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Surface structure and saccadic control

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SURFACE STRUCTURE AND SACCADIC CONTROL

by

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of the requirements for the Doctor of Philosophy
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CERTIFICATE OF APPROVAL

PH.D. THESIS

This is to certify that the Ph.D. thesis of

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has been approved by the Examining Committee for the thesis requirement for the Doctor of Philosophy degree in Psychology at the May 2018 graduation.

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ABSTRACT

Saccadic eye movements are guided by attention. Indeed, some saccade trajectory effects serve as an index the attentional strength of visual objects in the map of visual space used to plan a saccade. One approach to understanding saccade planning relies on simple tasks in sparse displays (containing a single target and distractor object) to develop neurophysiologically plausible models of saccade behavior. Under tightly controlled conditions, saccade trajectories can be well predicted by representing displays of objects with simple visual features and their relative salience.

But the world in which the saccade system typically operates is not sparse, and observer eye movements are guided by more than just salience. As such, another approach has been to examine saccadic behavior in complex scenes and complicated goals. Such scene context can drastically affect saccades in ways that are not well predicted by a context-free and expectation-free representation of visual salience.

This dissertation starts to bridge this gap between these literatures by focusing on object surfaces. Covert shifts of attention operate on representations informed not just by stimulus salience and location-based expectations, but also by the perceptual organization of object surfaces. Covert attention can be guided by surface context, such that targets and distractors are processed differently as a function of whether they are on the same or different surface. These effects are fragile, however, and have previously only been demonstrated in relatively engaging tasks and with strong perceptions of objecthood.

The present work tested the strength of the relationship between attention and saccades by testing whether surface context guides orienting eye movements. Observers made saccades to objects that could be organized with different surface structure. In four experiments (Chapters 2 and 3) I found no evidence that the saccade map encoded surface context. But in two experiments (Chapters 4 and 5) I demonstrate saccade trajectories are sensitive to surface context, independently of low or high task engagement. This demonstrates that object surface-based representations are not necessarily fragile and can affect the oculomotor map even for simple saccadic orienting for which the surface is task-irrelevant. This lends evidence to the theory that the nature of the representation of vision is one of object surfaces, and suggests that the strength of object encoding is stronger than has been previously demonstrated.

PUBLIC ABSTRACT

We tend to move our eyes to wherever we are paying attention. Frequently, where we look is consistent with a goal. Reading, driving, and even looking at a friend across the dinner table all involve the control of rapid eye movements – saccades – from one object to the next. Sometimes the eyes and attention can be "captured" by objects unrelated to the goal that distract us, such that our internal focus of attention moves to the distracting object and so, too, moves the saccade. Understanding how objects guide internal attentional processing and eye movement behaviors, particularly as it affects distraction, is theoretically important for understanding the relationship between attention and saccades, and understanding what kinds of stimuli are distracting and what aren't.

In most laboratories, experiments tend to use simple tasks in pared-down displays of a single target dot and a single target distractor. Under tightly controlled conditions, saccades can be well predicted simply by taking into account what the objects look like and what the task goal is. But the world in which the saccade system typically operates is not so simple. One difference is that objects in the world can appear on different surfaces: instead of two dots in empty space, a slightly more realistic scene would be two apples on a table. Decades of study have demonstrated that the surface structure of the world affects internal attentional processing. What is less understood is how this surface structure affects saccades. I tested whether that surface structure affects saccades. One hypothesis is that because saccades are closely linked to attention, they, too, will reflect object surface structure. The other hypothesis is that what is known about surface structure is largely due to contrived laboratory studies with complicated tasks that aren't as simple as moving one's eyes. As such, it is possible saccades will be insensitive to surface structure in the environment.

I measured the eye movements of human observers making saccades from the middle of a computer screen to a target dot elsewhere in the display. I manipulated where the distractor was, and also manipulated whether the target and distractor were on the same or different surface. Saccades were sensitive to the surface manipulation in 2 of these experiments. This suggests that surface structure, in addition to stimulus appearance and task goals, plays an important and under-studied role in saccades.

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1. INTRODUCTION

The visual world is comprised of richly structured scenes of complex objects. Imagine a relatively simple scene: a blue mug of coffee and a black notebook on a white desk. The image projected by this world on the retina of the eye is a two-dimensional mosaic of unorganized feature information: a straight edge between the black and white here, a region of blue there. Our perceptual experience, however, matches neither an array of meaningless conjunctions of features like orientation and color, nor partially-formed objects like a desk that happens to have mug- and notebook-shaped holes in it. Instead, what is perceptually experienced is a representation of object surfaces.

This parsing of the world into surfaces occurs – according to a prominent theory of vision based on decades of research – both involuntarily and at an early level in the visual system (He & Nakayama, 1994; Nakayama, He, & Shimojo, 1995). Surface-based representations are not only what is experienced phenomenologically; it is also a fundamentally a surface-based representation that is accessed by numerous visual tasks (Rensink & Enns, 1995; Behrmann, Zemel, & Mozer, 1998; Ernst, Palmer, & Boynton, 2012; Valdes-Sosa, Cobo, & Pinilla, 2000), even when surface organization of the scene is task irrelevant (Atchley, Kramer, Andersen, & Theeuwes, 1997b; Egly, Driver, & Rafal, 1994; He & Nakayama, 1992; Hollingworth, Maxcey-Richard, & Vecera, 2012).

Understanding the nature of visual representations is foundational to understanding what information is used and how when observers move and act in the world. A behavior frequently performed by humans and other animals is the *saccade* – a rapid, ballistic eye movement that rotates the eyes so that the high-resolution fovea is moved from one location in the visual environment to another. Saccades are frequently useful in performing goal-directed tasks that involve spatial scanning of the environment, such as visual search or reading. Sometimes the eyes move to items that capture attention in a way not aligned with task goals, in a phenomenon known as stimulus-based oculomotor *capture*.

The goal if this dissertation is to examine whether the visual coordinate system used to program a saccade is one that is informed by surface structure, or is invariant to surface structure.

In the sections below, I first review control of spatial attention, which is broadly conceptualized to fall under the integrated control of stimulus-based, goal-based, and probability-based processes. I then review the behavioral and neurophysiological literature on object-based and surface-based processing, with the specific aim of examining the evidence for surface-based encoding that is sufficiently early in the visual system to be expected to affect saccades.

Evidence from human behavioral research using manual responses suggests that object-based processing only arises under specific experimental conditions and tasks that require attentional selection and shifting throughout the display. But the neurophysiological literature suggests there is evidence for early modulation of visual stimulus-generated activation when that stimulus forms an object edge or falls within the boundaries of an object. This object-based encoding degrades over time. It is possible that surface-based effects will be more robust in saccade paradigms than manual response paradigms. Two seminal studies that find evidence for object-based processing in saccades during highly-engaged tasks in which object-based effects may be reflective of top-down or probability-based processes. I test two hypotheses: that the trajectories of saccades will reflect surface context and degree of task engagement.

Control of Spatial Attention: Stimulus, Goals, and History

Visual spatial attention allows for the selective processing of some visual information at one region while deprioritizing the processing of information at other locations (Carrasco, 2011). A mechanism for selective prioritization is necessary because the brain has a limited capacity to process the rich, continuous array of visual information it receives from the optic nerve (Desimone & Duncan, 1995). The fundamental question in spatial visual attention concerns the mechanisms that control what is selected next for processing. What controls where I am currently attending and where I attend next?

One useful and productive way to test theories of visual attentional processing has been to characterize attentional control as reflecting activity in a map of visual space. Seminal theories of attentional processing invoke an attentional map, e.g. the “master map of locations” of Feature Integration Theory (Treisman & Gelade, 1980) and the “activation map” of Guided Search (Wolfe, 1994). Visual items are represented at their corresponding locations in the map, and each item has a corresponding degree of activity that is high or low. These representations of items compete for attentional selection in a winner-take-all process, and the region of highest activity is what is selected by visual attention. Once selected, the basic features of the feature maps are available for report.

In these and other foundational characterizations of attention, attention has long been dichotomized as under the control of two independent processes: bottom-up or stimulus-based attention (in which attention is controlled by visual information in the scene), and top-down or goal-driven attention (in which attention is controlled by task goals). These two components are thought to both feed into a unified map that integrates over these sources of information and guides spatial attention. I review these components in the following sections.

Bottom-up contributions to the control of spatial attention

The focus of attention can be driven by feature information in the visual representation. A single bright item among item among darker items, or a vertical bar among horizontal bars, is physically *conspicuous* or *salient*: it is physically distinctive from other information in the scene and can "capture" spatial attention to the location of the conspicuous region. The goal of many saliency models is to understand what makes a region in an image salient to a human viewer, where 'salient' is typically operationalized as 'capturing spatial attention when the observer is freely viewing the image without a goal.' Models of salience are broadly consistent that a region is salient if it is sufficiently featurally different from its surroundings. Feature-based salience is the most extensively modelled mechanism of visual attention, and these models vary in instantiation but are generally predictive of first fixations in free viewing tasks (Borji, Sihite, & Itti, 2013).

Salience is based on the features of early vision, such as size and orientation, that are represented in the earliest representations of the visual world. Primary visual cortex (V1) is an anatomical map in retinotopic coordinates of neurons that each are selective for a specific feature dimension (e.g., bars oriented at zero degrees) in a specific receptive fields (region of visual space from which this neuron receives information; Engel, Glover, & Wandell, 1997; Hubel & Wiesel, 1968). In the instantiation of the seminal saliency model proposed by Itti & Koch (2000), all items produce local peaks of activity corresponding to their features and locations. Items that are featurally similar mutually inhibit each other, perhaps in a winner-take-all competition (Koch & Ullman, 1985). When no one item is featurally distinct, these featurally similar items have reduced activity and are less likely to be salient. When a conspicuous target is present among homogenous distractors, there is only mutual inhibition between the homogenous distractor items. As such, the conspicuous item's peak remains highly active and wins the competition for selection (i.e., is salient).

In functional theories like Guided Search that incorporate stimulus-driven factors into an overall activation map, the architecture is similar to the neurophysiologically plausible processes just described. The visual world is processed in parallel channels that code for specific features of early visual signals (e.g., color and orientation). For each channel, a feature is assigned a location on a functional map of the visual world, with each peak of activation corresponding to each item's location. The strength with which an each item's activity in this feature map is a function of the differences in its feature space (Duncan & Humphreys, 1989; Rosenholtz, Li, & Nakano, 2007), and within each map, activity is based on local (within-feature) differences such that the most active item is the most unusual in its channel. The information in these maps is fed forward to the activation map.

In sum, salience describes the component of visual attention that is based on stimulus features that exist early in the visual system. Salient items are conspicuous from featurally similar backgrounds that result in the "bottom-up" (stimulus-based) control of spatial attention. Salience is described as a mechanism for "bottom-up" control over visual attention because it is a consequence of the nature of the competitive representation in these early stages of vision that feeds forward to stages of attentional selection. Stimuli that are salient can produce shifts of attention that are also described in the literature as *exogenous orienting*: a stimulus-driven, involuntary, rapid covert or overt orienting response toward the salient region (Carrasco, 2011; Posner, 1980).

Top-down contributions to the control of spatial attention

If spatial attention was purely controlled by bottom-up salience, observers would constantly be shifting attention to the shiniest items in the room, from most to least salience. This is clearly not (always) the case because, typically, attention is not purely controlled by the features of the visual world around us. The control of attention can also be informed by task goals or knowledge. For example, one might be searching for the ketchup in a crowded refrigerator. Because the refrigerator is full of different colored objects, there is no one strong salient signal to guide you to your target. But knowing that ketchup is red allows for goal-driven knowledge to preferentially enhance the feature representation of “red” and suppress other colors. This re-weighting of features is integrated into the activity in the activation map, such that any peaks of activity in the activation map associated with “red” receive a biasing signal. Activity in these regions increases while the representations of other items undergo mutual inhibition, and the red item wins the competition for attentional selection.

Top-down control is imperfect. An item that is strongly bottom-up salient but not the target of the task can produce a higher peak of activity in the activation map than the task-relevant target. In this instance, the bottom-up salient distractor wins the competition in the attentional map and is the first item selected. This kind of selection has been described in the literature as *endogenous orienting*: a voluntary, sustained covert or overt orienting response toward the salient region (Carrasco, 2011; Posner, 1980).

The third component of visual attention: Selection history

Guided Search and similar functional models are successful in predicting visual search behavior as a function of bottom-up and top-down components in a variety of displays. Additional evidence has suggested the inclusion of a third component. Awh, Belopolsky, & Theeuwes (2012) characterized attention as operating over a *priority map*, and include selection history along with saliency- and goal-based processes. Selection history is incorporated as a unique term because items that have been selected often – perhaps because they have been associated with a reward (Anderson & Yantis, 2013; Bucker, Silvis, Donk, & Theeuwes, 2015) – continue to be selected more frequently than other items, even when they are neither salient nor relevant to the task goal.

To summarize, visual spatial attention can be characterized as operating over a priority map to which salience, task goals, and selection history independently contribute.

These signals are integrated to bias competition of items represented in the priority map to be selected for attentional processing.

Object surfaces are the units of attentional selection

In the previous section I reviewed that theories of visual attention posit that attention operates on a common attentional map, which integrates visual information, task goals, and selection history to produce peaks of activity that guide spatial attention. Evidence from covert visual search tasks suggest that the visual representation that informs search is sensitive to information beyond the basic features of vision. The nature of visual information accessed by seemingly early visual tasks, such as visual search, is not one of basic features and their retinal coordinates but one of object surfaces.

One impactful demonstration that attention selects objects, rather than an unbound collection of features, was in Duncan (1984). In this work, observers saw displays of an outline of a box that varied along two dimensions (size: large or small, and gap: on the left or right side of the box) and a line that varied along two dimensions (style: dotted or dashed, and orientation: tilted clockwise or counter-clockwise). The stimulus was briefly displayed then masked. Observers were to report the identities of two features. Some observers reported two features of the same object (e.g., the box) and other observers reported one feature from each of the objects (e.g., box's size and line's orientation). If attention accesses a representation that is based on stimulus features independently of object organization, then performance should not vary between whether observers were accessing two features of the same object versus two features of a different object. If, however, attention access a representation that is informed by the perceptual organization of features bound into objects, such that attention fundamentally selects objects and then accesses the features of that object, then there should be a performance benefit for reporting features from one object compared to two. Duncan found accuracy was higher for observers reporting features from the same object compared to different objects.

This suggests that the nature of what is selected is object-based, and that selection of an *object representation* allows improved access to the feature information that produce it relative to the same feature information distributed across two objects.

Similar object-dependent selection occurs in visual search. In visual search paradigms, many attention effects reflect a surface-dependent coordinate system. He & Nakayama (1992), for example, showed that visual search for a shape-defined target among similar distractors proceeded only after amodal surface completion (the representation of surfaces behind other occluding surfaces) occurred. It was concluded that surface completion occurred quickly and involuntarily because the task was designed such that performance would have been better if observers had been able to prevent surface information from guiding search (see also (Davis & Driver, 1994; Davis & Driver, 1998; Rensink & Enns, 1995). Based on similar effects to those of He and Nakayama, Enns and Rensink used the term "pre-emption" to refer to the fact that, at least for purposes of visual search, the representation of objects in a scene in terms of its surface content seems to pre-empt, or take precedence over, a representation of the scene in terms of features alone. As such, the visual representation that informs motion perception and visual search is not one of basic features: it is of rapidly perceptually organized object surfaces (He & Nakayama, 1992; 1994; Nakayama et al., 1995).

This longstanding theory of vision posits that surface-based information forms a critical intermediate stage of vision, closely following the immediate representation of visual features. Neurophysiological research has indicated that neurons in V1 – previously thought to be sensitive only to basic features – change their activity as a function of perceived surfaces, even those formed by illusory contours (Knierim & Van Essen, 1992; Roelfsema, Lamme, & Spekreijse, 1998). V1 activity modulation as a function of illusory contours can happen within 18-20 milliseconds after the initial response to the stimulus. In the language of maps, the earliest representations of basic visual features are followed by a representation of the scene into object surfaces. These object surfaces are instantiated within the attentional map that informs basic visual tasks.

Covert spatial attention is surface-dependent

In the map that guides spatial attention, attention *moves* to the highest peak first. These shifts in spatial attention from one location to another are highly sensitive to Euclidian spatial distance. Stimuli can be selected by their locations in the visual field (Eriksen & Hoffman, 1973; Posner, 1980). Spatial cueing paradigms consistently show evidence for spatially-dependent attentional selection, such that targets appearing closer to a cue are more quickly detected than targets that appear farther from the cue (Henderson & Macquistan, 1993; McCormick & Klein, 1990). This suggests that there is a gradient of spatial attention, such that items closest to the current focus of attention (or fixation) are preferentially processed compared to items farther away. Evidence also suggests that the map of spatial attention encodes stimulus information beyond simple features located at in retinotopic space. The spatial gradient of attention can be informed by the boundaries of object surfaces.

Objects can attract attention in a stimulus-driven manner (Chen, 2012). One elegant demonstration of this examined whether a task-irrelevant object informs spatial orienting (Kimchi, Yeshurun, & Cohen-Savransky, 2007). In their displays, observers were to report the color of a target rotated “L” shape that was identified by its location relative to an exogenous cue. The target appeared among eight other rotated L shapes of the same or different color. In the No-object condition (50% of trials), the target and distractors appeared at random locations in the display. In the Within-object condition (12.5% of trials), the target and three distractors were located and at orientations such that they appeared to form a square that included the target. In the Outside-object condition (37.5% of trials), a square was formed by four distractors and the target appeared outside of the square boundaries. Notice that the Within-object condition was infrequent so as to not produce an observer bias to orient toward the object. In each trial, observers were first told that the target would appear above, below, left, or right of the cue. The targets and distractors were then displayed for 0-500 ms, followed by the onset of an asterisk (exogenous cue) from which observers would report the color of the L that appeared above, below, left, or right of it. If spatial attention is invariant to the perceptual organization of objects, then the object condition should not affect responses. However, manual response times indicated object-based costs and benefits. RTs were fastest when the target formed part of the object, slowest when it was outside of the object boundaries, and intermediate in the No-object condition.

This suggests attention is pre-allocated to objects in a manner that benefits processing of the elements in that object, or produces costs for elements outside that object. Because the object was task-irrelevant, the authors interpreted this to suggest that the perceptual organization of the square was bottom-up salient and produced an exogenous covert orienting response. Some models of saliency have begun to incorporate objects. For example, in one computationally implemented model, neurons extract border ownership to form a perceptional organization of objects and their figure-ground assignments (Russell, Mihalaş, Heydt, Niebur, & Etienne-Cummings, 2014).

Additional experiments using spatial cueing paradigms, in which observers are cued to a likely location of a target, exhibit findings consistent with the hypothesis that the coordinate system of spatial attention is surface dependent even when the surface organization of the scene is task irrelevant (Atchley et al., 1997b; Egly et al., 1994; He & Nakayama, 1992; Hollingworth et al., 2012). In Egly, Driver, & Rafal (1994), two unfilled rectangles were displayed on either side of fixation such that the four ends of the rectangles were arranged in a square with all items equidistant from fixation. One end of one of the rectangles briefly brightened in luminance to serve as a spatial cue. Then, four items (one target and three distractors) appeared in the four corners of the display and observers were to quickly respond to the presence of a target gray square. On 75% of trials, the cue was valid: the target appeared in the cued region. On the remaining 25% of trials, the cue was invalid such that the target appeared at another location. On half of these invalid trials the target appeared on the other end of the cued end of the rectangle (invalid same object), and on the other half the target appeared at the location equidistant from the cue but in the other rectangle (invalid different object).

Note that the rectangles themselves are not relevant to task performance, and thus if attention operated on a spatial map invariant to object based coordinates, performance should be equally slow at both the invalid locations compared to the valid location. But responses were significantly slower when the target appeared in an invalid location in the different object compared to an invalid location in the same object. This finding suggests object-based representations inform the simple covert orienting of spatial attention even when these object surfaces are task irrelevant, and even when they are partially occluded such that their boundaries are informed by amodal completion (Moore & Fulton, 2005; Moore, Yantis, & Vaughan, 1998).

There is also evidence that surface context affects distractor processing in a variant of search called the additional singleton paradigm. I will first describe the paradigm generally.

In the additional singleton paradigm, observers select a typically shape-defined target (e.g., circle) from among numerous distractors of a different shape (e.g., diamond), one of which could be a salient color singleton distractor (red among green). Observers report the identity of a feature such as a horizontally or vertically oriented bar inside the target. The typical finding is that manual response times are slower in the presence compared to absence of this color singleton, and that this manual RT cost is reduced when the distractors are featurally heterogeneous (Bacon & Egeth, 1994; Theeuwes, 1992; Theeuwes & Godljn, 2002). Eye movement recordings of observers doing this task can show reduced rates of oculomotor capture by the singleton as a function of heterogeneity in the search array (Theeuwes, De Vries, & Godijn, 2003), suggesting that at least one of the mechanisms underlying the manual RT cost in the presence of a singleton is that spatial attention moves toward the distractor singleton.

Vatterott & Vecera (2015) examined whether spatial attention can be figured using location-based cues or surface structure. In their design, observers were given a Location Cue (arrows pointing to four of the eight items in the array) or a Surface Cue (defined by the "cross" or "table" object which bounded four items) that accurately cued the four potential locations of the shape-defined target. The question is whether activity in the attentional map can be configured using spatial information, object information, or both, such that this information would mitigate singleton-related manual RT slowing. A color singleton could be absent, present on the Cued region, or present on the Uncued region. Their findings were that in the Location Cue condition, the singleton produced a manual RT cost regardless of whether it was at a Cued or Uncued location. Critically, in the Surface conditions, the singleton-related manual RT cost was present when the singleton was on the same object as the target, but absent when the same singleton was on a different object. This suggests that object structure can mitigate distractor-related activity when location information cannot, and suggests that surface structure can reduce the distracting effect of a salient singleton distractor.

Mechanisms of surface-based effects in covert spatial attention

The mechanisms proposed to underlie object surface-based processing effects include *attentional spreading*, *attentional prioritization*, and *attentional switching*. Because they are not mutually exclusive, and because object-based processing in saccades has not been studied so thoroughly, it is difficult to *a priori* develop stringent hypotheses about saccade behavior as a function of object surfaces. Nonetheless it is worth briefly describing theoretical development concerning the mechanisms of object-based processing.

The *attentional spreading* view proposes a sensory modulation of stimuli and features on surfaces, such that attention spreads throughout an attended object such that the rate and efficiency of perceptual processing of items within the object boundaries occur (Egly et al., 1994; Vecera, 1994). In one demonstration of this, a modified version of the Egly paradigm demonstrated that spatial attention spread within a gradient conformed by object boundaries, such that perceptual sensitivity to items within that object was enhanced compared to items equidistant from the cue but in another object (Hollingworth et al., 2012). Within-object items gain an enhanced perceptual (bottom-up) representation compared to outside-object items (Shomstein & Yantis, 2002). This representational enhancement could feed forward to the priority map, and bias the activity of the distractor such that its activity is increased when it is on a relevant surface and suppressed when on an irrelevant surface.

Another possible mechanism is attentional prioritization of on-surface items (Yantis & Johnson, 1990). Under this view, items on an attended surface do not necessarily have an enhanced *perceptual* representation, but receive top-down attentional priority and are more likely to be selected by attention relative to items on the unattended surface (Behrman, Zemel, & Mozer, 1998; Watson & Kramer, 1999). Here, the priority map activity representing targets and distractors could be scaled by top-down modulation and thus be selected more frequently as a potential saccade target.

Finally, object-based effects might arise due to differential costs of *attentional shifting* between rather than within objects (Brown & Denney, 2007; Lamy & Egeth, 2002). Brown and Denney (2007) found evidence that objects are “sticky”: it took observers longer to disengage attention from an attended object compared to when attention did not have to disengage from an object. If attentional shifting is a mechanism that drives object-based effects in manual responses and in saccades, it is possible that targets and distractors might not be more or less representationally active in the priority map as a function of surface context, but that saccade latencies will differ depending on whether disengagement from one object must occur to saccade to the target.

