assumpção, L., Müller, H. J., & Shi, Z. (2016). From foreground to background: How task-neutral context influences contextual cueing of visual search. *Frontiers in Psychology, 7*, 852.

Zang, X., Jia, L., Müller, H. J., & Shi, Z. (2015). Invariant spatial context is learned but not retrieved in gaze-contingent tunnel-view search. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, *41*(3), 807.

Zang, X., Zinchenko, A., Jia, L., Assumpção, L., & Li, H. (2018). Global repetition influences contextual cueing. *Frontiers in Psychology*, *9*(402).

Zellin, M. (2013). *Implicit adaptation to change in memory-guided visual search* [Doctoral dissertation, lmu].

Zellin, M., von Mühlenen, A., Müller, H. J., & Conci, M. (2014). Long-term adaptation to change in implicit contextual learning. *Psychonomic Bulletin and Review*, *21*(4), 1073-1079.

Zhao, F., & Ren, Y. (2020). Revisiting contextual cueing effects: The role of perceptual processing. *Attention, perception, and psychophysics*, *82*(4), 1695-1709.

Zhao, G., Liu, Q., Jiao, J., Zhou, P., Li, H., & Sun, H. J. (2012). Dual-state modulation of the contextual cueing effect: Evidence from eye movement recordings. *Journal of Vision*, *12*(6), 11-11.

Zheng, L., & Pollmann, S. (2019). The contribution of spatial position and rotated global configuration to contextual cueing. *Attention, perception, and psychophysics*, *81*(8), 2590-2596.

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