Covert object-based effects require attentional engagement and time

Object-based effects generally obtain when the task requires a high degree of engagement with the display (for review, see Chen, 2012). Engagement has no formal definition in this review but is broadly considered to relate to attentional selection and re-orienting throughout the display (such as needing to select a target among distractors based on its features). There is evidence to suggest that greater engagement is necessary for object-based effects. More specifically, object effects occur when an observer is less rather than more certain about the target position (Shomstein & Yantis, 2002; but see Chen & Cave, 2006), when an observer must adopt a broad rather than localized spatial attentional window (e.g., Lavie & Driver, 1996; Shomstein & Yantis, 2002), and when spatial re-orienting is required (e.g., Brown & Denney, 2007; Lamy & Egeth, 2002).

Although "engagement" has not been formally defined in the context of object-based effects, a broader engagement-like framework of the control of spatial attention has been proposed (Wilder, Mozer, & Wickens, 2009; 2011). In this framework, the current locus of attention is under the control of an interaction between task specificity and contextual scale. Task specificity refers to the degree to which attentional control is reliant on goals, and contextual scale refers to the scale with which the visual scene is processed.

Effects of object-based attention can perhaps be formalized similarly: object-based processing arises from a two-dimensional space of object encoding duration (brief, extended) and engagement with the display (low, high).

Pragmatically, this suggests that evidence of object surface-based processing in saccades will be more probable in a task that incorporates a degree of positional uncertainty and encourages observers to adopt a broad focus of attention across the display. (Saccades necessarily involve a shift of attention and as such that precondition is met.) Theoretically, however, the question of why engagement may be a precondition to object-based effects is worth unpacking. There are multiple reasons that high-engagement tasks are more likely to produce object-based effects. High engagement tasks tend to be difficult (i.e., demand greater attentional resources overall), and may require searching throughout the display (attentional selection and switching, including perhaps attentional selection of the object surface itself), which may take time (producing a longer exposure time to the object surfaces). Is it possible that merely prolonged exposure to object surfaces is sufficient for object-based effects?

Multiple experiments, typically using spatial cueing and flanker paradigms, indicate that it takes more rather than less time to establish a representational object sufficient to drive object-based processing. Chen & Cave (2008), for example, demonstrated object-based processing when the stimulus display was present for 1,005 ms prior to the onset of the cue, but found no evidence of object-based processing when this duration was 120 ms. Similar investigations have found evidence of object-based processing for longer rather than shorter display durations (e.g, Avrahami, 1999; Law & Abrams, 2002). However, Duncan's (1984) work presented objects for just 50 ms and observers exhibited object-based selection. As such, display time per se is unlikely to be the sole determinant of object-based effects. It is more likely that object-based representations depend on a minimum exposure time, engagement, and the "goodness" of the object representation (e.g., uniform connectedness, closed boundaries; see Chen, 2012 for review).

Because of the wide variability of shorter to longer exposure times that have produced evidence of object-based processing in behavioral paradigms, it seems likely that it is the greater engagement with the display, rather than exposure time, is critical to demonstrate object-based processing. This is an open question, however, the answer to which is difficult to determine with human manual RTs. Object-based information could enter at any stage or component prior to the execution of a manual response – i.e., the initial neural response to stimulus onset, processing of the display, response selection, response latency, and movement time. Object-based processing could arise early in the feed-forward response to the visual stimuli, and the strength of the object surfaces might accumulate over extended exposure duration, such that object-based effects are a consequence purely of visual information. Alternatively, object effects might arise later in the system if engagement with the display promotes attentional processing of the object surface in a way that changes response selection.

A better way to answer the question of the timecourse of object-based encoding is with neurophysiological research, which I review below. By way of preview, neurophysiological evidence from macaques indicates that object contour information is encoded rapidly and early in the visual system, in tasks that do not require processing of or responding to the object contours. This suggests a potential for object-based effects to arise in relatively reflexive saccades.

Early encoding of object contours and surfaces in early visual cortex

Neurophysiological research on object-based modulation suggests rapid encoding (or extraction) of context and object contours in the visual system, and that edges are particularly active in the early visual system. Specifically, stimuli within a V1 cell's classical receptive field (RF) provokes activity, and this activity changes as a function of the object contour information surrounding that stimulus – i.e., outside that cell's RF. In macaque V1 neurons selective for a given orientation, the firing rate of these neurons is modified by the presence of other oriented bars outside this RF (Knierim & Van Essen, 1992). Contextual modulation happens quickly: after an initial response latency of 40 ms to the onset of the display, context-based modulation occurs within the next 18-20 ms. Similar logic has examined modulation to object surface edges. V1 cells also change their firing rates as a function of whether they are an edge of an object for texture- and contrast-defined objects (Lee, Mumford, Romero, & Lamme, 1998; Zhou, Friedman, & Heydt, 2000). In both of these studies, firing rates increased when the RF contained an edge that was part of an object (e.g., an edge of a square) compared to when the edge was not part of a square. This modulation occurred 20-30 ms after the initial onset-related activity and peaked with a mean normalized firing rate of 30 (normalized relative to base firing rate).

Lee and colleagues presented an additional manipulation that placed the cell's RF in the middle of an object to test whether its firing rate for a stimulus in its RF would change simply by being within the boundaries of an object. In this condition, object-based modulation was present but substantially slower and lesser relative to the object-edge modulation: about 50 ms after the onset-related response, a neuron inside an object boundary fired at 15 times the normal firing rate, compared to 12 when the neuron was outside the object surface. Similar findings have been obtained when macaques performed a curve-tracing saccade task, such that the firing rate of a neuron whose RF was at a line segment was affected as a function of whether the RF was on the target or distractor line (Roelfsema et al., 1998). The modulation was modest, with approximately a difference of about 20 spikes-per-second between the on-target and on-distractor surface conditions, and arose approximately 200 ms after the initial stimulus onset response. Such modulation occurs in macaques performing tasks that are independent of the surface context (e.g., a fixation monitoring task), and as such this modulation is unlikely to be due to any top-down task-driven expectation. Surface-based modulation in these experiments declines over time, such that the differential firing between on-surface and off-surface conditions is absent after 200 ms following stimulus onset.

This early contour- and surface-based modulation of information in the visual system is consistent with multiple bottom-up and top-down mechanisms (note that both could occur in the same system). For both mechanisms, the system at some point extracts relevant cues, such as occlusion features and contour shape. What differs is how the extraction occurs. In bottom-up models, information proceeds in stages of increasing complexity. At each stage, outputs are integrated, and object contour signals emerge and are fed forward in the system. In top-down feedback models, ambiguous low-level information is fed forward to a higher level at which occlusion features and contour shape are present. This information is integrated and then contour information is fed back to earlier stages. There is some evidence in favor of bottom-up models for border ownership encoding in V1, V2, and V3: in the context-based modulation of activity did not sharpen over time, as would be expected with feedback models (Zhou et al., 2000).

To summarize, neurophysiological evidence from macaques indicates neurons in V1 and other early areas quickly and strongly increase firing rates when the neuron lies on an object's edge, and that neurons also increase firing rates when the neuron is within an object boundary. Neural signatures of object surface-based information arise early in the visual stream.

The visual information fed forward to the saccade-planning regions in the frontal eye fields is likely to have information about the object surface on which a stimulus appears. Why, then, is exposure duration insufficient to promote object-based processing that affects manual RTs? It is possible that surface-based information is only weakly retained in the system initially, and this signal degrades over time or at each stage of processing. Engagement may promote re-processing of the display or attention to the surface, which may retain or increase the object surface-based activity in the map of visual space accessed for a manual or saccadic response. If this is true, it is possible that the fragility of surface-based effects in manual responses has more to do with degradation of the strength of the object-based encoding in the visual signal than engagement per se, and that accessing the visual signal more quickly would be more likely to find object-based effects independently of engagement. Alternatively, it is possible that saccadic tasks, like manual response tasks, require high engagement to demonstrate object-based processing.

Interim Summary

Evidence from visual search and spatial cueing paradigms suggest that the priority map that informs visual attention also represents object surface information, such that the coordinate system of the priority map that guides covert shifts of spatial attention is dependent on object surfaces. One consequence of this is that the distracting effect produced by potentially distracting items is contingent on the object surfaces on which the target and distracting item appear. The instantiation of this surface information seems to occur in the visual representation of the world independently of top-down goals. Objects inform bottom-up processing of salience and can produce or inform exogenous shifts of attention, but these effects may only arise under conditions of high engagement. Neurophysiological evidence, however, suggests an early encoding of object edges and surfaces in the visual system. This suggests an early source of object information that could contribute to saccades.

The following sections overview the theoretical links between covert attention and saccades, and the existing work on surface-based effects in saccade programming.

Saccades and the Premotor Theory of Visual Attention

Overt and covert spatial attentional control are closely related. Early versions of the "premotor theory of attention" Sheliga, Riggio, & Rizzolatti (1994) suggested that a shift of covert spatial attention was simply an unexecuted saccade. This theory was built on a large body of evidence of tight links between covert and overt attention. For example, the execution of a target-directed saccade is preceded by a complementary shift of covert spatial attention to that location (see e.g., Zhao, Gersch, Schnitzer, Dosher, & Kowler, 2012). That an overt shift of spatial attention relies on a shift of covert spatial attention suggests that the priority map that informs covert spatial attention also informs saccades. For example, distracting items can produce attentional capture which can result in manual response time effects and saccade landing position effects (Hunt, Mühlenen, & Kingstone, 2007). In turn, this suggests that saccades, like covert attention, may be controlled within surface-based representations.

Like theories of covert attention, theories of saccade programming also rely on studying the consequences of distractors in the presence of a saccade target. Saccades to targets can be affected by non-target information in the scene in multiple ways. For example, the presence of a salient distractor can cause a saccade's trajectory to curve along its path toward (McPeek, Han, & Keller, 2003) or away from (Sheliga, Riggio, & Rizzolatti, 1994) the distractor, even if the saccade eventually lands on the target. Saccades can also miss the target and instead land at a point in between the target and distractor, an effect known variously as a *center-of gravity* effect (Coren & Hoenig, 1972) or a *global* effect (Findlay, 1982a). In the case of full oculomotor capture, a saccade can fail to ever land on the desired target and instead land on the distractor (Theeuwes, Kramer, Hahn, Irwin, & Zelinsky, 1999).

The proposed mechanism for these effects on saccade trajectories is that the target and distractor both produce orienting responses that generate two active, competing saccade programs: one to the target and the other to the distractor (Doyle & Walker, 2001; Sheliga et al., 1994; Tipper, Howard, & Jackson, 1997; Van der Stigchel, Meeter, & Theeuwes, 2006). Because a saccade can only land at one location, there is competitive integration between these two saccade plans that must be resolved by either local interactions or by top-down inhibition of the distractor (Godijn & Theeuwes, 2002;

Ludwig & Gilchrist, 2003). If competition is resolved fully in favor of the target, no oculomotor capture or deviation occurs. If competition is resolved in favor of the distractor, oculomotor capture occurs. The same competitive process may result in a peak that averages the target- and distractor-related peaks, resulting in a global effect. The distractor peak might not be fully inhibited, leading to deviation toward the distractor; or the distractor peak might be inhibited, resulting in deviation away.

Computational models based on this underlying neural architecture vary in implementation, but succeed in generally predicting both the saccade deviation and the landing-position errors that occur in the presence of distractors (Kruijne, Van der Stigchel, & Meeter, 2014; Port & Wurtz, 2003; Walton, Sparks, & Gandhi, 2005). Neurophysiological evidence is consistent with this cognitive framework of neural activation and competition. The neural control of saccade trajectory occurs largely through specific activation within retinotopically organized layers of cells within the from projections from the frontal eye fields to the superior colliculus (for review, see Sommer & Wurtz, 2000; Van der Stigchel, 2010). In classic population code models, local peaks of activation within these neural maps – with the peaks representing the retinotopic locations of the target and distractor – elicit potential saccade plan vectors that originate at the current fixation point and terminate at the target or distractor (Robinson, 1972).

In sum, behavioral and neurophysiological evidence suggest a saccade plan map, like the map of covert attention, that integrates perceptual (bottom-up) and attentional (top-down) information. Evidence for this comes from paradigms that manipulate targets and distractors. Consistent with this framework is the observation that the magnitude of a distractor's effect on saccade deviation is greater when the distractor is featurally similar rather than dissimilar to the target, thereby eliciting greater activation in the non-target area than would be elicited by a distractor with non-target features (Doyle & Walker, 2001; McSorley, Haggard, & Walker, 2004; Mulckhuyse, Van der Stigchel, & Theeuwes, 2009; White, Theeuwes, & Munoz, 2012). This is evidence that salience and top-down factors can weaken or strengthen the degree of saccade deviation, and that this deviation reflects oculomotor enhancement or suppression of the distractor representation.

Existing research on surface structure and saccades

If attentional control is informed by the surface structure of scenes (e.g., He & Nakayama, 1994; Nakayama, He, & Shimojo, 1995), and if there are strong functional links between functional saccadic control and covert spatial attention (e.g., Hoffman & Subramaniam, 1995; Kowler, 2011; Sheliga et al., 1994; Van der Stigchel et al., 2006), it follows that saccadic control may also reflect the structure of the scene within which the saccades are being made. The models of saccadic control just described, however, do not include surface structure. There is evidence that surface information informs some saccade behavior. This section reviews that evidence and finds that although there is evidence that object surfaces ultimately do guide saccade behavior, to date there has been no investigation of whether object surfaces inform the visual contribution to the saccade map independently of selection history[1] and task relevance of the object surface.

Melcher & Kowler (1999) examined the visual representation that is used to determine an object's centroid in saccade execution. They asked observers to saccade to the "average" or centroid of a cluster of dots. The critical manipulation was that some of these dots formed an outline of a shape, within which another cluster of dots existed off to the side of the shape. One possibility is that the centroid would be an object-blind average of the individual coordinates of dots considered separately, as a retinotopic activation-map model would predict. Alternatively, the centroid might be informed by the object boundaries implied by the of the cluster of dots. These two centroids could be different from each other, depending on the distribution of dots within the cluster. Saccade landing positions were closer to the center of the implied object boundaries than to an object-blind average of the individual points, suggesting that at saccadic control in this task was mediated by a perceptually organized representation of the object surfaces.

In this task, observers were instructed to take as much time as necessary to "look at the target as a whole" and adopt a long saccadic latency to produce an object-based

[1] Scene gist is known to affect saccades (Henderson & Hollingworth, 1999; Hollingworth, 2009; Oliva & Torralba, 2007; Torralba, Oliva, Castelhano, & Henderson, 2006). Short- and long-term memory can inform first saccades in a scene; for example, when entering a kitchen to look for the bread, saccades may be guided to regions that are not bottom-up salient but which are probabilistically likely locations of the bread.

organization of the scene and select a saccade endpoint accordingly. This may have promoted high engagement and produced an extended duration with which to process and organize the scene. As such, this is evidence that the saccade map *can* access what appears to be a surface-informed representation when there is an extended display time, high engagement of the scene, and when doing so is consistent with the task goals. With mean saccade latencies of over 500 ms, it is unclear from this work whether a saccade initiated under low-engagement task demands would access a visual representation that is necessarily informed by object structure.

Other work by McCarley, Kramer, & Peterson (2002) examined saccades in the Egly, Driver, & Rafal (1994) object cueing paradigm. Their question examined whether saccades would exhibit behavior that was informed by object-sensitive or object-invariant information. First, two unfilled red rectangles appeared and one end of one rectangle was cued by changing from red to white. Then, after the observer's eyes had moved to one of the four ends of the rectangles, three rotated Ls and one target – a rotated T that pointed left or right – appeared in the ends of the rectangles. The cue was most often valid, such that in 60% of trials the target appeared in the cued region. In 20% of trials the target appeared 4.8 degrees visual angle from the cued location but within the same rectangle (invalidly cued same-object), and in the remaining 20% of trials the target appeared equidistant from the cued location but in the other rectangle (invalidly cued different-object). Observers were to quickly report the orientation of the target.

There was evidence for object-based effects in both manual and saccadic responses. Manual responses followed the original pattern: manual response times were faster for targets that were invalidly cued on the same object compared to targets invalidly cued on the different object. Fixations on valid trials tended to go to the cued location and remain there (where the target appeared). On invalidly cued trials, first fixations went to the cue, but the question is whether surface context affected the next fixation. The next fixation was more likely to land on the target when the target was at the same-object location (82% of fixations on invalidly cued same-object trials) than when it was at the equidistant different-object location (71% of trials). This suggests that the saccade plan is sensitive to the object-based surface context of a scene.

These findings indicate that surface information is encoded in the saccade plan. But it is not clear whether these surface-based effects indicate surface-dependent representations in the visual information informing a saccade regardless of the task. This is a high-engagement task in which rectangles may themselves have been attended, and the spatial cueing paradigm may have generated a top-down or selection-driven spatial bias to remain within an object boundary.

First, in this paradigm, parts of the surfaces changed color as a task-relevant cue, perhaps causing the surfaces themselves to be attended. If the surface was attended, then via attentional spreading or prioritization, the cue might have promoted attentional enhancement throughout the cued object. This would predict first saccades being systematically biased to land closer to same-object items than different-object items. But landing positions of initial saccades to the cue item were *not* systematically biased in the direction of the within-object item compared to the different-object item. This suggests that cueing the end of one object did not result in a spreading of attention in a manner that affected the programming of the initial saccade, and therefore that the first fixation to the cue was programmed independently of object surfaces.

Second, cueing and the gaze-contingent procedure may have produced a location-based bias (i.e., in object-blind coordinates) in saccade target selection for the second fixation. The gaze-contingent design was that the target and distractors would not appear on the screen until observers' eyes were detected in any of the four spatially-defined windows at the locations to be filled by items. Because the cue validly cued the target's true location on most trials, observers' best strategy was to saccade to the cued region – even though there was no target or distractor visible at that time. Using a saccade to trigger the onset of the items is a good experimental strategy to prompt observers to make saccades throughout the display even if items could be discriminated parafoveally. But it means that on 80% of trials (60% valid trials and 20% invalidly cued same-object trials), observers programmed a saccade to a region within a bounded rectangle (i.e., the cue), then the target appeared within that bounded rectangle. In only 20% of trials would observers saccade within one bounded rectangle only to have the target appear within the other rectangle. This selection history may have produced a spatial bias, such that the observer might have known, explicitly or implicitly, that they were ultimately going to make one or two saccades within the cued rectangle on 80% of trials. This would produce the observed results of the second saccade: more frequent saccades to the target when it was invalidly cued in the same object than when it was invalidly cued in the different object (even though the invalid trial types were themselves equally likely). In other words, cueing and surface information could have produced strategic or history-based biases in the programming of the saccade. What was interpreted as an object-based effect of saccade programming could more precisely be described as a conversion of object surfaces into location-based biasing of a surface-blind saccade map.

To summarize, existing investigations demonstrate that saccades can be programmed in coordinates that exhibit sensitivity to object surface information but, as of yet, only under high engagement tasks when object contours are task-relevant or associated with selection history. There is evidence that the priority map of the saccade is informed by object surfaces consistent with task goals and selection history, but no evidence to date whether object surfaces are always encoded in the saccade map, such that they guide the deployment of saccades under low engagement and without a selection bias.

Existing work examining saccades and object surface structure

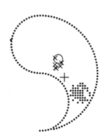
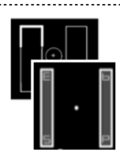
		Surface processing time before saccade	**Biases to expect target on certain locations**	**Engagement**
Melcher & Kowler (1999)		0 ms + latencies (400-800 ms avg)	no (no “target” visible)	high; observers told to process scene and adopt long latency
McCarley, Kramer, & Peterson (2002)		584 ms + latencies (181 ms avg)	yes; probability that cued surface contains target is .8	high; task involves cueing, shifting attention, and feature-based selection

Figure 1.1. Melcher & Kowler (1999) and McCarley, Kramer, & Peterson (2002) examined saccade behavior as a function of object edges and object surfaces. In both of these studies, there was long exposure to object surfaces and a high degree of observer engagement with the task.

Hypothesis: The saccade map is surface-dependent

Covert shifts of spatial attention are informed by object surface structure. Object-based effects in covert attention are strongest when shifts of attention are required (Lamy & Egeth, 2002; Shomstein & Yantis, 2002) and when the task requires high engagement with the scene. Shifts of covert attention share significant functional architecture with saccade programs, and models of saccade production invoke competitive integration between saccades programmed to items that generate strong activity in the priority map. Neurophysiological evidence suggests early and strong encoding of whether a region forms an object boundary (surface presence), and somewhat early and weak encoding of whether a region is within an object (surface context), even in the absence of high engagement.

> **H1**: Saccades will be affected by the object surface context on which the target and distractors appear. Specifically, saccade distractor-related trajectory effects will be strongest when a distractor is on the same surface as a saccade target, and weakest when a distractor is on a different surface from the saccade target.
>
> **H2:** High engagement is not a precondition to demonstrate object surface-based effects in saccades.

Saccades might also exhibit sensitivity to the presence of surface structure, such that saccade trajectories are affected by the presence of boundary information (independently of the organizational context of these object surfaces). This effect would obtain in trajectory effects that differ as a function of surface presence generally compared to no surfaces.

Existing work demonstrates surface-based saccade modulation in high-engagement tasks. Because of the early modulation of physiological signals that encode object surface boundaries in the visual signal, it is possible that low-engagement tasks that rapidly access this visual signal reveal early encoding of surface structure, but it is also possible that high engagement is required in saccade tasks as in covert tasks to determine the presence of object-based processing. As such, engagement may arise as an important factor in saccadic behavior in the presence of object surfaces. Figure 1.2 places the existing work on saccades and objects in the context of the dimensions of surface exposure time and of engagement that I examine in this dissertation.

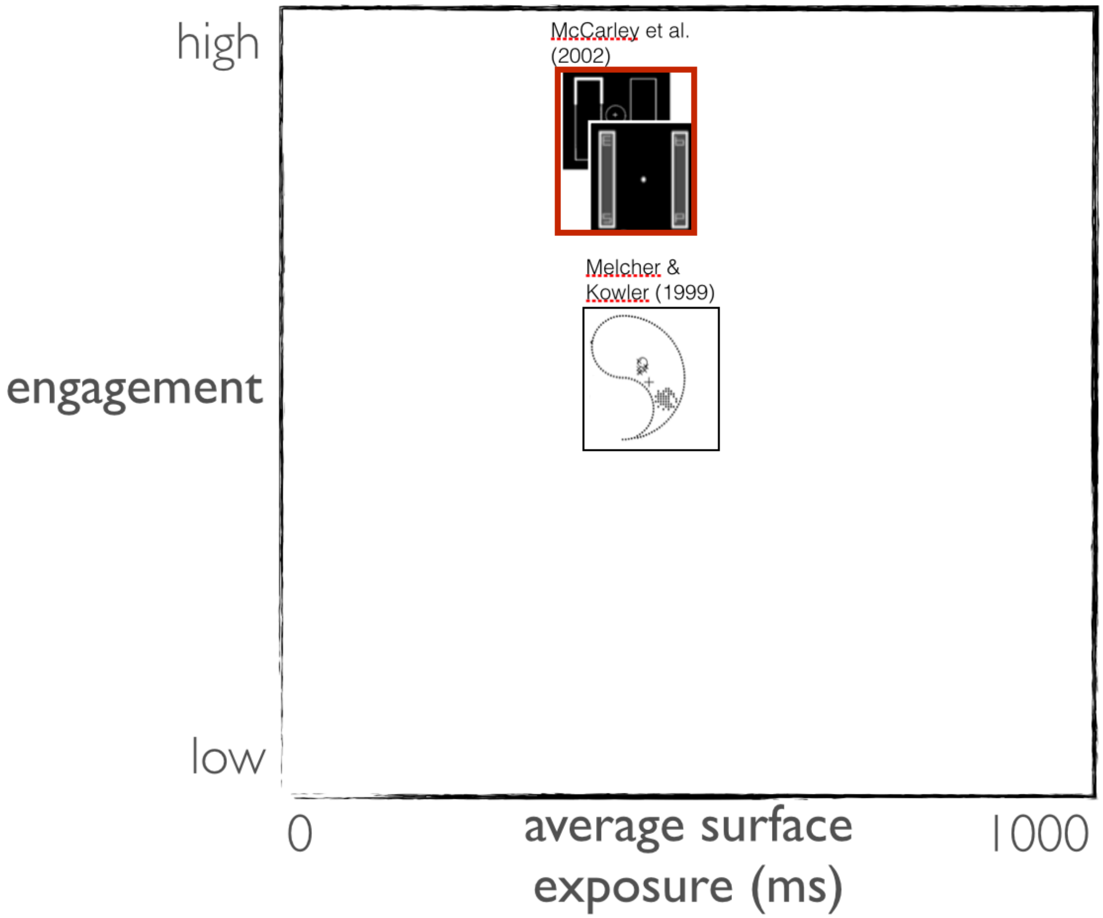


Figure 1.2. Covert research on object-based attention is consistent with the hypotheses that a minimum encoding time and high level of engagement with the task and display are necessary preconditions for object-based effects. The existing work on saccades and objects both had moderate exposure durations and high task engagement. This dissertation will explore the remainder of this space.

Common or distinct architectures underlying manual and saccadic responses

One question concerns what kind of saccade effects should be predicted and what they reveal about the architecture of the visual system. Most object-based effects are in manual response times, rather than response accuracy. If manual and saccade motor programs rely on a shared priority map of attention, one prediction is that surface context will produce effects on saccade response time. However, a common attentional map could produce different kinds of patterns in the motor effectors used to respond to information in these maps.

Saccadic responses are often initiated quickly, with the activity between SC and the onset of the saccade taking on average 20 ms (Munoz & Wurtz, 1993). Manual responses take longer, with approximately 75-85 ms between activity in primary motor cortex and the initiation of finger movement (reviewed in Bompas, Hedge, & Sumner, 2017). Research examining the common mechanisms and information used to produce manual and saccadic responses generally suggest that both effectors rely on the same information, but are expressed differently. Hunt et al. (2007) proposed that the same internal process of attentional capture by a distractor is reflected in manual response times and saccade landing position (i.e., capture), due to the differential level of information accumulation that occurs before the initiation of a saccade compared to the initiation of a manual response. Computational modeling of saccadic and manual decisions suggest that both systems rely on shared information and processing principles, although distractors seem to produce stronger effects in saccades (i.e., landing position) than manual responses (Bompas, Hedge, & Sumner, 2017).

As such, I predict surface mitigated distractor-related effects would arise in the oculomotor trajectory – deviation, landing position, and rate of capture by a distractor.

Alternative hypothesis: Saccades are insensitive to surface context

The alternative hypothesis is that the execution of a saccade does not reflect an obligatory encoding of surface-dependent representations. Posner (1980) proposed that although covert and overt spatial attention likely relied on a common system the relationship is a functional rather than completely dependent one. This conclusion was drawn because of the dissociations between covert and overt attentional orienting. That these dissociations exist suggests the possibility that the architecture used to program an orienting saccade may rely on a visual representation that is less informed by perceptual organization of object surfaces.

There exists evidence that saccades are programmed in a coordinate system that is insensitive to perceptual mis-localizations. Wong & Mack (1981) examined whether a saccade target is programmed to a perceived coordinate or an actual coordinate. They manipulated perceived and actual saccade target positions by maintaining or moving a reference frame around the saccade target, and found that, generally, saccades landed on actual target positions instead of the perceived position. Observers only programmed saccades to perceived coordinates when the coordinates were stored in memory for a task report. This suggests that the visual representation used to execute an orienting saccade is not the same representation accessed for conscious report. Van der Stigchel & de Vries (2015) found that when a saccadic global effect occurred in the context of a fine-grained discrimination task, there was no evidence for perceptual enhancement at the region where the saccade landed. One interpretation of this decoupling is that covert attention did not select the retinal location of the saccade landing position. Instead, perhaps the *intended* landing position was covertly selected. Or both the target and distractor that produced the global effect were selected by covert attention, and the competitive integration between these two saccade programs was resolved at a different time from the saccade execution. These findings together indicate that although covert shifts of spatial attention are tightly linked to saccades, this coupling is not rigid.

Furthermore, neurophysiological evidence suggests saccade trajectories depend on information outside of the prefrontal saccade planning region. Microstimulation of the frontal eye field neurons associated with the "salience map" does not always result in changes to a saccade trajectory (Juan, Shorter-Jacobi, & Schall, 2004).

As such, the alternative hypothesis is that saccades and manual responses operate on distinct attentional maps such that saccades are insensitive to perceptual organization. There is some neurophysiological evidence to suspect this is the case, because saccades and manual responses rely on different anatomical pathways. These anatomical pathways might change the weighting of bottom-up, top-down, and history-based contributions that are used to program these two responses. The motor signal to produce a saccade is generated from the brainstem, which integrates direct projections from the superior colliculus (SC) and the frontal eye fields. The SC also receives visual inputs directly from V1 and the optic nerve (Sparks, 2002). This could suggest a stronger weighting of surface-blind, feature-based information in the programming of a saccade. The programming of manual responses involves the primary and supplementary motor cortices, which are sensitive to visual information but are more strongly modulated by task-relevant processing of signals (Trappenberg et al., 2001). This could suggest a stronger weighting of top-down, task-relevant information in manual responses.

These known dissociations are evidence that the coupling between covert and overt attention are weaker than would be claimed by strong versions of the premotor theory of attention. It is possible that surface structure might not affect the saccade plan at all, or might only do so when the surface structure is informative about the retinotopic or spatiotopic coordinates of the saccade target. This would raise the possibility that although object surface information can inform covert visual representations and attention in tightly controlled tasks, the way orienting saccades are performed in day-to-day life are insensitive to extra-retinal (i.e., object surface) information.

Overview

Examining the impact of surface structure in a variety of displays and tasks allows the test of the hypothesis about whether surface structure informs the saccade plan at all, and if so, whether it does so independent of engagement-related task demands.

In Chapter 2, Experiment 1 uses a paradigm similar to Melcher & Kowler (1999) to examine whether the perceptual completion of an object surface under an occlude informs the computation of object boundaries and centers in a saccade-to-centroid task. I tested whether saccades to the centers of objects that are informed by amodal completion of one object surface underneath an occluding object, or whether the objects boundaries are defined by contrast-defined edges without completion of object surfaces.

In Experiments 2-4 throughout Chapter 3 I modified standard displays of equally salient targets and distractors in saccade-to-target spatial orienting tasks, such that surface structure was absent or present. Figure 1.3 depicts this logic. When the distractor was present, it could appear on the same or different surface as the target. On the top is depiction of a display and curvature of a saccade. On the bottom is the interpretation: the distractor produced oculomotor distraction. The middle and right columns depict possible findings from the conditions in which the target and distractor are on different surfaces. In the middle column, the saccade exhibits less curvature. The conclusion from this is that the surface structure mitigated the distractor-related activity in the saccade plan, and that the coordinate system of the saccade map is surface dependent. On the right column, the distractor-related effect is unaffected by the surface manipulation, with the conclusion that the saccade map is surface invariant.

Surface structure was generally uninformative to the orienting task: surfaces were never cued and target selection was based on either its location or its features. I used target and distractor sizes, features, tasks, and distances that were similar to published findings of distractor-related saccade trajectory effects to maximize distractor-related saccade deviation or the global effect. As such, throughout Chapter 3, I used exogenous orienting, saccade-to-target tasks to examine whether object surface context informs the representations of targets (and distractors) in the priority map used to program a saccade, in tasks in which the surface context might inform the visual representation but is independent of the saccade task goals and selection history.

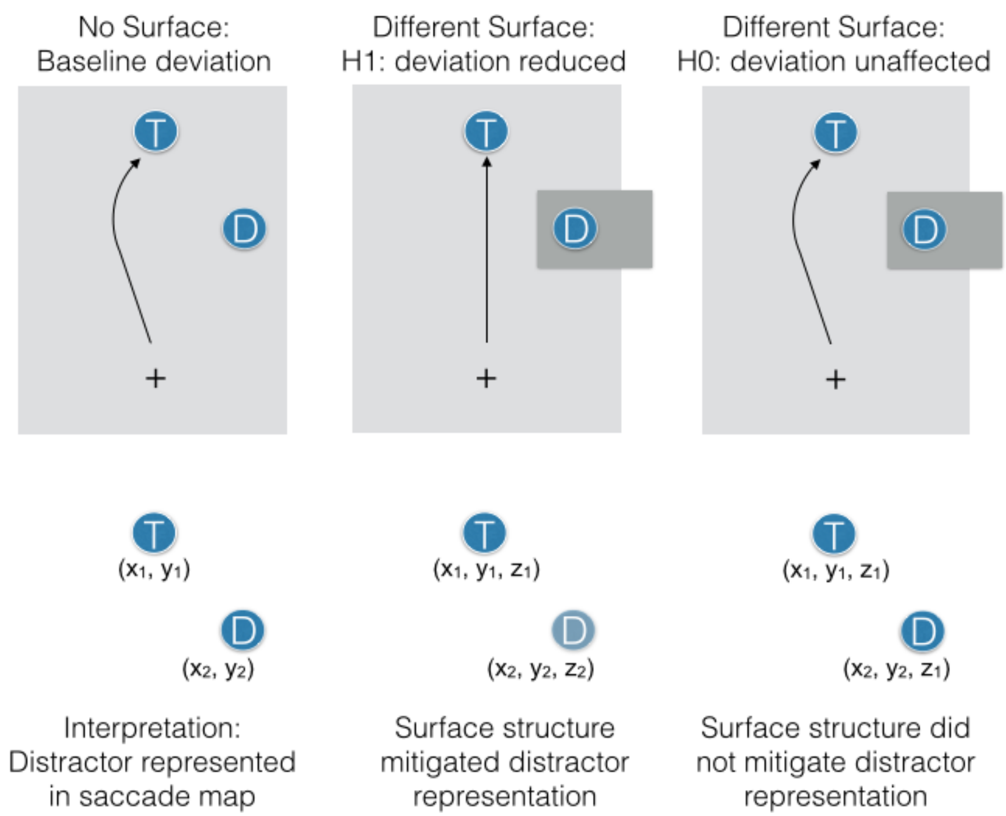


Figure 1.3. Depiction of possible saccade patterns and interpretations.

In Chapter 4 I tested whether saccades are informed by surface structure when the surface structure is task relevant and could inform endogenous components to the saccade. I conducted a saccade-dependent extension of Vatterott & Vecera's (2015) work on location- and surface-based cueing in the additional singleton paradigm. In this task, observers use knowledge about the target's features to select it from among multiple distracting items, and the surface structure was task-relevant. The motivation was twofold: first, to test whether saccade landing positions show evidence of capture that had been reflected in manual response times, and second, to test whether making the surface context task-relevant to the saccade would produce surface-mitigated effects in the saccade plan.

Because the primary goal of this work is to examine whether object surfaces inform the coordinate system of the saccade map in a manner that depends on or is independent of engagement, in the final empirical Chapter 5 I used surfaces similar to those used in Chapter 4 and a saccade-to-target task in which the target and distractor could appear on the same or different surface. Critically, the surfaces did not inform the saccade plan. I also introduced an engagement manipulation, such in the latter half of the experiment observers reported the surface structure in the scene, such that the surfaces were relevant to the judgment task without informing the saccade. This allows the comparison of trials in which the surfaces were never relevant to any task, and trials in which the surface context had to be attended to perform the judgment task. The goal is to test whether being asked to report about the context of the surface structure in the scene produces an obligatory spreading of spatial attention throughout the surface in a way that modulates distractor-related saccade effects.

The general findings of these experiments are discussed in the context of surface-informed representations in the map that programs the saccade.

2. SACCADES TO CENTROIDS OF OCCLUDED OBJECTS

In this experiment the goal was to examine whether amodal surface information, in which object surfaces are 'completed' underneath an occlude (Ringach & Shapley, 1996), informs saccades to object centroids. I used a task in which observers were asked to make an eye movement to the center of a shape, a *saccade-to-centroid* task. Melcher & Kowler (1999) created displays of clusters of dots. Many of these dots formed an object contour, but some of them were clustered inside the implied object. This generated two separable hypotheses about possible object centroids. The object-invariant centroid was calculated by taking the geometric mean of all dot locations, regardless of whether they were inside the implied object boundary. The object-dependent centroid was formed by calculating the center of area of the object implied by the surface boundaries, with no contribution of the dots within the boundary. They presented these objects in the periphery and observers made saccades from fixation to the middle of the object.

In Experiment 1 I asked whether a partially occluded surface would cause the saccade landing position to be biased toward the centroid of the implicit completed surface, rather than to the centroid of the image-level shape. Although observers could make a saccade to the centroid of an irregular shape (Melcher & Kowler, 1999), the centroid was not computed with regard to the shape of the implied (completed) surface. Instead, saccades landed near the centroid of the two-dimensional shape on the retina. In other words, saccadic control was invariant by the surface structure of the scene.

Experiment 1: Saccades to the Centroids of Occluded Objects

Adapting the task of Melcher and Kowler (1999), I asked observers to make saccades to the centroid of irregularly shaped objects, thus ensuring that the shape of objects within the scene be taken into account (see Figure 2.1). In addition, I included a condition in which a second surface was depicted as being in front of the other, occluding it and implying that the actual shape of the back surface was different from the image shape (see Figure 2.1B). The critical question was whether observers would saccade to the center of the implied object or to the center of the image shape. The latter would provide an example of surface structure influencing saccadic control. The former would be consistent with the hypothesis that perceptually filled-in surfaces are not included in the representation on which saccadic control is based.

Figure 2.1 illustrates the different objects that were used. There were two baseline conditions. One was a full unoccluded rectangle (Figure 2.1A). The other was a "pan" shape with part of the original rectangle missing (Figure 2.1B). The third condition was an occluded rectangle that included the image of the pan shape but – assuming amodal completion – would be perceived as the rectangle shape (Figure 2.1C). If amodal completion contributes to saccade endpoint calculations, as it does to visual search (Rensink & Enns, 1998), then the saccade landing positions in the Occluded Rectangle should be more similar to saccade landing positions of the Unoccluded Rectangle condition than the Pan condition. If, however, saccades are controlled within a coordinate system that is insensitive to or invariant to amodal completion, then saccade landing positions in the Occluded Rectangle condition should be more similar to those in the Pan condition than the Unoccluded Rectangle.

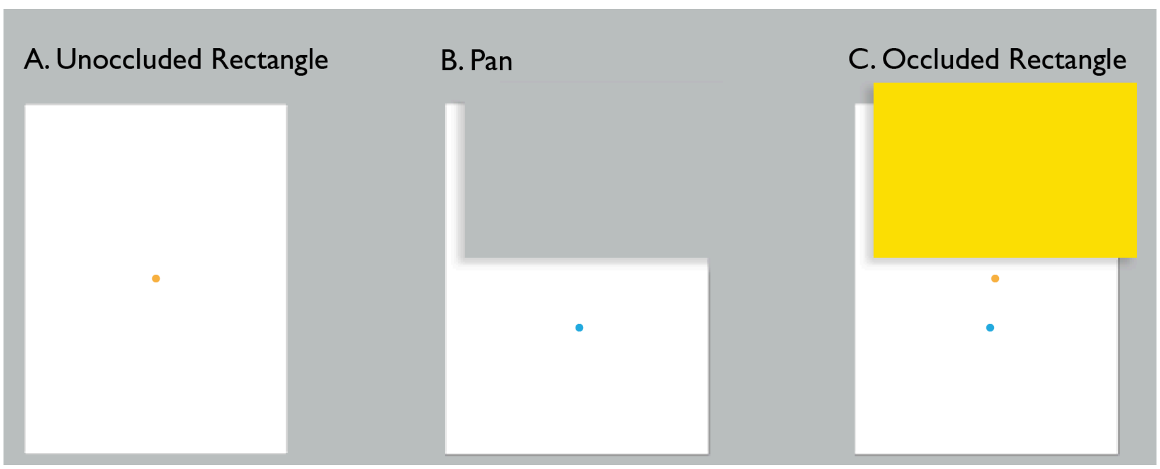


Figure 2.1. The three object types presented in Experiment 1. The centroids are marked here, but were not visible in the actual display seen by participants.

Participants. Six people (aged 18-50) who were research assistants or lab members (including one lab member familiar with this hypothesis) participated. Note that Melcher and Kowler (1999) used two to three participants in their work. All reported normal or corrected-to-normal visual acuity and color vision.

Stimuli. The baseline stimulus was a white rectangle that (see "Unoccluded Rectangle" in Figure 2.1) measuring 5.8 × 7.8 dva. The Occluded Rectangle condition was created by drawing a 5.8 × 3.9 dva yellow rectangle largely overlapping the white rectangle such that 5.4 × 3.5 dva of the original white rectangle was obscured. Finally, the Pan was created by deleting the same obscured region from the white borders. This created differential centers-of-area between the Unoccluded Rectangle and the Pan that were 1.6 dva apart.

Task. Participants were asked to fixate, and to maintain fixation for 600 ms after the object onset in the left or right hemifield. During this 600 ms observers were asked to use their peripheral vision to locate the center of the white object. After 600 ms, fixation was removed from the display, signaling the observer to initiate a saccade to the centroid of the white object. Once the saccade had landed, 100 ms elapsed before the display was cleared to reveal only the gray screen. The participant initiated the next trial by pressing the spacebar.

Procedure. During the experiment instruction, participants were shown images of the three types of objects they would see and were explicitly informed that the Occluded Rectangle was the same as the other Unoccluded Rectangle, and that it "happened to have a yellow table on it." As such, all observers were explicitly told how to perceptually organize these displays.

Participants performed 5 blocks of 54 trials. The object was equally likely to appear a baseline of 5.0 dva either leftward or rightward of fixation. On a given trial the object had an additional left/rightward jitter of 0, 1, or 2 dva, and was -1, 0, or 1 dva above or below fixation.

Design. This was a one-factor design with 3 kinds of objects (Unoccluded Rectangle, Pan, Occluded Rectangle). Object type was intermixed on each trial.

Results. Figure 2.2 marks, for each surface condition, each observer's mean landing position. First, I calculated landing errors as if the centroid was the same centroid as the Unoccluded Rectangle (e.g., as if the Occluded Rectangle had been amodally completed), and compared that to the landing errors from the centroid of the actual Unoccluded Rectangle. I found a significant difference in landing positions, $t(5) = 5.15$, $p = .004$, suggesting that the oculomotor system considers the centroids of the Unoccluded

Rectangle and the Occluded Rectangle to be different. For the other test, I calculated landing errors for the Occluded Rectangle as if the centroid was the same centroid as the Pan, and compared these landing positions. There was no evidence for a difference between landing positions between the Occluded Rectangle and the Pan, $t(5) = 0.44$, $p = .7$.

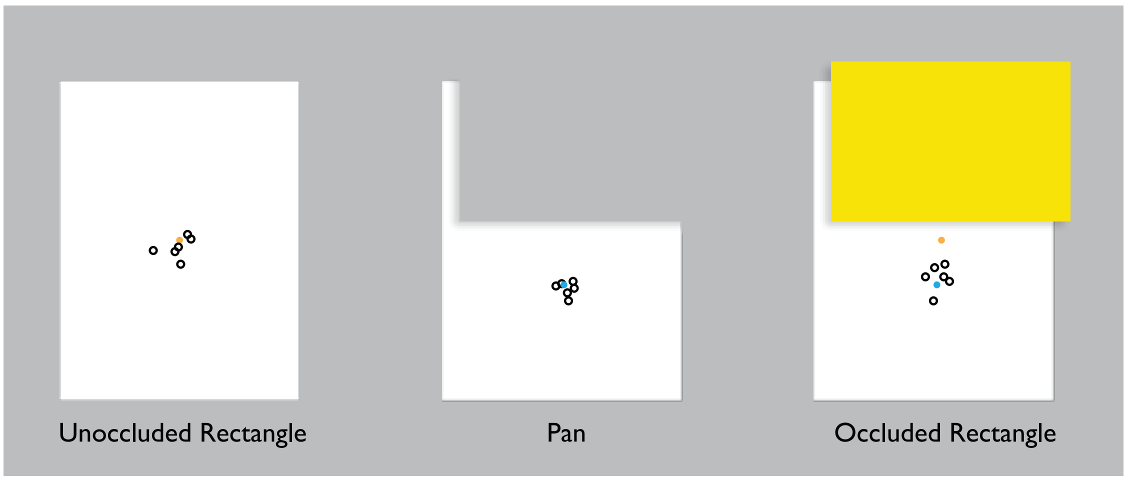


Figure 2.2. Mean landing positions (open o) for each observer from Experiment 4. Potential centroid locations are drawn in orange and blue and were not visible to observers. In the Occluded Rectangle condition, saccades tended to land closer to the “Pan” centroid than the “Unoccluded Rectangle” centroid.

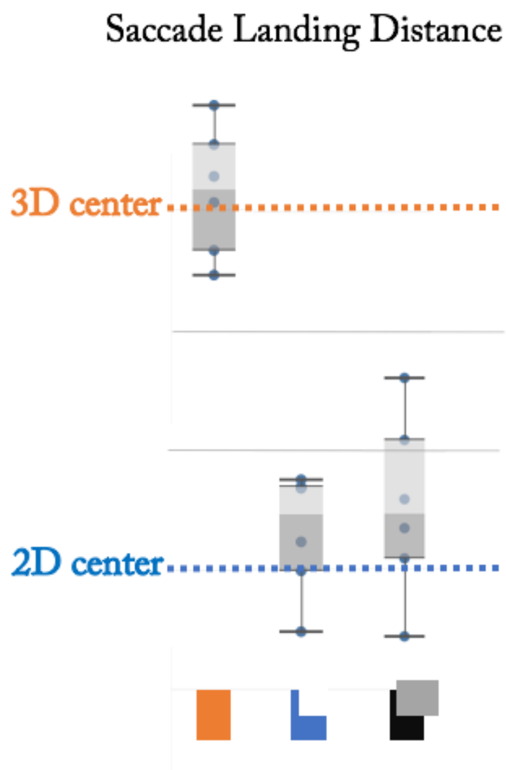


Figure 2.3. Boxplot of each observer's mean saccade landing distance relative to the 2D center (based on the centroid of the Pan) of the Unoccluded Rectangle, Pan, and Occluded Rectangle. Saccades to the Unoccluded Rectangle were far from the location of the Pan's center, but saccades to the Pan and to the Occluded Rectangle were close to the Pan's 2D center. The orange dashed line marks the "3D center" of the Unoccluded Rectangle, which was 3 degrees visual angle from the center of the Pan ("2D center," blue dashed line).

Discussion. These findings suggest that the object centroids calculated for a saccade do not take into account the amodal completion of an obscured object. Instead, saccades were programmed as if the Obscured Rectangle was functionally the same as the Pan – as if the obscuring surface had been deleted from the display. This finding was consistent across participants, despite the fact that all participants were aware that the Occluded Rectangle was the same as the Unoccluded Rectangle and that one participant was an author who was aware of the hypothesis of this experiment. In extending the logic of Melcher & Kowler (1999), these findings imply that, insofar as saccade endpoints are concerned, object centroids are determined without visual information contributed from amodal completion.

3. SACCADES ARE INSENSITIVE TO SURFACE CONTEXT UNDER LOW ENGAGEMENT

One prominent theory of visual processing holds that the functional representation of the visual world is parsed into object surfaces (He & Nakayama, 1992), and that it is this surface-based representation on which other visual processes – such as attentional selection – unfold. It is not yet known whether the saccade coordinate system, which has strong functional overlap with the attentional system, incorporates surface-based representations in the programing of orienting saccades.

Saccade trajectories are affected by distractors in the scene. In particular, salient distractors can produce deviation in the saccade trajectory's deviation – the angular difference between what would have been a straight path to the target and the actual path of the saccade. The magnitude of these trajectory effects increases when the distractor is featurally similar rather than dissimilar to the target (Mulckhuyse et al., 2009; White et al., 2012), an effect which contributes to the conclusion that deviation is an index the attentional strength of the distractor (Van der Stigchel et al., 2006).

In Experiments 2 - 4, observers made saccades to targets in displays that either included or did not include an additional distractor. In some conditions, a set of surfaces was added to the background such that the target and distractor, when present, could appear either on the same surface or on different surfaces. The logic was that if saccades are controlled within representations that include surface information, then distractors that appear on different surfaces from the target should not affect the saccade as much (or at all) compared to when target and distractors are on the same surface.

Experiment 2: No Evidence Surface Structure Moderates Curvature

Experiment 2 used displays in which a target disc appeared with or without a distractor disc and with or without a set of overlapping surfaces in the background (see Figure 3.1). The *No Surfaces* condition (see Figure 3.1, top row) was expected to replicate standard effects of distractor presence on saccade deviation and landing error. Specifically, greater deviation and landing position errors were expected in conditions in which the distractor was present compared to absent. There were two conditions with surface structure that I will label *Same Surfaces* and *Different Surfaces*. In the Same Surfaces condition, a central surface was in front of four smaller surfaces and the target and distractor were both presented on the front central surface. In the Different Surfaces condition, the four smaller surfaces were presented in front of the large central surface and while the target was presented on the larger central surface, the distractor was presented on one of the four smaller front surfaces.

If saccadic control is mediated by scene structure, then the impact of distractors on saccade deviation and landing position in these Same Surfaces and Different Surfaces conditions could differ. Specifically, the expectation was that distractors would have less impact in the Different Surfaces condition than in the Same Surfaces condition. This is because, assuming surface information is included in the representation on which saccadic control is based, the distractor on a different surface from the target should elicit less activation than a distractor on the same surface as the target. In contrast, if surface information is not included in the representation within which saccadic control is based, it should not make no difference what the surface content of the display is. The No Surfaces conditions provides a measure of the impact of including any surface information beyond the single implied surface of the monitor on which stimuli are presented on saccadic control. One possibility is that the effect of the distractor will be greatest in the Same Surfaces condition because the common surface on which the target and distractor appear is smaller than that of the whole monitor. Another possibility is that these two conditions will not differ because in both cases the target and distractor appear on a common surface.

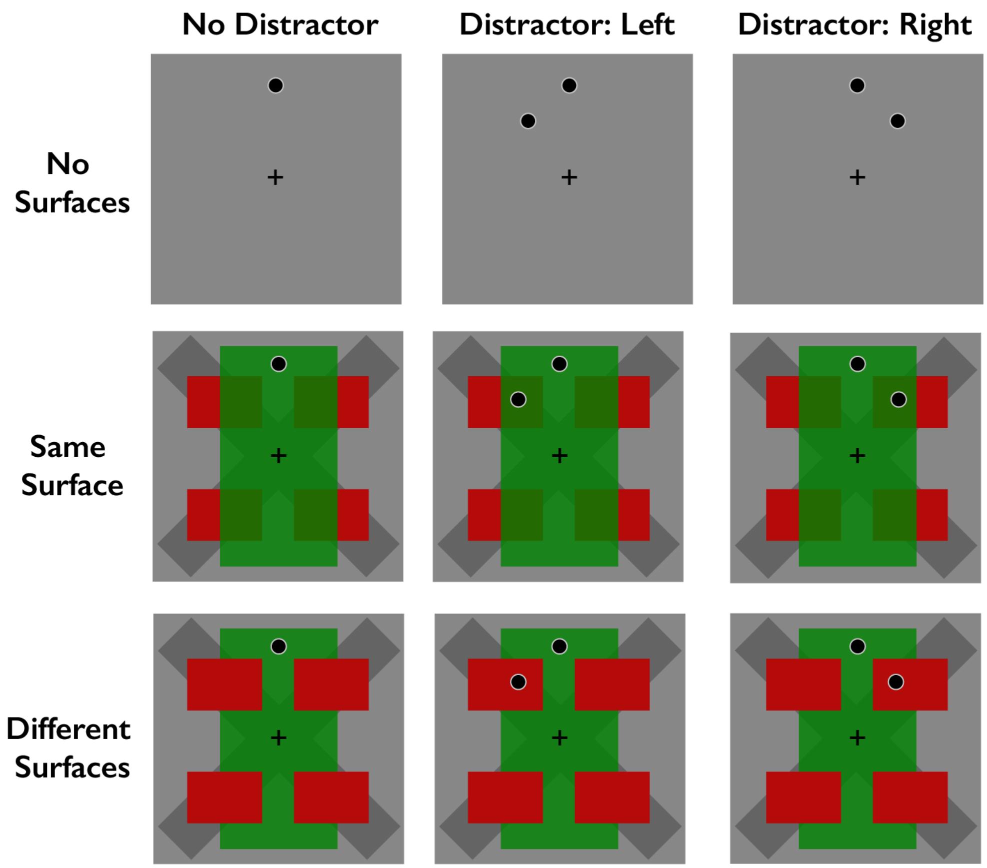


Figure 3.1. Illustration of conditions in Experiment 2. (Here, the target dot is drawn in the upper hemifield, but the target also appeared in the bottom hemifield.)

Participants. Participants were 12 University of Iowa undergraduate students and lab members (18-28 years old) who reported normal or corrected-to-normal visual acuity and color vision, gave informed consent, and received course credit for participating. One participant was replaced due to poor calibration.

Apparatus. Experiments were developed in MATLAB (R2010a, 32-bit) using the Psychophysics Toolbox (Version 3.0.8 beta; (Brainard, 1997; Pelli, 1997); and were run on an Apple Mac Pro (OSX 10.6.7) with an NVIDIA Quadro FX 4500 graphics card driving a 17-in. CRT monitor set to 1024 × 768 resolution at a refresh rate of 100 Hz. Participants completed the study in a partially darkened room. Viewing distance was fixed at 60 cm using a chinrest. Eye movement data were recorded with an EyeLink 1000 desk-mounted eye tracker recording at 1000 Hz.

Stimuli. The target and distractor objects were 1.2° × 1.2° black dots on a gray background, bounded by a white outline for maximal contrast and salience regardless of surface condition. The target appeared 9.4° above or below fixation. A distractor, when present, was 5.6° from the target and 6.8° from fixation. These distances and locations of the targets and distractors were selected to be similar to those used in previously documented distractor-related trajectory effects (Doyle & Walker, 2001).

When surface structure was present, there were 7 surfaces in the display. The first was a large Central Surface, drawn in red or green, upon which the fixation cross and the target would appear. There were also 4 identical smaller Critical Surfaces: two in the left/right hemifields and two in the upper/lower hemifields relative to fixation. These were drawn in red or green. In the Different Surfaces condition, critical surfaces could be drawn on top of the central surface, such that if a distractor dot was present, it appeared to be on a critical surface while the target was on the central surface. In the Same Surfaces condition, the critical surfaces were drawn "beneath" the central surface, such that if a distractor dot was present, it was on the same central surface as the target. Finally, there were two dark gray rectangles forming an *X* shape underneath all surfaces to further promote the representation of a scene of overlapping objects. All displays were horizontally and vertically symmetric. Figure 3.2 provides a screen capture from the experiment, overlaid with additional size, distance, and luminance information.

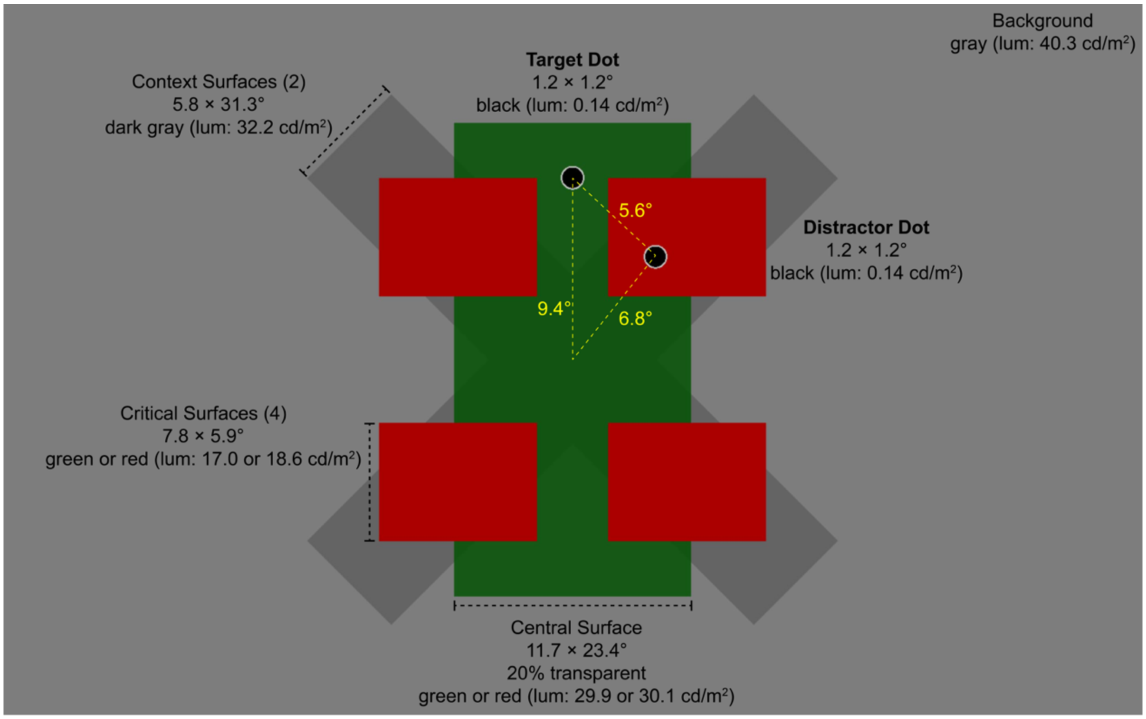


Figure 3.2. Actual display from Experiment 2 with distractor present, Different Surfaces condition, overlaid with size, distance, and luminance information.

Task. Participants were asked to fixate until the target appeared, at which point they were to move their eyes as quickly as possible from fixation to the target dot. They were instructed the target would always appear either directly above or below fixation. They were informed that sometimes there would be square cartoon tables in the scene, and sometimes not, and that sometimes another dot would be in the display, but that the task – to saccade to the target as quickly and accurately as possible – was always the same.

Procedure. Each experiment consisted of a single session that lasted approximately 1 hour. Following the informed consent process, participants were guided through a set of written instructions and images that described the task.

Figure 3.3 illustrates a typical trial sequence. Fixation and surface structure (or a surface-less gray screen) was present for 800-1200 ms before the onset of the dot(s), as well as a 450 Hz 400 ms tone that cued participants to saccade to the target. The display remained on the screen for a further 1000 ms, then disappeared. The participant initiated the next trial by pressing the spacebar.

Participants completed 7 blocks of trials. Each block started with a 9-point calibration and validation of the eye tracker.

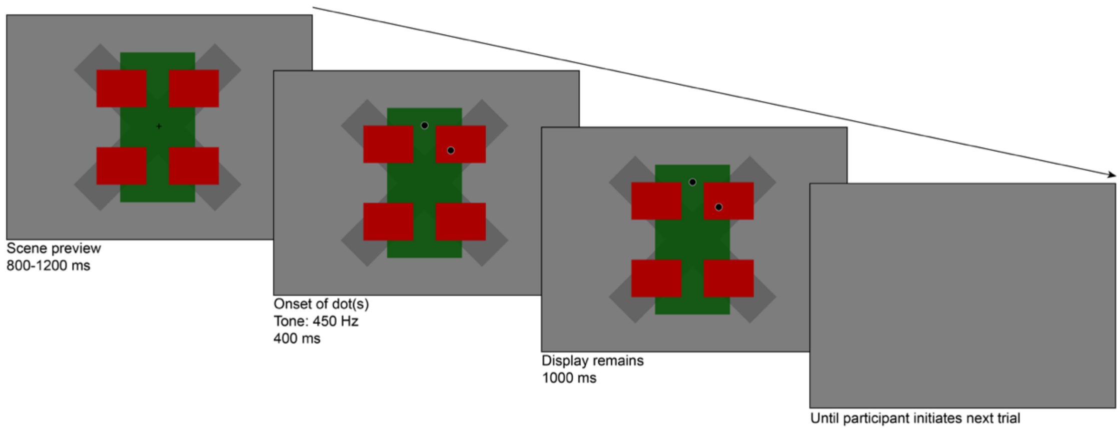


Figure 3.3. Trial sequence for a Different Surfaces display. In No Surfaces displays, the scene preview period was a gray screen.

Design. A fully factorial 2 (Distractor: absent, present) × 3 (Surface condition: absent, same, different) within-subjects design was used. All conditions were mixed within experimental blocks of trials. Data were collected from 7 blocks of 36 trials each, yielding a total of 42 observations per condition. The surfaces or surface-free gray screen were present for 800, 1000, or 1200 ms before the onset of the target (and distractor, if present). The target was equally likely to appear in the upper or lower hemifield, and the distractor (if present) was equally likely to appear to the left or the right of the target in the upper or lower hemifield.

Measures & Analysis. Trials were excluded if there was a blink after target onset (0.9% of total trials excluded), if the first saccade did not originate within 2 degrees of fixation (10.0% of trials), and if the saccade landed more than 8 degrees visual angle from the target centroid (0.7%). For the deviation analysis, I used custom MATLAB code to analyze mean signed average deviation in degrees relative to the straight vector from the start of the saccade to the correct target location (Godijn & Theeuwes, 2002; 2004). A deviation was calculated in degrees of angular difference for each data point (1 per millisecond), and then all deviation values for that saccade were averaged to produce the saccade's mean deviation (signed negative for deviation toward the distractor and positive for deviation away). Subject mean deviations and mean landing distance for each condition were submitted to within-subjects ANOVAs with $\alpha = .05$. Greenhouse-Geisser corrections were used when Mauchly's test of sphericity yielded $p < .1$. Effect sizes are reported with partial eta-squared η_p^2 as output by SPSS. I also report Bayes Factors analysis of critical t-tests to determine the evidence in favor of the null versus alternative hypotheses, using an r-scale factor of 1 because saccade of the consistent-yet-small effect sizes of deviation and landing position effects (Rouder, Speckman, Sun, Morey, & Iverson, 2009).

Results. Although saccade trajectories deviated more in the presence of a distractor, this distractor-related deviation was unaffected by surface context. However, the presence of surfaces reduced saccade curvature for faster saccades.

Figure 3.4 shows a subset of saccade paths from all observers when the target was in the upper hemisphere, including the infrequent trials in which saccades landed on the distractor (which were not included in the deviation analysis). Each path has been shifted along (x, y) coordinates so that the origin of the saccade appears to start at exactly the "fixation" origin point. As such, the landing positions of these saccades do not reflect actual landing positions, but otherwise the saccade path (i.e., deviation) is untransformed. Quite visible is a replication of the standard effect of a distractor on saccade deviation: saccade trajectories deviated more along their paths when a distractor was present. But saccade deviation was not mediated reliably by surface context. These impressions are bolstered by Figure 3.5 which shows mean deviation as a function of Distractor and Surface condition.

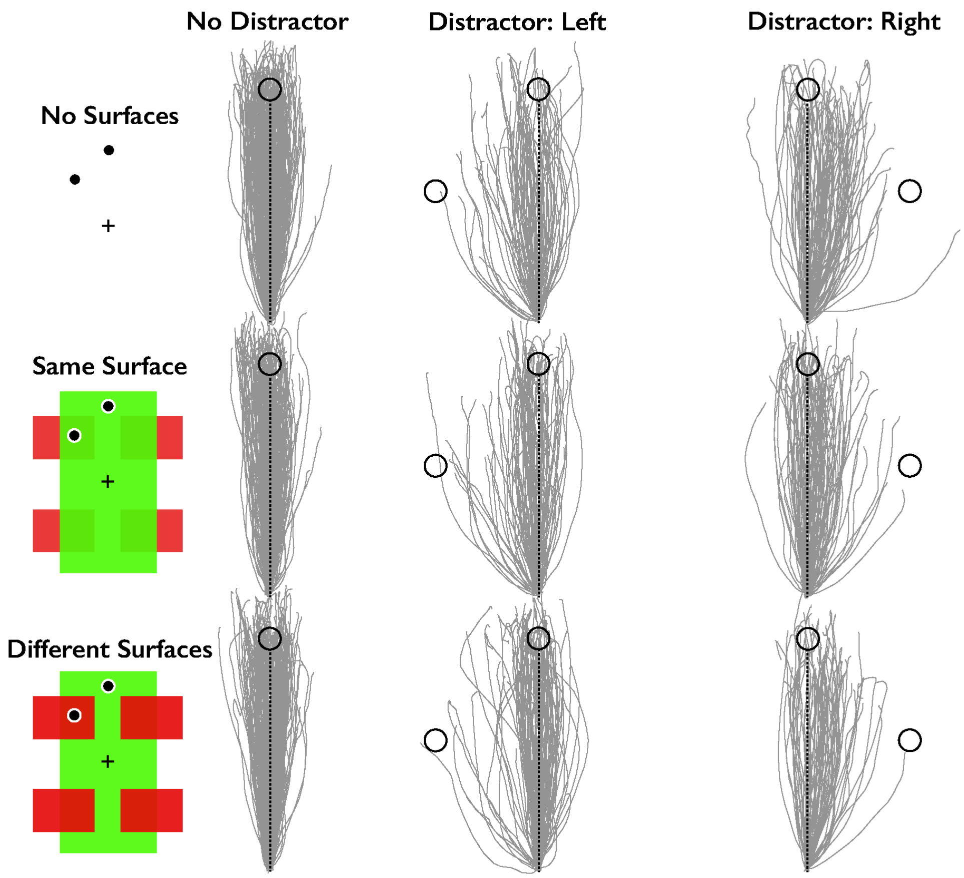


Figure 3.4. Saccade paths from Experiment 2. Saccade paths have been translated such that the origin is plotted at the vertical axis, and thus this figure is only an accurate reflection of saccade deviation, and not necessarily of landing position.

A 2 (Distractor presence) × 3 (Surface condition) repeated-measures ANOVA of mean saccade deviation supports these impressions.

Distractor presence reliably affected deviation, $F(1,12) = 16.63$, $p = .002$ $\eta_p^2 = .58$. There was no main effect of Surface condition, $F(2,24) = 0.01$, $p = .9$, $\eta_p^2 = .001$, nor of quartile, $F(3,36) = .45$, p = .7, $\eta_p^2 = .04$. Critically, distractor-driven deviation was not affected by the presence or type of surface structure in the display, as there was no evidence for an interaction between Distractor presence and Surface condition, $F(2,24) = 0.15$, $p = .86$, $\eta_p^2 = .01$.

I performed a Bayes Factors analysis of distractor-driven deviation, in which I compared the posterior likelihoods of two hypotheses: that there *was* a significant difference between Different Surfaces and No Surfaces, and that there was *no* significant difference. A Bayes Factors analysis (Rouder et al., 2009) indicated that the null hypothesis (no effect of surface structure on distractor-driven deviation) was 1.80 times more likely to be true than the alternative hypothesis.

I conducted a similar analysis of signed landing error. Again, the presence of a distractor reliably caused saccade landing error $F(1,12) = 132.75$, $p < .001$, $\eta_p^2 = .92$, but there was neither an effect of surface structure, $F(2,24) < 1$, $p = .5$, nor an interaction between distractor presence and surface structure, $F(2,24) < 1$ $p = .7$, $\eta_p^2 = .04$. A Bayes Factors analysis of distractor-driven landing error, for different versus no surfaces, found that the null hypothesis to be 3.45 more likely to be true than the alternative hypothesis.

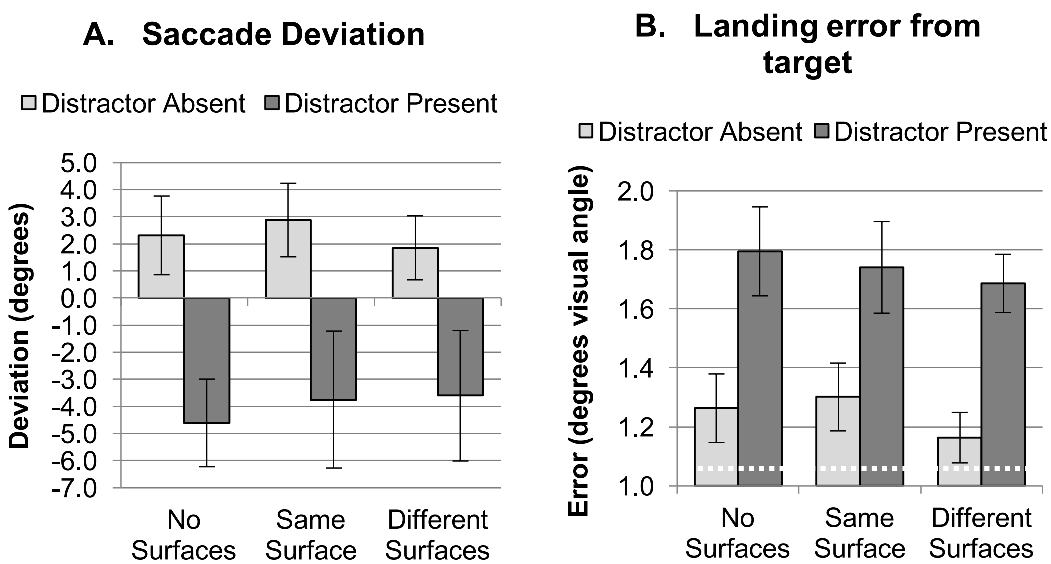


Figure 3.5. Results as a function of distractor presence and surface condition in Experiment 2. A. Mean saccade deviation (negative curving toward the distractor or left, and positive values curving toward or right). B. Landing position error from target of the first saccade. Error bars show standard error of the mean. Dashed white line in B marks the boundary of the target dot.

I defined full oculomotor capture as saccades that landed within 2 degrees of the distractor centroid. Capture occurred generally on 12.7±9.3% of distractor-present trials. Although capture was statistically different from zero, $t(12) = 5.35$, $p < .001$, it was unaffected by surface structure, $F < 1$, $p > .5$.

The prediction was that surface-based mitigation of saccade behavior would occur in saccade trajectories, and not latencies. Nonetheless, I conducted a latency analysis for saccades that correctly landed within two degrees of the target centroid. Although saccade latencies were generally faster when a distractor was absent (198.2±10.3 ms) compared to present (212.4±14.8 ms), $F(1,12) = 6.23$, $p = .028$, $\eta_p^2 = .34$, there was neither a main effect of surface structure nor an interaction, Fs < 2, ps > .1.

Discussion. Experiment 2 replicated the kinds of effects that distractors have been shown to have on saccadic deviation and landing position. Specifically, saccades had greater deviation and more landing error when a distractor was present compared to absent. These distractor-related effects, however, did not change with surface structure. Simply adding surfaces to the display had no effect, and there were no differences in the effects of distractors across the Same Surfaces and Different Surfaces conditions.

There are several specific aspects of this experiment that might have reduced any impact that surface structure might have on distractor-related behavior. First, it is possible that the displays did not evoke the percept of surface structure sufficiently strongly. Surface structure was rendered using occlusion and transparency. Additional cues (e.g., relative motion or binocular disparity) may have yielded more compelling surface structure and impacted saccade behavior. Related, the colors of some of the surfaces changed between trials to reduce the likelihood that observers would bind a specific color with any of the distractor or surface conditions. However, more consistent surface features may have supported stronger surface representations. Finally, in the Different Surfaces condition, the distractor always appeared on surfaces that were "closer" to the observer than the surface on which the target appeared. Near objects have been found to be prioritized for selection over far objects (Atchley, Kramer, & Andersen, 1997a). Such prioritization could have overridden any impact of same- versus different-surface structure on there might have been. If this were the case, it would be due to an impact of surface structure on saccade behavior (near versus far being defined by the surface structure), but not the kind of impact that the current experiment was designed to detect.

Experiment 3: No Evidence Photorealistic Surface Structure Affects Saccades

Experiment 3 was similar to Experiment 2 except that I used photorealistic stimuli (balls and tables; see Figure 3.6) to more strongly promote the perceptual organization of the scene into functional surfaces. The Different Surfaces condition was also modified such that the distractor and target were at the same implied depth relative to the observer. Otherwise, the logic was the same as that for Experiment 1. Each display started with zero (No Surfaces), one (Same Surface), or two (Different Surfaces) surfaces. A saccade target was always present, and a distractor was present on half of trials and in the same left/right hemifield as the target.

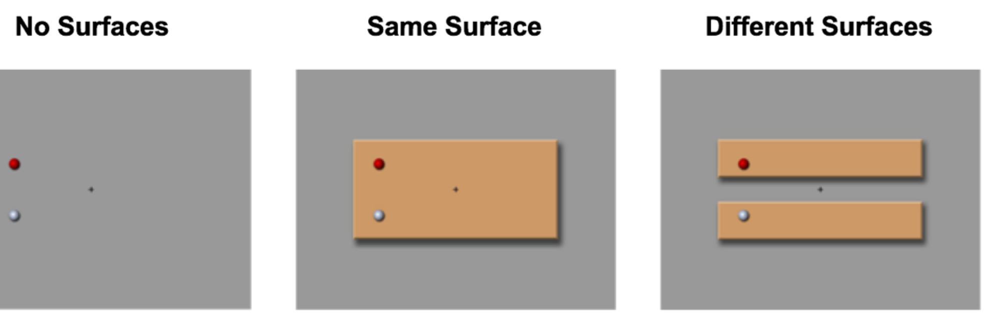


Figure 3.6. Examples of stimuli used in Distractor Present conditions of Experiment 3.

Participants. 5 participants (aged 18-21), all who reported normal or corrected-to-normal visual acuity and color vision and none who had participated in Experiment 1, completed this experiment.

Stimuli. The stimuli were generated in Photoshop and imported as textures in MATLAB. Embossing and shadow effects were added to the red ball, the gray ball, the large table, and the small table stimuli to promote the perceptual organization of a scene with surfaces.

The balls were 1.7 degrees visual angle (dva) in diameter. The tables were both 16 degrees in width. The large table (“Same surfaces”) was 8 dva in height, and the small table (two of which formed the “Different Surfaces”) was 3.0 dva tall. The mean luminance values for the red (target) ball, gray (distractor) ball, table, and gray background were 20.1, 34.2, 33.5, and 37.0 cd/m^2.

The balls occupied one of 4 positions, such that the target’s centroid was always 9.6 degrees to the left or right of fixation and 3.2 degrees above or below of fixation. The distractor (if present) occupied the coordinate in the same left/right hemifield as the target and had a centroid 6.4 dva from the target's centroid (3.0 dva separated the edges of the target and distractor).

Task. Observers fixated until the dot(s) appeared. When the red target dot appeared, they were to saccade to it as quickly and accurately as possible.

Procedure. The procedure was the same as Experiment 2, with changes noted below.

Participants completed 3 blocks. Surface condition was blocked and counterbalanced, such that block series were arranged in one of two orders: {No Surfaces, Same Surface, Different Surfaces} or {No Surfaces, Different Surfaces, Same Surface}. Before each block of experimental trials, after a standard 9-point calibration and validation, participants were reminded of their central task and were informed that the ball(s) would appear "on the ground", "on top of one big table", or "on top of two small tables," respectively.

For each trial, the fixation cross and the surface structure (whether ground only, large table, or two tables) were present for 500, 600, or 700 ms before the onset of the ball(s). After 600 ms, the balls disappeared off the table. The surface condition was maintained throughout the entire block. For example, in the "Same Surface" block, the large table was present with no onsets or offsets throughout the entirety of the experimental trials within block.

Design. Surface structure (No Surfaces, Same Surface, Different Surfaces) was blocked. The distractor was present on half of trials, and was always in the same left/right hemifield as the target. Data were collected from 3 blocks of 96 trials each, yielding a total of 96 observations per surface condition, of which 48 were distractor-present trials. The target was equally likely to appear in the same 4 top left, top right, bottom left, and bottom right positions. The surfaces or surface-free gray screen were present for 500, 600, or 700 ms before the onset of the ball(s).

Results. Figure 3.7 shows a mean saccade deviation and landing error as a function of distractor presence and surface structure. Distractors affected deviation and landing error, but Surface structure did not.

A 2 (Distractor presence) × 3 (Surface condition) ANOVA validated these observations. There was a replication of standard distractor deviation: saccade trajectories curved more when a distractor was present compared to absent, $F(1,4) = 41.62$, $p = .003$, $\eta_p^2 = 0.91$. As in previous experiments, there was no main effect of surface structure on saccade deviation, $F(2,8) = 0.31$, $p = .7$, $\eta_p^2 = 0.07$. Critically, surface structure did not interact with the distractor's presence to affect deviation, $F(2,8) = 0.45$, $p = .7$, $\eta_p^2 =.10$. Bayes factors comparing distractor-driven deviation with Different surfaces versus no surfaces were 1.92 in favor of the null hypothesis.

Landing error analyses revealed similar findings. The presence of a distractor caused greater landing errors, $F(1,4) = 53.42$, $p = .002$, $\eta_p^2 = 0.93$ but there was no main effect of Surfaces, $F(2,8) = 0.12$, p = .9, $\eta_p^2 = .03$, nor an interaction, $F(2,8) = 0.11$, $p = .5$, $\eta_p^2 = .43$. Bayes factors were 2.24 in favor of the null compared to the alternative hypothesis for distractor-driven landing errors when the target and distractor were on Different surfaces versus No surfaces.

Capture was again infrequent, occurring on 7.8% of trials, with no effect of surface structure, $F = .93$, $p = .4$.

Again, saccades deviated along their paths more and had greater landing error when a distractor was present compared to absent, but there is no evidence that these effects were mediated by surface structure.

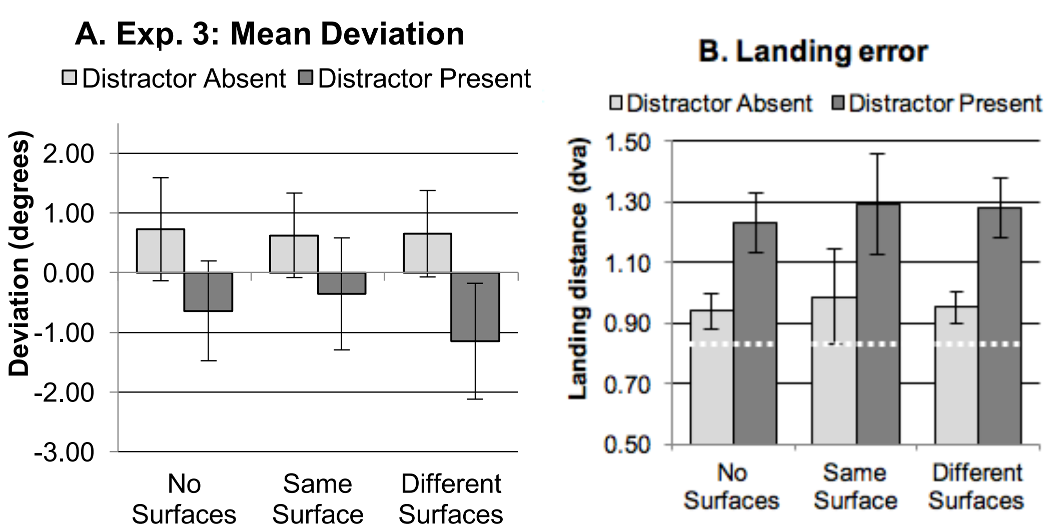


Figure 3.7. Results from Experiment 3: Mean deviation in degrees and Landing Error. Distractor presence affected saccade behavior, but Surfaces did not.

Discussion. As in Experiment 2, Experiment 3 showed greater saccade deviation and landing error when there was a distractor present rather than absent. However, also like Experiment 1, there was no evidence that these effects of the distractor changed with the surface structure of the scene. The evidence from Experiments 1, 2, and 3, therefore, is consistent with (completed) surface structure having little or no impact on saccade behavior.

It is possible that the distractor was only weakly effective and that any potential effects of surface structure on deviation were too small to detect. Consistent with this possibility is the fact that there were relatively low rates of full oculomotor capture by the distractors. There are a few reasons why the distractor may not have been very distracting. First, it is possible that the simultaneous and abrupt onset of the target and distractor in these experiments caused observers to perceptually group them as a unit and attend to them independently of the surface structure in the background, which onset earlier in the trial (Jiang, Chun, & Marks, 2002a; Yantis, 1992).

To provide a further test of the possible impact of surfaces on saccade behavior, therefore, Experiment 4 eliminated the onset asynchrony between the objects and surfaces, changed the distractor to red to make it more salient, and added a high-engagement task that forced observers to attend to the surface structure.

Experiment 4: Attended Surfaces Affect Scene Judgments but Not Saccades

The goal of Experiment 4 was to increase distractor salience, to more strongly promote the perceptual organization of the scene into relevant surfaces, to increase observer engagement, and to include a measure that allowed us to assess whether observers had processed the surface geometry of the scene. The surface (table) and balls appeared at the same time, eliminating any concerns that differential onsets might have caused. I also added a second task at the start of each trial in which observers judged whether the two balls were on the same surface (a table) or different surfaces (one on the table and one on the "ground," meaning the gray background).

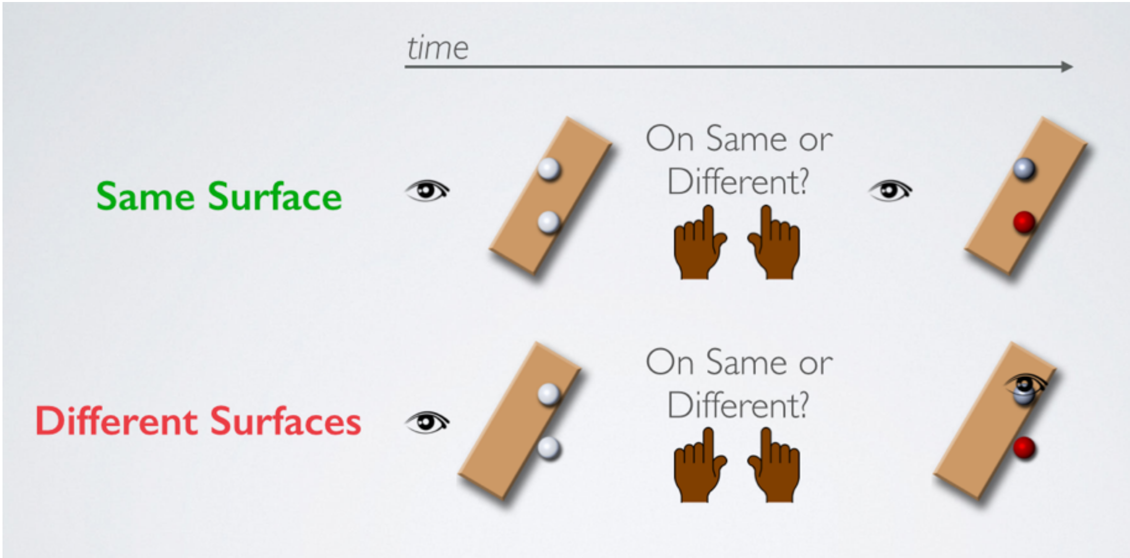


Figure 3.8. Trial sequence of Experiment 4.

Participants. Thirteen participants (aged 18-30), all who reported normal or corrected-to-normal visual acuity and color vision and none who participated in Experiments 1 or 2, completed this experiment. Three participants were replaced for frequent (>40%) saccades that landed more than 8 degrees from the target.

Stimuli. The balls were 0.6 dva in radius. The centroids of both balls were always drawn 7 dva to the left or right of fixation and 2 dva above and below fixation (such that 4 dva separated the centroids of the balls, and 2.4 dva separated their edges. The centroid of the table (3.7 dva wide and 10.7 dva long oriented at 30 degrees) was drawn varying eccentricities according to Surface condition, such that its center was 7 dva from fixation to encompass both balls (Same) or 8.5 dva from fixation to encompass only one ball (Different).

Task and Procedure. Two white balls and one table onset on the screen at the same time as fixation. Participants maintained fixation and pressed “f” if the balls were on the same surface (both on the table) and “j” if the balls were on different surfaces (one on the table, one on the ground). After this response, there was a 600 ms SOA before fixation offset and the balls changed color: one gray (target), one red (distractor). There was a simultaneous 500 Hz 80 ms tone that signaled the participants to saccade to the target as quickly as possible. The display remained on the screen for 1000 ms. Then the balls and surface were removed from the display. If the surface judgment was incorrect, feedback in the form of a 400 Hz 150 ms tone was provided. For all trials, the participant initiated the next trial by pressing the spacebar.

Participants performed 6 experimental blocks of 40 trials each.

Design. This was a one-way design that manipulated whether the target and distractor were on the Same surface or Different surfaces. The target, distractor, and surface were always present. The balls and surface always onset and offset together, and were equally likely to all appear in the left or right hemifield on a given trial. In "Different surfaces" trials, it was equally likely for the target or distractor to be on the table.

Results: Surface Judgments. Observers were 96.7±2.9% accurate on surface structure judgments, with no difference in accuracy between the two conditions, $F = 2.3$, $p > 0.2$. Response times, however, were significantly different when the two objects were on the Same Surface (782.1 ms) compared to Different Surfaces (765.7 ms), $F(1,12) = 5.44$, $p = .04$, $\eta_p^2 = .33$. This is evidence that the surface structure differentially affected covert processing of the scene.

Results: Saccades. Capture and deviation were unaffected by the surface manipulation. However, the slowest quartile of saccades showed different effects of Surface structure on landing position error.

Full oculomotor capture by the distractor occurred on 9.5% of Same Surface trials and 10.9% of Different Surface trials. Surface structure did not affect capture rates, $F(1,12) = 1.77$, $p = .21$, $\eta_p^2 = .14$.

Mean deviation and landing error are shown as a function of surface condition in Figure 3.9. A one-way repeated-measures ANOVA found no reliable effects of Surface condition on deviation, $F(1,12) = 1.89$, $p = .2$, $\eta_p^2 = .14$, nor of Quartile, $F(3,36) = 1.22$, $p = .3$, $\eta_p^2 = .3$, with no evidence for an interaction. A Bayes factors test of distractor-driven deviation, comparing Same versus Different surfaces, found BF of 3.52 in favor of the null hypothesis.

Landing errors followed the same pattern. There was no effect of Surfaces, $F(1,11) = 0.35$, $p = .6$, $\eta_p^2 = .03$, and Bayes factors were 3.94 in favor of the null hypothesis.

Surface structure did not affect saccade latency $F(1,11) = 1.88$, $p = .20$, $\eta_p^2 = .15$.

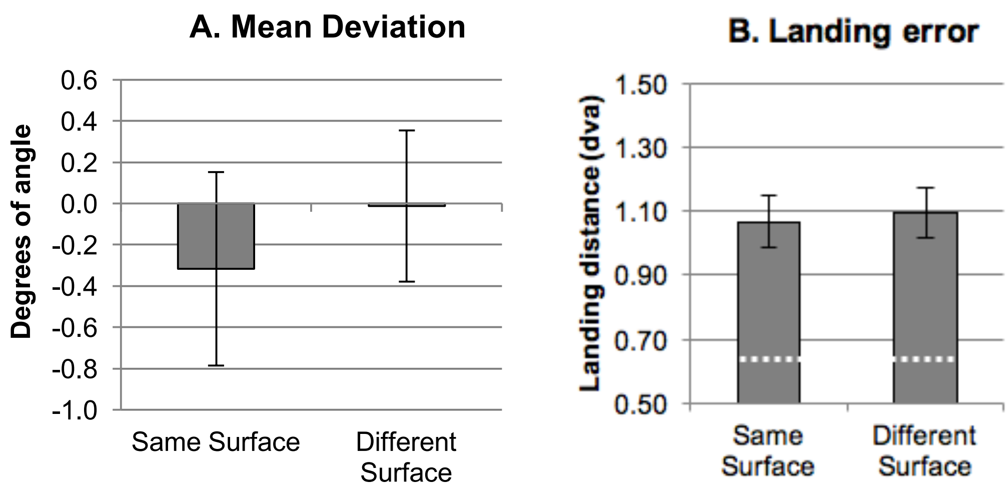


Figure 3.9. Results of Experiment 4: Mean deviation and landing error, as a function of surface condition.

Discussion. Even with evidence that observers had attended to the surfaces because they made judgments about the surface structure of the scene, and even with the conditions eliciting a higher percentage of capture trials, there was still no evidence that saccade curvature was affected by the surface structure of the scene within which the saccades occurred.

Chapter Discussion

The visual world is comprised of complex scenes of objects. One longstanding theory of visual processing holds that this visual information is obligatorily parsed into object surfaces (He & Nakayama, 1992), and that surface-based coordinates form the representation on which attentional selection unfolds. Indeed, within the domain of covert attentional selection, surface structure has been found to fully mediate distractor-related effects in both visual search (Vatterott & Vecera, 2015; Moore, Grosjean, & Lleras, 2003) and divided attention tasks (Ernst, Palmer, & Boynton, 2012). I tested whether overt attention is also fully mediated by a surface-based coordinate system. The premotor theory of attention (Sheliga et al., 1994) interpreted the numerous and compelling findings of common functional overlap between covert and overt attention, and proposed that attention and saccade planning rely on the same functional processes. As such, I predicted that surface information would dramatically impact the saccade plan in the same capacity that it affects covert attentional tasks.

In Experiments 2-4, I used a well-established baseline effect of distractor-driven saccade deviation (e.g, Doyle & Walker, 2001; Theeuwes et al., 1999) to examine whether this deviation was modulated by surface structure, such that the saccade target and distractor objects could be on the same or different surfaces. These three experiments replicated the baseline effect: namely, that saccades deviated from a straight path with greater magnitude when there was a distractor present, compared to when it was absent. This deviation was not, however, affected by surface structure. These findings obtained when targets and distractors were simple dots on translucent surfaces (Experiment 2), when scenes were photorealistic balls on top of tables (Experiment 3), and when surface structure was made task relevant (Experiment 4). These same experiments also found no effect of surface structure on saccade landing position, such that the distractor caused a "global effect" (Findlay, 1982) that was not affected by surface structure.

In Experiments 2-4 saccade deviation and landing positions were consistently affected by distractor presence and consistently unaffected by surface structure. Critically, in Experiment 4, manual response times were significantly different for Same versus Different Surface in surface judgments made preceding the saccade; still, despite evidence for differential processing of these scenes, there was no evidence that surface structure mitigated saccade behavior.

I conclude that, in contrast to converging evidence of strong effects of surface structure on covert attentional processing, there is no compelling evidence from Experiments 1-4 that the human saccade system obligatorily encodes surface geometry in the execution of an orienting saccade to a target – even when the surface context itself has been attended (Exp. 4).

That saccade behavior *can* be invariant to surface structure does not imply that saccade behavior *will always be* invariant to surface structure. The present experiments varied the photorealism of the displays and the task-relevance of the surfaces, but these displays were relatively sparse and it is possible that other kinds of surface displays would produce surface-modulated effects on distractor trajectories in orienting saccades.

Another possibility is that orienting saccades are never sensitive to surface context. Indeed, it is possible that our experiments have simply established one boundary condition of displays for which surface structure does not affect the saccade plan, but that other displays and tasks may find strong effects of surface geometry. In other words, perhaps covert and overt attention do rely on the same underlying map and processing, but surface structure might not be expressed in the saccade trajectory. Hunt et al. (2007) proposed that the same internal process of attentional capture can be differentially expressed in manual response times or in saccade trajectories due to the differential level of information accumulation that occurs before the initiation of a saccade and the initiation of a manual response. I have controlled these tasks and displays so that all information is available to both systems quickly, but it remains a possibility that these two different measures of internal processing could find differential effects.

There may be task differences that would produce evidence of surface-contingent saccade trajectory changes. It seems likely that when observers perform high-engagement tasks, like those that involve visual search for something within a more complex environment, then saccade landing positions would be guided by the surface geometry of the scene. The most obvious cases of this are when a surface (e.g., a desk in a room) provides spatial guidance for the target of search (a pen). This "obvious" case might provide the other boundary of the spectrum along which surface structure does or does not affect saccade deviation or landing positions.

Finally, it is notable that there was evidence that the added visual complexity of surfaces alone did not affect saccade latency, deviation, or landing positions even in the absence of distractor effects. This suggests that scene complexity alone does not necessarily affect covert attentional behavior. It also raises the intriguing possibility that the covert attentional system is generally insensitive to complex scene structure that is task-irrelevant and does not inform the observer of a target's features or retinal location. If true, then this would establish an invariance for computational and neurophysiological models of saccade programming: such models could effectively proceed without engaging the perceptual organization of surfaces, instead prioritizing retinal information from basic features (i.e., salience), and top-down guidance (i.e., of target-matching features or of contextual cues for locations).

The logic in Chapter 3 was to start with distractor-related saccade effects in low-engagement tasks that minimally build upon existing saccade work, and to add different kinds of surface structure to test whether the trajectory effects that index attention are affected by surfaces. But the surface manipulations used in Chapter 3 that have not been validated by other research to produce surface-based processing. The lack of evidence of distractor modulation in these experiments is that the null effects could indicate either a weak manipulation of the surfaces, or provide further evidence that even strong surfaces require a high engagement task to reveal object-based processing. To test these requires starting with a known object-based effect. In Chapter 4, I sought to first replicate an existing effect that demonstrates modulation of covert distraction by surface context, and then to extend that work in a saccade paradigm.

4. SURFACES MITIGATE COVERT DISTRACTION UNDER HIGH ENGAGEMENT

Object boundaries conform the shape of spatial attention, such that a salient color singleton distractor only produces attentional distraction when it is on the same surface, but not a different surface, as a target (Vatterott & Vecera, 2015). To briefly summarize their work, observers searched for a circle among seven diamonds and reported the orientation of the bar inside the circle. Each block was preceded either with a Location Cue (arrows pointing to four of the eight locations) or a Surface Cue, such that there were two overlapping surfaces in the scene and the target appeared on one of them. One of the diamonds could be a different color, and was thus a salient singleton. When present, this singleton could appear on the Cued region or an Uncued region. Manual responses were fastest when there was no singleton. When a singleton was present at a Cued Location or Uncued location, there was a slowing of manual response times, suggesting that observers could not use the Location Cues to configure attention to avoid distraction. When the singleton appeared on a Cued Surface, there was a manual RT cost, but this cost was mitigated when the singleton was on an Uncued Surface. The implications of this are significant: attentional distraction is a function of not just the spatiotopic coordinates and the salience of a stimulus, but also the scene context in which that stimulus occurs.

However, this previous work contained stimulus-based perceptual grouping cues (a known factor to mitigate distraction; Kerzel, Born, & Schönhammer, 2012) that were confounded with the surface manipulation. Figure 4.1 depicts this concern. In Vatterott & Vecera's displays, there were two kinds of blocks: those with location cues (no surfaces) and those with surface cues. In the location cue blocks, all stimuli appeared on a gray background. In the surface cue blocks, stimuli appeared on overlapping black and white surfaces. The different surface luminances serve to strongly promote object-based segmentation of the scene, but also may have inadvertently introduced two stimulus-based confounds. First, because the stimuli in surface conditions appeared on black-and-white backgrounds instead of a gray background, these scenes are overall more heterogeneous – a known factor in reducing the manual RT cost (Bacon & Egeth, 1994).

Second, when the color singleton was on the Same (Cued) Surface as the target, the "background" underneath it matched the target; and when the singleton was on a Different Surface, it had a different background than the target (see Figure 4.1). Feature-based perceptual grouping can allow reduction of the singleton-related manual RT cost (Kerzel, Born, & Schönhammer, 2012).

As such, it is possible the surface-based reduction of the manual RT cost found by Vatterott & Vecera was due not to the surface structure of the scene, but to the confounded stimulus features that could allow grouping.

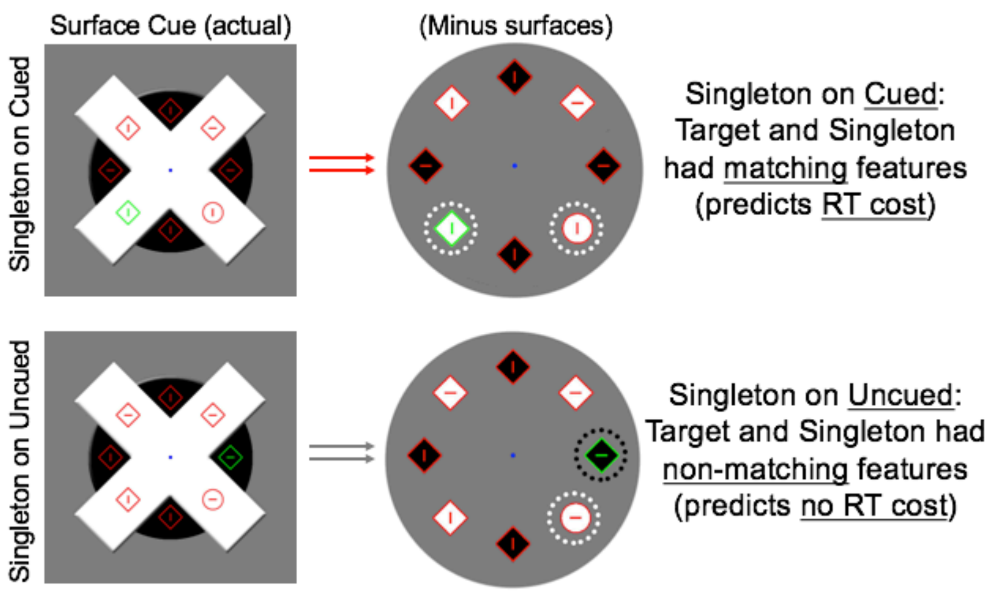


Figure 4.1. Illustration of the Surface displays and local feature confounds in Vatterott & Vecera (2015).

Because of the correlation between feature matches and the Surface manipulations, it remains an open question whether surface structure in the absence of stimulus grouping cues can mitigate distraction in the additional singleton paradigm and, if so, by what mechanism. In Experiment 5 I extend[2] previous findings using similar

[2] I started with a full replication (N=22) of Vatterott & Vecera (2015) and replicated the pattern of results, including the critical interaction between Singleton presence and Location/Object Cue, $F(2,42) = 5.61$, $p = .007$, $p\eta^2 = .21$, which was driven by the presence of the color singleton producing a manual RT cost in all contexts except when it was on an uncued Surface.

surface structure but eliminating stimulus-based grouping cues. In Experiment 6 I examine whether surface structure affects saccadic distraction.

Experiment 5: Surface structure and covert spatial attention

Experiment 5 used the same displays and task as Vatterott & Vecera (2015), but equated for stimulus-based heterogeneity in two important ways.

First, instead of using background stimulus objects that alternated between white and black on a flat gray background, I used a background luminance that was always the same gray for the no-surface background displays and for the objects in the surface displays. In contrast to the alternating white and black "cross" and "table" objects used previously, this study had surfaces of the same gray luminance. Thus eliminating the potential contribution of color-based grouping cues to the Surface manipulation.

Second, I changed the colors of the search array stimuli. Vatterott and Vecera used red and green stimuli that produced different levels of stimulus-to-background contrast ratios that were vastly different for both green and red on the white, black, and gray backgrounds of the original work. I used green and blue stimuli that were different in hue and in contrast polarity but had a similar magnitude of contrast difference relative to the gray background luminance that was used for the Location and Object cue conditions. As such, I largely controlled for differences in local stimulus heterogeneity.

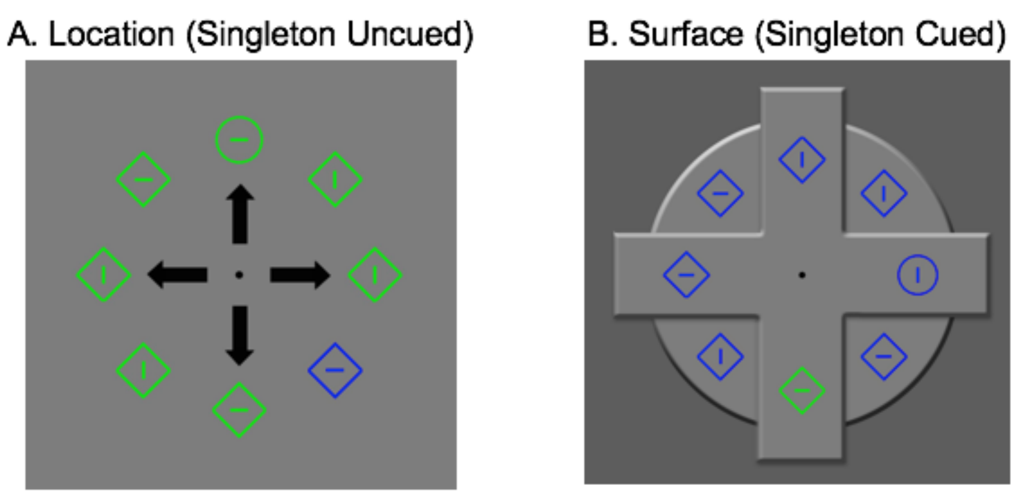


Figure 4.2. Illustration of two conditions. A. Location Cue blocks; image depicts a singleton present at an Uncued Location. B. Surface Cue blocks; image depicts singleton present, on a cued surface.

If the same pattern of results found in the original study is replicated, then I can conclude that the manual RT reduction is likely due to surface structure and not heterogeneity and local feature-based grouping.

Participants. Participants were 24 University of Iowa undergraduate students and lab members (18-23 years old) who reported normal or corrected-to-normal visual acuity and color vision, gave informed consent, and received course credit for participating. One participant was replaced due to poor calibration.

Stimuli. I will first describe the critical changes I made from the original work. First, instead of using background stimulus objects that alternated between white and black on a flat gray background, I used a background luminance that was always the same gray (34.2 cd/m^2) for the no-surface background displays and for the objects in the surface displays. This eliminating the potential contribution of local color-based grouping cues. In surface displays the background beyond the objects was 9.6 cd/m^2 to promote object segregation. Figure 4.2 illustrates the new stimulus features.

I also changed the colors of the search array stimuli. Vatterott and Vecera used red and green stimuli with luminance values of 37.8 and 115.5 cd/m^2. For the present conceptual replication, I used green and blue stimuli with luminance values of 49.3 and 19.8 cd/m^2. Relative to our baseline gray background of 34.2 cd/m^2 these are 15.1 cd/m^2 brighter and 14.4 cd/m^2 darker, respectively, and as such the green and blue stimuli are different in hue and in contrast polarity but have a similar magnitude of difference (salience) relative to the background. The search stimuli colors alternated pseudorandomly on each trial to be all blue or all green except for the singleton (if it was a singleton-present trial).

Other stimulus factors were largely unchanged from the original study but will be reported here. In all trials there were eight search stimulus objects, each 0.8 degrees visual angle (dva) in radius, arranged like a clock 6.3 dva from the fixation dot at the middle of the screen. Search array stimuli were separated by 4.8 dva. Seven were diamonds with 1 circle (the target). Inside each search object was a bar that was oriented vertically or horizontally, and was large enough (0.5 x 0.2 dva) such that its orientation could be discerned peripherally while a participant maintained fixation.

In the Location Cue blocks, four arrow cues (each 1.9×0.5 dva) indicated the four potential locations of the target. In this sense the cues were 100% valid but not spatially specific. In different blocks, the arrows pointed consistently either to the cardinal (north, east, south, west) locations of the search array, or to the "diagonal" (northeast, northwest, southeast, southwest) locations. The position of the target was chosen pseudorandomly from among the four pointed-to locations. In the Surface Cue blocks, observers were cued to attend to the top "cross" shape[3] that bounded four search stimuli. The cross could be oriented such that it bounded either the cardinal or diagonal regions of the search array. As such, both the Location and the Surface cues indicated four potential target locations. In Location blocks, the actual coordinates of the four potential target locations were unchaged, but in the Surface blocks, the four potential target locations could alternate between trials.

The arrows and the search array onset at the same time. The display remained on the screen for 2000 ms or until the participant pressed a button on the keyboard indicated their response to the orientation of the target bar. The display terminated upon response. If a response was not detected within 2000 ms, the trial was counted as a timeout error and a display with text encouraged the observer to respond faster. For all error trials – timeouts, erroneous judgments, or a key that was not used in the task was pressed – a 50 ms 400 Hz tone was played to indicate the wrong response.

Task. Participants were asked fixate during the trial events. Observers were asked to look for the circle-defined target and to report the orientation of the line inside of it by pressing "f" if the bar inside of it was oriented vertically and "j" if it was oriented horizontally. They were asked to respond as quickly as possible while maintaining at least 90% accuracy.

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[3] This is a slight departure from procedure in Vatterott & Vecera (2015), in which the target could appear on the top "cross" shape or the bottom "circle" shape between blocks. I made this change for two reasons. First, during my full replication of the original experiment, participants frequently noted confusion for being cued to the "circle". Second, I wished to better equate the Surface and Location cue conditions in terms of figure-ground segregation. The arrows in the Location cues could produce a percept of the cued stimuli being parsed as "figure", or closest to the observer, with the others as "ground." This would be consistent across all Location conditions. As such, I chose to only cue a Surface that was on the plane closest to the observer.

Procedure. Each experiment consisted of a single session that lasted approximately 1 hour. Following the informed consent process, participants were guided through a set of written instructions and images that described the task. Observers were told that sometimes a different colored item would be present but that it was never the target. No description of the singleton manipulations was given.

Observers began the experiment with 64 practice trials. The first half of practice used Location Cues and the second half used Surface Cues. A researcher remained in the room to answer questions and to emphasize maintaining fixation. Following the practice trials, observers completed 896 trials divided into eight blocks of 112. Four of the blocks were Location Cues and four were Surface Cues, with an order that was selected randomly for each participant.

Design. A fully factorial 2 (Display: Location, Surface) × 3 (Singleton condition: Absent, On Cued, On Uncued) within-subjects design was used. All conditions were mixed within experimental blocks of trials. Data were collected from 8 (2 for each Display type) blocks of 112 trials each.

Measures & Analysis. In following the procedures of Vatterott & Vecera, I focused on analyzing mean manual RTs for accurate trials, eliminating a trial if the RT was too fast (less than 300 ms; 0.1% of trials) or two slow (greater than 1500 ms; 3.7% of trials). Subject mean RTs and arc-sined proportion correct for each condition were submitted to within-subjects ANOVAs with $\alpha = .05$. Greenhouse-Geisser corrections were used when Mauchly's test of sphericity yielded $p < .1$. Effect sizes are reported with partial eta-squared η_p^2 as output by SPSS.

Results. Figure 4.3 shows mean manual RTs for correct trials as a function of condition. Responses were fastest when there was no singleton present, and slower in the presence of a singleton. However, when the singleton was on an Uncued Surface, the manual RT cost was reduced.

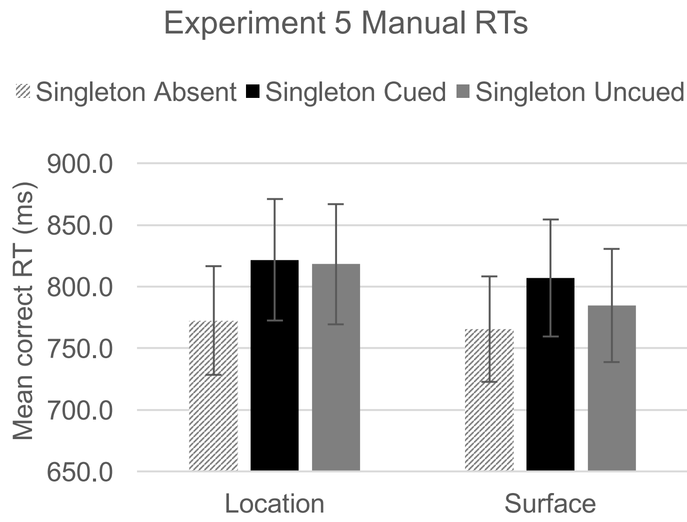

Figure 4.3. Mean manual response times as a function of condition from Experiment 5. Error bars show standard error of the mean. Singletons were equally distracting at cued and uncued Locations. Singletons were distracting on cued Surfaces, and measurably less distracting on uncued Surfaces.

A 2 (Display Type) × 3 (Singleton condition) repeated-measures ANOVA supports these impressions. RTs were marginally faster overall for Surface cues (779.6 ms) than Location cues (795.7 ms), $F(1,23) = 4.11$, $p = .055$, $p\eta^2 = .15$ (the original study found a significant main effect in the same direction). RTs were affected by whether the Singleton was absent, on the cued region, or on the uncued region, $F(2,46) = 47.84$, $p < .001$, $p\eta^2 = .68$. Critically, however, the singleton had different effects depending on whether the Display was a Location or a Surface: there was an interaction, $F(2,46) = 4.84$, $p = .017$, $p\eta^2 = .16$. To examine the differential patterns of these effects, I analyzed RTs in the same manner as Vatterott & Vecera.

First, I examined the effect of the singleton in the Location display. When the singleton was on a cued location there was a manual RT cost of 50.9 ms relative to the singleton-absent display, $t(23) = 6.83$, $p < .001$. When the singleton was at an uncued location there was a manual RT cost of 49.6 ms, $t(23) = 7.35$, $p < .001$, and there was no evidence that the manual RT cost differed between the cued and uncued locations, $t(23) = .17$, $p = .87$.

I did a similar analysis in the Surface displays. When the singleton appeared on a cued surface there was a manual RT cost of 43.2 ms, t(23) = 5.93, p < .001. When the singleton was on the uncued surface, the manual RT cost was smaller (20.8 ms) but present, $t(23) = 3.70$, p = .001. In contrast to the Location displays, there was evidence that the manual RT cost differed between cued and uncued surfaces by 22.4 ms, $t(23) = 3.12$, $p = .005$.

I also analyzed accuracy. Accuracy was high (mean error rate of 6.8%), and the same 2 × 3 ANOVA on arc-sined proportion correct found no main effects or interaction of the Cue or Singleton manipulations on accuracy, all *p*s > .08. This also is in line with Vatterott & Vecera's findings.

Discussion. Experiment 5 partially replicated and extended the findings of Vatterott & Vecera. Although singletons at uncued Locations caused slower RTs compared to when there was no singleton, the manual RT cost caused by singletons on uncued Surfaces was slightly but not fully mitigated: RTs were significantly slower than when there was no singleton, but significantly faster than when the singleton was on the cued surface. This pattern of the main effects, interaction, and t-tests partially replicates Vatterott & Vecera (2015), who found a full mitigation of the manual RT cost when the singleton was on an uncued surface.

This is a slight difference compared to Vatterott & Vecera. One possibility is that surface structure and feature-based perceptual grouping allow for more mitigation of the manual RT cost than surface structure alone. To explore this would involve experiments that manipulated both of these factors independently and is beyond the scope of this chapter.

Nonetheless, this is an extension of the original demonstration by Vaterott & Vecera that object surface boundaries can reduce singleton-related distraction. The present work demonstrates that surface context does allow for mitigation of a singleton-related manual RT cost – even in the absence of local feature-based stimulus features that could allow for grouping. With this confirmation of a critical finding of surface-mitigated distraction in the covert allocation of attention, this task and these displays can be used to examine surface mitigations of singleton-driven oculomotor behavior.

Experiment 6: Surface structure and overt spatial attention

Experiment 6 was similar to Experiment 5, with the goal of examining saccade behavior as a function of the Surface and Singleton manipulations. Oculomotor behavior in the additional singleton paradigm has been examined. The singleton tends to produce strong oculomotor capture in homogenous displays, and reduced capture in heterogeneous displays (Gaspelin, Leonard, & Luck, 2016; Theeuwes, 1992; Theeuwes et al., 2003). This pattern of differential capture reflects the pattern found in the manual RT cost reduction, and suggests that at least one mechanism that describes behavior in the additional singleton paradigm is one of a covert, followed by overt, spatial shift of attention toward the singleton.

In Experiment 6, the first prediction is that if object surfaces allow for the same benefits in oculomotor control as reflected in manual response times during a high engagement search task, erroneous saccades to the singleton will be less frequent when the singleton is on an uncued surface compared to a cued surface. Note that if this effect obtains, the conclusions will be similar to those drawn by McCarley et al., (2002): that under high engagement and when the surface is task-relevant, saccades exhibit object-based processing.

Compared to Experiment 5 I will make two sets of significant changes. First, the location cue condition will be changed to a "no cue" condition. This has multiple benefits. A no-cue establishes a baseline from which to assess the effect of cued object surface structure: more specifically, it tests whether cues can aid orienting toward the target or whether there is a cost overall to using the cues. The cost of this change is that in the previous Location versus Surface cue comparisons, both cue types indicated the four locations at which the target could appear; as such, the Surface Cue condition not only contains surfaces but arguably contains half the relevant set size than a No Cue condition.

The second set of significant changes are to the stimuli. The objects in the search array will be spaced farther apart and the lines inside of them drawn smaller so as to naturalistically require foveation to resolve its orientation. The search array diamonds/circles will be drawn with thicker borders to provide peripherally discriminable shape information.

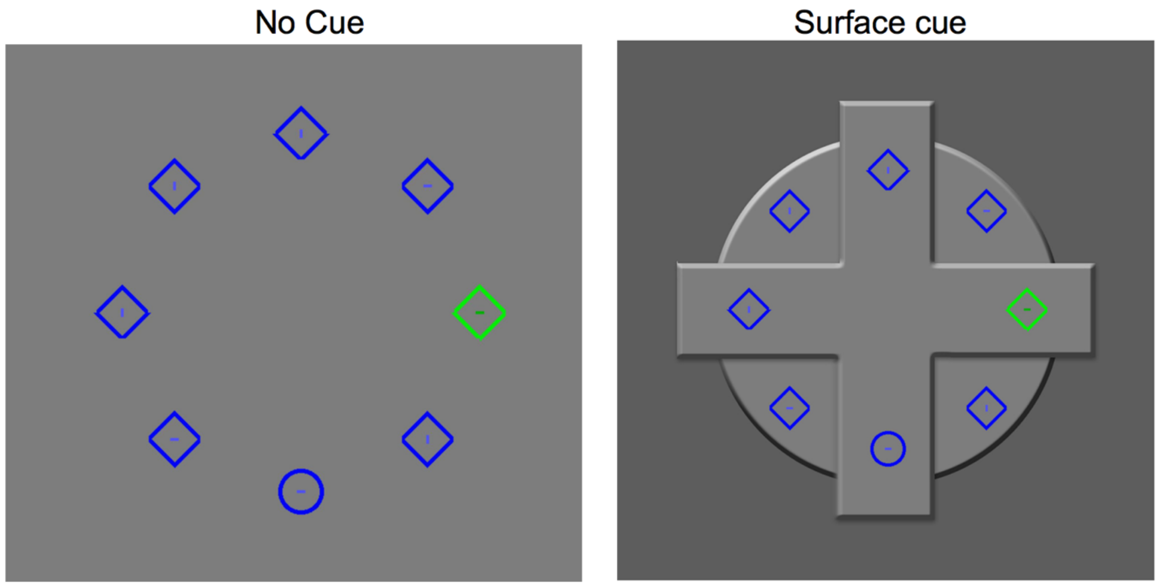

Figure 4.4. Two kinds of displays used in Experiment 6. On the left is the No Cue, Singleton Present (Cued) condition, and on the right is the Surface Cue, Singleton Present (Cued).

Participants. 21 participants (aged 18-21), all who reported normal or corrected-to-normal visual acuity and color vision and none who had participated in Experiment 5, completed this experiment.

Stimuli. Stimuli were unchanged from Experiment 5 except for the following changes. Each search array item was farther from fixation (6.9 dva) and the lines inside the search items were smaller (0.2 x 0.02 dva). I also kept the 2 (Display: No Cue, Surface Cue) x 3 (Singleton: Absent, on Cued, on Uncued) factorial manipulation and controlled the possible singleton conditions in the No-cue conditions to have the same potential coordinates as the Surface cues. In the No-cue conditions, the "Cued" Singleton could appear ±2 or ±4 'steps' from the target, and the "Uncued" Singleton could appear ±1 or ±3 steps away (as such, note that the "Uncued" singletons could occupy the two positions closest to the target). In the Surface Cue conditions, these positions corresponded with being on the same or different surface. In the no cue condition, the singleton is technically always uncued, but the position rule remained the same.

Task. Same as in Experiment 5. No recordings were made during practice blocks.

Procedure. Same as Experiment 5, with changes noted below.

Observers experienced two kinds of blocks: either No Cue or Surface Cue. They were told in both that the target could spatially appear at any of the 8 coordinates, but that in the Surface Cue blocks it would appear on the "cross" surface.

Before each block, the calibration of the eye tracker was checked to ensure that error was less than 1 degree. If the calibration was off, the participant was re-calibrated.

Design. As Experiment 5, I used a 2 (Display: No Cue, Surface Cue) × 3 (Singleton: Absent, Present: "Cued", Present: "Uncued") design.

Results: Manual RTs. Figure 4.5 shows mean manual RTs for correct trials as a function of condition. Recall that in the "No Cue" displays, I created "Cued" and "Uncued" singleton conditions in which the singleton appeared at the same locations it would have appeared in for the Surface Cued/Uncued conditions. As such there should be no difference between the "Cued" and "Uncued" conditions when there was No Cue.

Responses were fastest when there was no singleton, and slower in the presence of a singleton. Responses were also overall slower when there was a Surface Cue. Critically, when the singleton was on an Uncued Surface, the manual RT cost was absent.

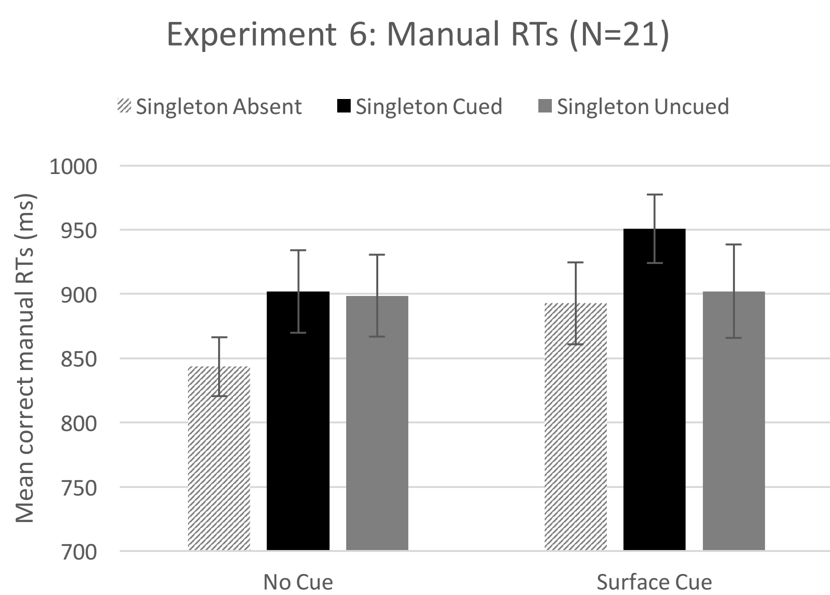

Figure 4.5. Mean manual response times as a function of condition from Experiment 6. Error bars show standard error of the mean. In the "No Cue" condition, the "Cued" and "Uncued" black and gray bars indicate different target positions (see text for details).

A 2 (Display Type) × 3 (Singleton condition) repeated-measures ANOVA supports these impressions. Mean accurate RTs were significantly slower in the presence of Surface Cues compared to No Cue, $F(1,20) = 39.16$, $p < .001$, $p\eta^2 = .67$. RTs were affected by whether the Singleton was absent, on the cued region, or on the uncued region, $F(1.64,32.74) = 14.70$, $p < .001$, $p\eta^2 = .42$. Critically, however, the singleton had different effects depending on the Display: there was an interaction, $F(2,40) = 3.65$, $p = .035$, $p\eta^2 = .15$.

I examined the effect of the singleton in the Surface displays. When the singleton was on a cued Surface there was a manual RT cost relative to the singleton-absent display, $t(20) = 4.36$, $p < .001$. There was evidence that the cost differed between the cued and uncued Surfaces, $t(20) = 2.37$, $p = .028$. Most critically, when the singleton was at an uncued Surface there was no evidence for a manual RT cost relative to the singleton-absent display, $t(20) = 0.98$, $p = 0.38$.

Results: Target Fixations. I defined "correct" fixations as the proportion of first saccades that terminated on the target out of the total number of first saccades that landed within 0.5 dva of the boundaries of either a target, distractor, or singleton. Figure 4.6 shows "correct" target fixations as a function of Display and Singleton type. Correct fixations were not affected by the presence of a Surface Cue, but did differ as a function of the Singleton manipulation.

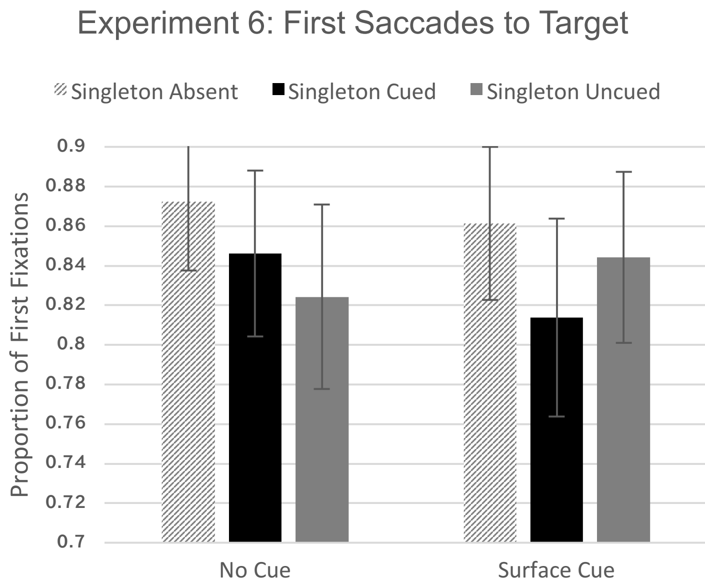

Figure 4.6. Mean proportion of trials in which the first saccade went to the Target (and not the Singleton or Distractor) as a function of condition from Experiment 5. Error bars show standard error of the mean. Saccades were less accurate when a Singleton was present, but this was unaffected by the Cue manipulation.

A 2 (Display Type) × 3 (Singleton condition) repeated-measures ANOVA supports these impressions. Saccades to targets were unaffected by whether the Display had no cue or Surface cues, $F(1,20) = 0.12$, $p = .73$, $p\eta^2 = .01$. Target fixations were, however, affected by the Singleton manipulation, $F(1.64,32.85) = 6.01$, $p = .009$, $p\eta^2 = .23$. There was no evidence that these factors interacted, $F(2,40) = 1.98$, $p = .15$, $p\eta^2 = .09$.

Results: Capture. I defined "capture" as the proportion of first saccades that terminated on the singleton distractor out of the total number of first saccades that landed within 0.5 dva of the boundaries of either a target, distractor, or singleton. Figure 4.7 shows oculomotor capture by the singleton as a function of the Display type. Capture was reduced when the singleton was on an Uncued Surface relative to all other conditions, and did not increase when it was on the cued Surface.

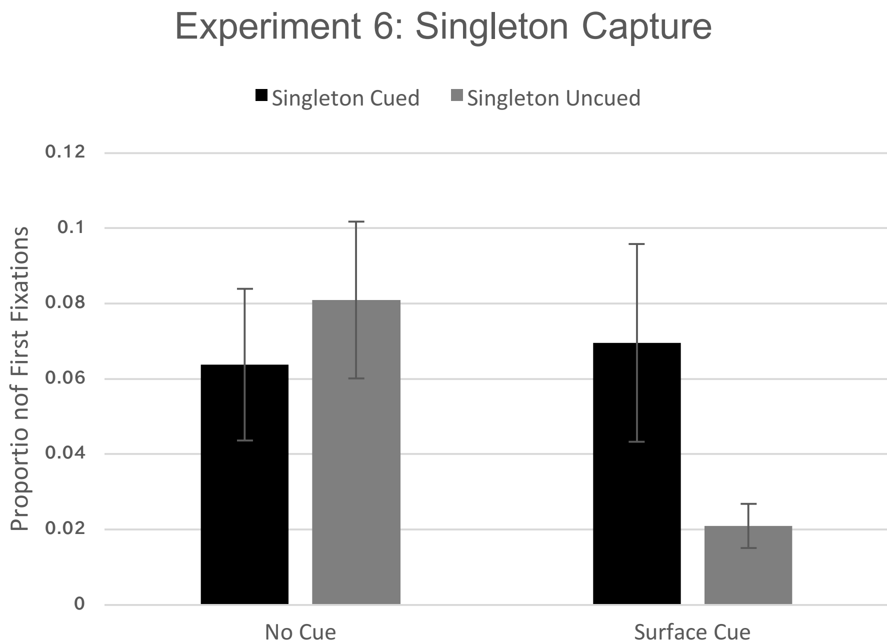

Figure 4.7. Mean proportion of trials in which the first saccade went to the Singleton (and not a Target or Distractor) as a function of condition from Experiment 6. Capture was reduced when the singleton appeared on the Uncued Surface. Error bars show standard error of the mean.

A 2 (Display Type) × 2 (Singleton: On Cued, On Uncued) repeated-measures ANOVA on the arc-sin square root of capture proportion supports these impressions. Capture was slower in the presence of Surface Cues compared to No Cue, $F(1,20) = 5.25$, $p = .03$, $p\eta^2 = .21$. Capture was also affected by whether the Singleton was on the cued region or on the uncued region, $F(1,20) = 5.36$, $p = .31$, $p\eta^2 = .21$. Critically, however, there was an interaction, $F(2,40) = 5.71$, $p = .03$, $p\eta^2 = .22$.

To explore this interaction, I conducted three t-tests. First, I wished to test whether Surface structure produced different rates of capture. Singletons on the Same surface as the target produced more capture than singletons on a Different surface, $t(20) = 2.88$, $p = .009$. Second, relative to the “No Cue” baseline, I wished to assess whether Surface structure increased capture by singletons on the Same Surface, decreased capture by singletons on the Different surface, or both. There was no evidence that a singleton produced more capture on the Same surface compared to no surface, $t(20) = .66$, $p = .5$.

There was, critically, evidence that a singleton on a Different surface produced less oculomotor capture than when there was no surface present, $t(20) = 2.75$, $p = .01$.

Discussion. Experiment 6 replicated and extended the findings of Experiment 5 in three important ways. First, manual response times indicated a full mitigation of the manual RT cost when the singleton was on a Different surface, such that it was as if that singleton was absent from the Surface displays. This is a slightly different finding than Experiment 5 in which I found only a partial mitigation of the manual RT cost as a function of surface structure. It is possible that the display – in which the search array was at a larger eccentricity compared to Experiment 5 – resulted in a singleton that was overall less salient, such that the singleton did produce capture but at a rate that was overall lower and thus more likely to be subject to a fully mitigated RT cost. There was another difference: that the Surface cue conditions produced overall slower RTs than the No Cue condition. This may have occurred simply because cue utilization may take time. The conclusion from the manual RT data is that I replicated and extended the critical findings of Vatterott & Vecera (2015) and of Experiment 5. This suggests that even in an "overt" version of this task using these displays, singletons produce a spatial re-orienting of attention that can be mitigated by surface structure in a manner that is consistent with what is found using a "covert" task.

The second two critical findings are from the saccade data. I found no evidence that singletons on the Same surface produced more capture than singletons in the absence of surface structure, and thus I conclude that there is no evidence of enhancement, spreading, or prioritization of the singleton as a function of the cued Surface in the saccade map. I did, however, find evidence of active suppression of the singleton (Gaspelin et al., 2016): singletons on the Different surface produced significantly lower capture than singletons on the Same surface or with no surface structure whatsoever. This suggests that the mechanism by which object surface structure affects the saccade map is by singleton suppression and not enhancement.

There is additional evidence against surface-based enhancement. Enhancement of on-surface items might not necessarily have resulted in greater capture by the singleton. If one imagines an attentional priority map, then perhaps all items on the cued Surface would be increased in salience relative to when there is no Surface structure. As such, perhaps there was not an increase in capture of the singleton, but an increase in target fixations. But I found that target fixations were only affected by the Singleton manipulation, with no effect of the Display nor an interaction.

As such, the conclusion from Experiment 6 is that there was active suppression of the singleton when it is on a Different Surface but not the Cued Surface as the target.

Chapter Discussion

In this chapter I set out with two goals. First, to replicate and extend a critical finding by Vatterott & Vecera (2015) that object surface structure mitigates the manual response time cost associated with singleton-related distraction in the additional singleton paradigm. And second, to see whether saccade behavior would reflect object-sensitive effects in this high-engagement task.

Vatterott & Vecera's work forms the critical foundation to my original question about how surfaces affect saccades in the presence of a salient distractor. In Experiment 5, I extended their work by making critical changes to the displays that removed stimulus feature-based grouping cues that were confounded with their Surface manipulations. I found that even in the absence of local feature-based grouping cues, surface structure still affected distractor processing: the singleton-related manual RT cost was present regardless of whether the singleton appeared on a Cued Location, Uncued Location, or Cued Surface, but was partially mitigated when the singleton was on an Uncued Surface. That I found partial rather than full mitigation of the singleton-related cost is a slight departure from the original findings by Vatterott and Vecera. This could result from a number of different reasons ranging from theoretically important (surface structure alone yields some mitigation of the manual RT cost, whereas surface structure plus feature-based grouping cues yields full mitigation) to more mundane (experimental or statistical fluke). In any case, the first goal was established: I confirmed that surface structure affords unique benefits relative to location-based cueing in the additional singleton paradigm.

The second goal in Experiment 5 was to examine how surface structure would affect distractor-related activity in the saccade map. I modified the displays slightly so as to require saccades to the target to perform the discrimination task. I also changed the

"Location Cue" condition to a no-cue condition so that I could assess surface-based processing relative to a neutral baseline (Yeshurun & Rashal, 2016) and thus examine whether surfaces promote performance benefits, costs, or both.

I examined singleton capture as a function of whether there was no surface structure present, whether it was on the Cued Surface with the target, or on the Uncued Surface not containing the target.

There were three critical findings. First, manual response patterns were consistent with the original findings of Vatterott & Vecera: when the singleton was on an uncued Surface, there was no evidence for any manual RT cost. This is in contrast with Experiment 5, in which I found partial but not full mitigation of the singleton-related cost. It is possible that Experiment 6's display – in which the search array stimuli were more eccentric – resulted in a singleton that was overall less salient, such that the singleton did produce a salience signal and a degree of capture but at a rate that was overall lower and thus probabilistically more likely to demonstrate a full mitigation of the manual RT cost.

The other critical findings concerned oculomotor capture. I specifically was testing whether there is evidence of active oculomotor suppression (Gaspelin et al., 2016) of the singleton when it was on the Uncued surface. I found evidence in support of this mechanism: capture by a singleton was significantly reduced on an Uncued Surface, in comparison to the Cued Surface or the baseline no-cue condition. This suggests that surface boundaries afford active suppression of the singleton in the saccade map.

There was no evidence that capture by the singleton increased when it was on a Cued Surface compared to a display with no cueing, nor any evidence that saccades to targets were aided by the presence of the surface cue. This is in line with similar findings by McCarley, Kramer, & Peterson (2002) of no saccadic enhancement of the target representation in the saccades to targets in the the Egly, Driver, & Rafal paradigm. This is further evidence against the idea that spatial attention spreads throughout the bounds of an attended surface, such that all stimuli on the attended surface are equally "boosted" in salience or priority (e.g., increased signal of on-surface items), in a manner that affects oculomotor programming. It is possible that spatial attention does spread throughout the bounds of the attended surface, but that *attentional control* (e.g., signal-to-noise) is increased, such that the salient signal of the singleton and the increased attentional control of the Cued Surface 'balanced' each other out to produce the same rate of capture as if there was no surface structure. However, the strongest evidence for this account would be an increase in first fixations landing on the target when it is on the cued surface compared to no cue, and I found no evidence of that. As such, I conclude there was no evidence of enhancement of items on the cued Surface in the saccade map.

Comparison to Chapter 3

Experiment 6 produced a novel finding: evidence for surface-based encoding in the saccade map. This is an important boundary condition to establish that, at some level, it is possible to find evidence in favor of surface-based encoding in the saccade map. But it is in stark contrast to repeatedly finding no evidence of this in Experiments 1-4 in Chapter 3. What changed?

One possibility is that the displays used in previous chapters did not strongly promote surface-based processing. In the discussion sections for Experiments 1, 2, and 3, I noted the potential pitfalls that could have counteracted any possible surface-based mitigation of the distractor activity, but overall it is possible that even were those factors controlled for, the displays – which were neither based on previous studies, nor tested to determine whether they produced distractor mitigation in covert tasks – simply did not promote strong object-based organization, a factor necessary for object-based effects (Chen, 2012). One way that these displays differed from those in Experiments 2-4 was that in previous experiments, the stimuli to be fixated were solid dots or spheres that appeared "on top of" surfaces, whereas here the stimuli were line drawings, such that the surface underneath them was visible. This may have resulted in the saccade task objects appearing to be more integral to the surfaces underneath them. It is possible that this is critical for object-based effects. As such, I consider it the most likely possibility that objects must appear to be integral to surfaces to produce surface-based mitigation of processing those objects.

There were significant differences in engagement. In the low-engagement tasks of Experiments 2-4, observers simply needed to saccade to a location- or feature-defined target, sometimes in the presence of a distractor that was spatially proximal and featurally similar to the target. Here, observers needed to use a shape-defined feature to detect a target, and in the Surface Cue conditions were provided a cue to narrow down the possible locations of the target. Needing to search throughout the display requires shifts of spatial attention that may serve to re-sample the display and promote a stronger object representation. The surface structure of the scene was task-relevant, and as such top-down attentional control settings may have resolved competition in favor of items on the cued shape.

Finally, it is possible that independently of task difficulty, the number of items in the display (two in Experiments 2-4, versus eight in Experiments 5-6) resulted in different competitive dynamics in which object surfaces could have effects. A salience map representing eight items may be noisier and involve more items competing for the focus of attention compared to the two items in Experiments 2-4. Stronger top-down attentional control may be needed to resolve competition in favor of the shape-defined target from among the numerous distracting items. Resolving competitive dynamics could take time, and it is possible that this additional time is what allowed surface information to enter the visual system and modify the priority map.

In sum, perhaps the resolution of inter-object competition was simpler in Experiments 2-4, such that surface structure was neither obligatorily encoded for the task over time nor useful for task performance.

This is a replication and extension of the finding that cued object surface structure can mitigate costs related to covert distraction. Furthermore, this is a novel demonstration that scene surface structure is incorporated into the saccade plan in a manner that also reduces overt distraction. The mechanism by which surfaces afford this is consistent with active suppression of the singleton on the uncued surface, with no evidence for enhancement or prioritization of the singleton on a cued surface.

This bolsters an important boundary condition established by McCarley et al. (2002): object surface structure does affect the saccade map when the surfaces are used to cue task-relevant locations. It remains possible that these surfaces may have been encoded in the salience map of the saccade, such that even were they not task-relevant they may have mitigated distractor processing.

5. SURFACE STRUCTURE AND ENGAGEMENT

In Chapter 4, there was evidence that surface structure affected the execution of a saccade when there was the object surface was cued and relevant to the programming of a saccade. The task required stronger top-down guidance in the form of feature-guided search for a target rather than a reflexive orienting saccade. This is in contrast to Chapter 3, in which three experiments found no evidence for surface-based processing in an orienting saccade task.

Does this mean that surface-based effects *only* arise in the saccade system under conditions of both surface task relevance and high engagement? Such a conclusion is premature. It is possible that surface structure is subject to obligatory encoding in the saccade map regardless of task specificity, but that the surfaces in Experiments 1-4 were insufficiently compelling to be perceived as surfaces and that the surfaces in Experiments 5-6 were sufficiently compelling. If this is true, then using surfaces that resemble those in Experiments 5-6 but in an orienting task should reveal surface context-based encoding in the saccade map even when surfaces were irrelevant to the saccade task.

On the other hand, it is possible that the null effects in Experiments 1-4 occurred because no surface context, regardless of how visually compelling the surface organization, is encoded in the saccade system if it is not relevant to the task. If this is true, then only using surfaces that are demonstrably compelling will have no effect on the saccade system, such that surface based effects only arise under conditions in which the surface structure is relevant to the saccade task (i.e., such that the saccade reflects surface structure only as a function of goal-driven modulation of activity in the saccade map).

Experiment 7: Surface structure but not engagement affects saccade trajectories

Experiment 7 used a similar saccade task as the first three experiments: observers were to quickly saccade to a target in the presence of a distractor. As in all experiments, I manipulated the presence of surface structure such that this target and distractor could appear with no surface structure, on the same surface, or on different surfaces. I also introduced a manipulation of engagement in different phases of the experiment. In the first phase of the experiment, participants did only the saccade task. In the second phase of the experiment, after the saccade task was completed, observers were to make manual responses to indicate judgments of the surface structure of the scene.

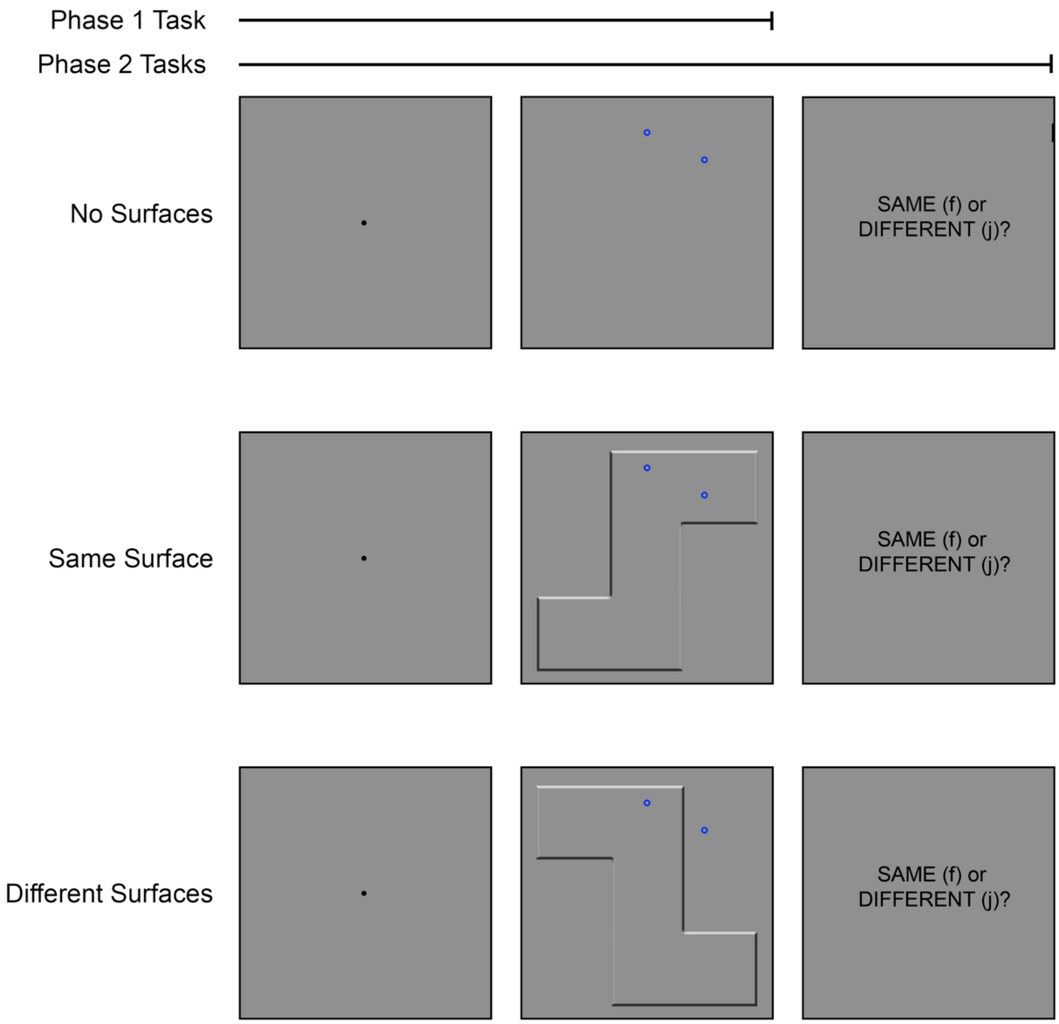

Figure 5.1. Illustration of the design of Experiment 7 depicting the No Surface, Same Surface, and Different Surfaces conditions and the tasks used in Phase 1 and Phase 2 of trials. These illustrations show target above fixation and distractor right; in the experiment the target could appear unpredictably above or below fixation, and the distractor to the left or right.

The first question is whether I will find any evidence of surface-based encoding in any saccade behavior (specifically, in landing position effects such as landing distance and capture rate). If I find that surface structure does affect oculomotor behavior, that is some evidence of obligatory encoding of surfaces even when they are not relevant to the saccade itself. This finding would contrast with findings from Experiments 1-4, and would suggest that obligatory surface-based encoding can arise in a saccade only when saccade objects appear integral to the surface structure of the scene. Critically, I will also assess whether there is an interaction such that surface-based effects only arise when surface structure is task-relevant. If that interaction obtains, it suggests that task relevance of the surface structure can partially explain that surfaces affected saccade behavior when they were task relevant in Experiments 4 and 5, but not when they were task-irrelevant in Experiments 1-4.

The second question concerns whether I will find evidence that surface structure differentially affects covert surface judgments, either in manual accuracy or manual response times. Specifically, I am testing whether there is a match between the covert surface judgments and the overt saccades. The prediction is that if overt and covert responses rely on a shared map, then I will find the presence (absence) of a manual RT effect if I find the presence (absence) of a saccade landing position effect. If overt and covert responses do not rely on a shared map, then I should find a mismatch between the overt and covert measures.

Participants. Participants were 12 University of Iowa undergraduate students and lab members (18-30 years old) who reported normal or corrected-to-normal visual acuity, gave informed consent, and received course credit for participating if they were enrolled in a credit-granting course. Three participants were replaced for having frequent (>15% of trials) first saccades that did not land within 2.5 dva of either the target or distractor.

Stimuli. The circles were always blue (19.8 cd/m^2) and the background luminance, regardless of ground or surface, was gray (34.2 cd/m^2).

The circles had a diameter of 0.5 dva then a border thickness of 0.25 dva (for a total stimulus width of 1.0 dva). The target circle was equally likely to appear 9.9 dva above or below fixation, and the distractor to the left or right side of the target such that it was 9.4 dva from fixation and 7.0 dva from the target.

The largest dimensions of the surface were 24.3 dva in width and height. The middle extent, on which the target always appeared, was 7.8 dva wide. The surface could be flipped horizontally such that the extended portion of it was on the left or right side of the screen.

For error trials (timeouts or distractor fixations) a 50 ms 400 Hz tone was played.

Task and Procedure. Figure 5.1 demonstrates the procedure. Each experiment consisted of a single session that lasted approximately 1 hour. Following the informed consent process, participants were guided through a set of written instructions and images that explained the primary task.

Observers were instructed to look for the circle-defined target and to report the orientation of the line inside of it by pressing “f” if the bar inside of it was oriented vertically and “j” if it was oriented horizontally. They were asked to respond as quickly as possible while maintaining at least 90% accuracy.

After calibration of the eyetracker, all observers participated in two phases. In the first phase, observers were to begin each trial by fixating. After 400 ms had elapsed of a good fixation (the eye remained within 2 dva of fixation), the target dot, distractor dot, and surface (if present) appeared. Observers were to saccade to the target as quickly as possible. If a saccade landed within 2.5 dva of the center of one of the dots, the trial terminated and the display disappeared after 100 ms. If the object fixated was the distractor, the trial was counted as “inaccurate” and an error tone was played. If the object fixated was the target, the trial was counted as accurate. The next trial (e.g., presentation of fixation) began automatically.

After the first (low engagement) phase, the experimenter paused the experiment to explain the second (high engagement) phase to the participant. In this phase, all trials began as described above: to fixate the fixation dot, and then to fixate the target as quickly as possible when it appeared. After the display disappeared, observers were to report whether the target and distractor appeared on the same or different object or level. To prompt them, text appeared on the screen that said “SAME (f) or DIFFERENT (j)?” until a response was entered. Note that the response was not confounded with the presence of surface structure. It was explained to participants that if the target and distractor were both on the ground (No Surfaces) or both on the table (Same Surface), they were to respond “Same.” Only if one object was on the table and the other on the ground (Different Surfaces) should they respond “Different.” If an incorrect response was made, a beep sounded.

Note that throughout the first phase, participants were not aware that they would be making a surface-dependent task judgment in the second phase.

Observers completed the two phases, with each phase comprised of 3 blocks of 72 trials each. Each block was a fully mixed design.

Design. A 2 (Task: Saccade Only, Saccade and Judgment) × 3 (Display: No Surface, Same Surface, Different Surface) within-subjects design was used.

Results: Saccades. Figure 5.2 shows that deviation was affected by task (Low Engagement saccade-only task, High Engagement dual-task) and by Surface condition, but not the interaction of these factors.

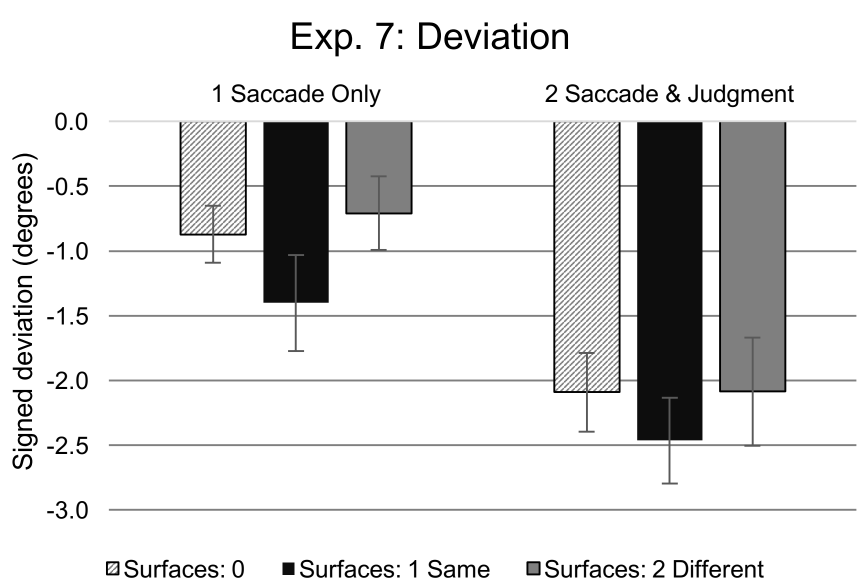

Figure 5.2. Mean saccade deviation as a function of Task and Surfaces in Experiment 7. Error bars show standard error of the mean. Deviation toward the distractor (-) was stronger in the second task, and there was a main effect of Surface context that was unaffected by Task.

I conducted a series of 2 (Task) × 3 (Display) ANOVAs. There was greater deviation toward the distractor in the second dual task phase than the first single task phase, $F(1,11) = 22.69$, $p < .001$, pη2 = .67. There was also generally greater deviation toward the distractor as a function of Surface presence, $F(2,22) = 3.82$, $p < .04$, $p\eta2 = .26$. There was no evidence for an interaction between Phase and Surface condition, $F < 1$, $p > .7$. To analyze the effect of Surfaces, I conducted three t-tests for deviation as a function of Surface (averaged over phase). Relative to the No Surface display, there was no evidence that saccade deviation toward the distractor was stronger in the Same Surface display, $t(11) = 1.80$, $p = .09$, or the Different Surfaces display, $t(11) = .6$, $p = .6$. But saccades deviated more towards distractors on the Same surface than Different surface, $t(11) = 4.21$, $p = .001$.

I conducted the same analysis for landing position errors. Landing position was affected by the presence of surfaces (see Figure 5.3). There was evidence that landing position error was affected by Display, $F(2,22) = 5.21$, $p = .01$, $p\eta2 = .32$, but not by Task or the interaction, $Fs < 2.5$, $ps > 0.1$. To analyze this landing position effect further, I conducted three t-tests. Relative to the No Surface display, saccade landing position errors were approximately 0.3 dva greater in both the Same Surface display, $t(11) = 2.78$, $p = .02$, and the Different Surfaces display, $t(11) = 2.60$, $p = .03$. But there was no evidence that position errors differed between the Same and Different Surfaces displays, $t(11) = .79$, $p = .4$.

I also assessed full oculomotor capture by the distractor, defined as a saccade that landed within 2.5 dva of the target centroid. Capture occurred on 4.7% of trials, with no evidence that capture was affected by the Surface or Task manipulations, all Fs < 2.0, ps > .3.

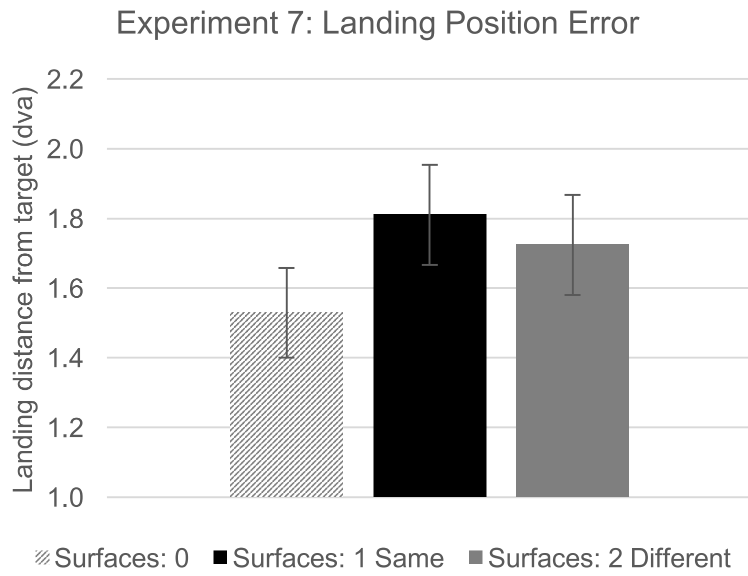

Figure 5.3. Mean landing position error as a function of Display in Experiment 7. Error bars show standard error of the mean. The edge of the target stimulus was at 1.0 dva. Landing position was unaffected by Surface presence, but was not affected by Task or the context of surface structure.

I analyzed latency of saccades to targets as well. Saccades were generally faster in the second phase than the first (180.3 and 166.1 ms, respectively), $F(1,11) = 5.69$, $p = .036$, $p\eta^2 = .34$, which is likely due simply to task learning, but there was no evidence for an effect of Display or an Interaction, Fs < 3.0, ps > .08.

Results: Surface Judgments. Figure 5.4 shows a mean manual RTs (calculated as the duration between the end of the saccade and the completion of the manual response) for correct trials as a function of Display. Responses were fastest when were no surfaces present, and slower in the presence of surface structure, with no effect of context.

A 3-factor (Display Type) repeated-measures ANOVA revealed a significant effect of Display on manual RTs, $F(2,22) = 10.46$, $p < .001$, pη2 = .49. I ran paired samples t-tests to examine the nature of this effect. RTs were faster when there were No Surfaces (655.8 ms) compared to Same Surface (718.0 ms), $t(11) = 5.65$, $p < .001$, or Different Surfaces (703.7 ms), $t(11) = 3.89$, $p = .003$. However, I found no evidence that whether the circles were on the Same or Different Surfaces affected the Same or Different surface judgments, $t < 1$, $p > .5$.

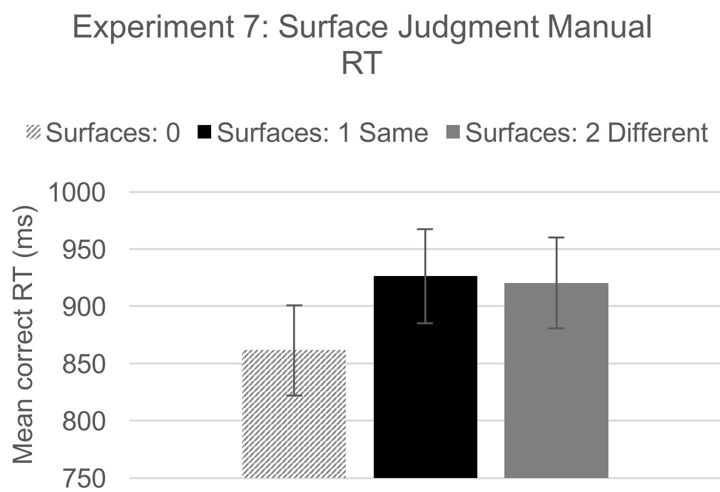

Figure 5.4. Mean correct manual response times as a function of Display in Experiment 7. Error bars show standard error of the mean.

Error rates were also affected by Display, $F(2,22) = 3.80$, $p = .038$, pη2 = .26. T-tests revealed that this was driven by significantly more errors in the "Different Surface" condition (4.1%) compared to the "No Surface" condition (1.3%), $t(11) = 2.92$, $p = .01$, but there was no significant difference between either of those conditions and the Same Surface displays (2.5%), ts < 2.0, ps > .1.

Recall that observers were to judge whether the target and distractor circles were on the Same (e.g., No Surface, Same Surface) or Different (Different Surfaces) condition. Responses were faster overall for Same compared to Different judgments, $F(1,11) = 4.88$, $p = .049$, $p\eta^2 = .31$. Error rates were unaffected by whether the scene structure had the items on the Same or Different surface, $F < 2.50$, $p > .1$.

Discussion. Saccades curved more towards the distractor when it was on the same surface as the target, compared to when it was on a Different surface or when there were no surfaces present. This is the first demonstration that surface context affects fine-grained spatial dynamics of the saccade trajectory. In this design, when a surface was present, the target appeared on it with a probability of 1, and the distractor appeared on the surface with a probability of 0.5. That curvature increased toward the on-surface target when it was on the same surface is consistent attentional spreading throughout the surface that increased the representational activity of the distractor.

Critically, although saccades did curve more toward the distractor generally when observers had to perform a surface judgment task following the saccade, there was no evidence that this effect interacted with task demands. This suggests that surface context affected the saccade trajectory independently of engagement, even when that engagement required attention to the surface context itself. As such, this is also a novel finding: surface context can affect visual processing in a low-engagement orienting task.

Saccade landing position error affected was by the presence or absence of surface structure, but not by surface context. This effect contrasts with the finding of object surface context-sensitive deviation. It is possible that they reflect different temporal dynamics of the system. Curvature describes the saccade trajectory en route to its final landing position, and may change on-line, whereas landing position measures the status of the system after competition has been fully resolved. It is possible that surface context rapidly affects the initial activity of the saccade plan, but that surface context fades by the time the saccade lands.

There was no evidence that these saccade landing position errors were affected by engagement (i.e., having to make a judgment about the surface content of the scene). Most importantly, although landing position errors were greater when there was surface structure in the scene, the magnitude of these errors was not significantly different as a function of whether the distractor appeared on the Same or Different surface. In other words, the presence of surface structure did affect the saccade but the context of that scene structure did not: saccades landed approximately 0.3 dva closer to the distractor when a surface was present. The lack of a surface context effect in landing position contrasts with the previous finding that surface context increased deviation toward the distractor.

Judgments of the scene context indicated surface structure drove differential processing of the scene context for the judgment task. Manual response times for correct trials were slower in the presence of Surfaces compared to no surfaces, but – like landing position errors – were no faster or slower as a function of whether the objects were on the Same or Different surface. Responses entered indicating “Same” were faster, however, for those indicating “Different,” with no evidence for a speed-accuracy tradeoff. This suggests that although manual responses for “Same” surfaces were significantly faster, this difference was not driven by the surface context of the objects.

The saccade map encodes surface context, independently of task engagement.

6. GENERAL DISCUSSION

Object Surfaces inform Vision

The goal of this dissertation was to examine whether object surfaces are represented in the visual information used to program saccades. Saccades are rapid eye movements that humans typically make several times per second. Saccades can be informed by bottom-up saliency, by top-down goal settings, and by prior history of saccades to previous locations. As such, sometimes saccades are directed to task-relevant information. When driving, for example, saccades should be directed to different locations around the road ahead to sample visual information relevant to the task of driving safely. Saccades can also be "captured" by distractors, such as a flashing restaurant sign that is representationally salient, resulting in a saccade to the sign instead of a task-relevant region. Understanding how people program saccades is therefore important not only to build a theoretical understanding of saccade programming, but to predict human attention and distraction in the real world. Furthermore, models of bottom-up saliency have only moderate predictive accuracy for first saccades in scenes (Borji et al., 2013). These models vary in architecture, and some include complex objects such as faces in addition to basic features in saliency calculations. It is possible that incorporating surface-based representations is necessary to improve the accuracy of these saliency models in predicting real-world human orienting behavior.

The visual world is comprised of complex objects in richly structured scenes, but the retinal image of this world is a two-dimensional mosaic of unorganized feature information. The reorganization of the retinal image into representations of object surfaces is, according to one prominent theory of vision, an early, involuntary process that builds the first level of visual representation (He & Nakayama, 1994; Nakayama et al., 1995). As such, it is a fundamentally surface-based representation to which later processes – such as visual search and object recognition – have access. It is critical to understand how the nature of these internal representations inform behavior, such as manual or eye movement programming.

Multiple studies have provided evidence that surface completion and other aspects of scene organization occur for stimuli that are not currently the focus of attention, a necessary condition for attentional processes to occur within a coordinate system that includes surface information (Davis & Driver, 1998; Kimchi & Peterson, 2008; Moore & Egeth, 1997; Moore, Grosjean, & Lleras, 2003). Object structure can be extracted extremely quickly, with as little as a 50 ms presentation (Duncan, 1984). To date, demonstrations of object-based effects on covert processing have required tasks of "high engagement" in which observers search throughout the display and may even attend to object surfaces. As such, engagement is claimed as a precondition for object surface-based processing. But neurons in macaque visual cortex change their activity as a function of perceived surfaces, even those formed by illusory contours, within 20 ms of stimulus onset (Knierim & Van Essen, 1992; Roelfsema et al., 1998), faster than top-down attentional modulation of activity in V1, which starts to occur around 150 ms after onset (Reynolds & Desimone, 1999). As physiological evidence suggests that the earliest representations accessed by the visual system are informed by object surfaces. Because saccades can be planned more rapidly than manual responses, they may access physiological encoding of object surfaces earlier.

In this dissertation, I tested two hypotheses.

H1: Saccades will be affected by the object surface context on which the target and distractors appear. Specifically, saccade distractor-related trajectory effects will be strongest when a distractor is on the same surface as a saccade target, and weakest when a distractor is on a different surface from the saccade target.

H2: Strong task engagement is not a precondition to demonstrate object surface-based effects in saccades.

I conducted experiments in which observers were to execute a saccade to a target defined by its location or feature that was displayed with or without a distracting item. Distractors produce well-documented effects on saccade trajectories in simple saccade-to-target tasks: saccades can deviate along their trajectory such that they curve toward the distractor but land on or near the target, and they can be misdirected entirely such that they land on the distractor instead of the target. Behavioral and neurophysiological research indicate that these effects "index" the representational activity (i.e., activation or suppression) of the distractor in the saccade map.

Using this metric, I manipulated whether a saccade target and distractor appeared on the same or different object surface. If object surfaces are represented in the saccade coordinate system, then the distractor should produce different levels of distraction depending on whether it is on the same or different surface of the target. I also manipulated the exposure time of the surfaces, and whether the task was high-engagement (Chen, 2012; Wilder et al., 2011), such that attention shifted throughout the display. My findings are summarized in Figure 6.1.

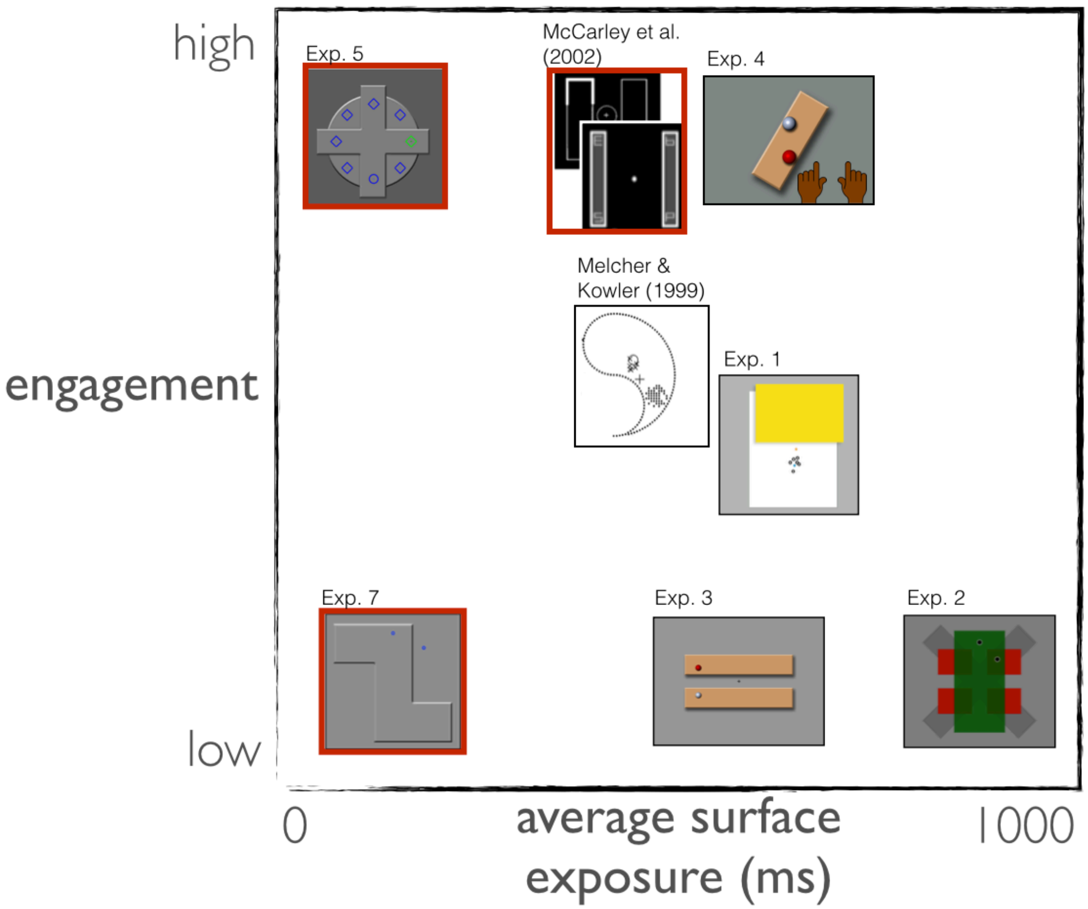

Figure 6.1. Saccades and surface structure as a function of encoding time and of task engagement. The present work explored this space. Experiments bounded in red produced evidence of object context-based processing in the saccade. In most experiments there was no evidence for surface-based encoding. Longer durations of surfaces did not necessarily result in object-based saccade effects.

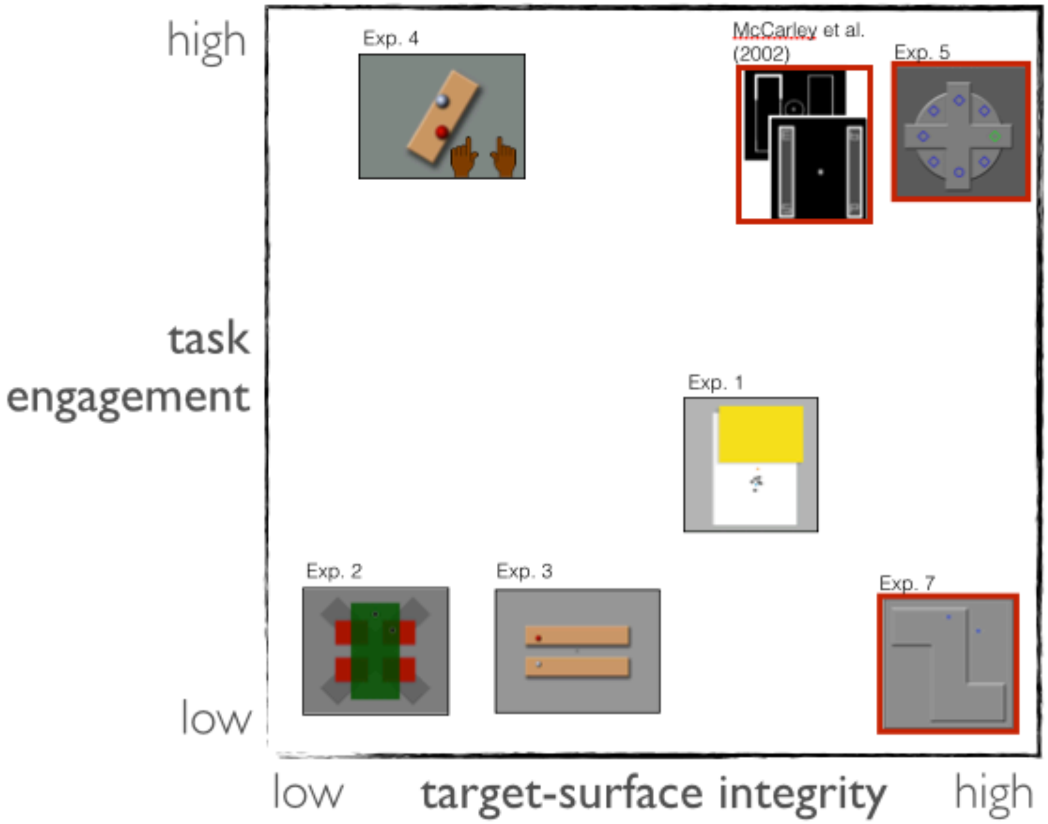

Figure 6.2. Saccades and surface structure as a function of engagement and target-surface integrity. Duration did not drive surface-based processing, but it seems a more probable explanation is that in Experiments 5 and 7 may have produced surface-based processing because the unfilled lines of the targets and distractors appeared to be more integral to the surfaces of the display, in contrast to the targets, distractors, and surfaces of earlier work in this dissertation.

Conclusion 1: Saccades are surface-dependent (provided strong object surfaces).

In Chapter 2, observers were asked to saccade to the centroids of objects. In the critical condition, the to-be-saccaded object was partially obscured by another object. This presents two potential centroids for the saccade: one as the center-of-area of the luminance contours (as if the occlude was "cut out" of the display), and one as the center-of-area of the amodally completed object (as if its contours were representationally extended beneath the occluder). Saccades tended to land closer to the luminance-defined center of area rather than a centroid informed by amodal object completion. In Chapters 3, 4, and 5, I presented unambiguous saccade targets in the presence of distractors, in paradigms that have previously been used to study saccade trajectory modulation as a function of attention. In these experiments, I consistently found that distractors were distracting in the oculomotor program: trajectories of saccades that landed near the target deviated more in the presence of a distractor, and saccades occasionally landed on the distractor instead of the target. Saccades reflected object surface context in two of five of these experiments.

The pattern of results is consistent with the notion that strong objecthood, independent of exposure time, is a precondition for object-based effects. Figure 6.1 demonstrates that, in contrast to what would be expected from the covert object-based attention literature, increased exposure duration to object surfaces did not produce object-based saccade trajectory effects, even in high-engagement tasks in which observers judged the surface context of the scene.

In the null-effect experiments, however, there were multiple display properties that may have weakened the organization of the scene as a set of objects. First, in these experiments there were separate temporal onsets of the context surfaces and the saccade target (and distractor) objects. Differential temporal onsets can prompt the organization of the scene into onset-based groups (Jiang, Chun, & Marks, 2002b), such that the temporal grouping may have overwhelmed alternative organizations of the scene. Second, the stimuli in the null-effect experiments were sparse dots or photorealistic spheres that were featurally distinct from the features of the surface context. This may be insufficient for objecthood; indeed, there is evidence to suggest that stimuli must appear to be integral to the surface on which they appear to promote a sufficiently strong object-based organization of the scene (for review, see Chen, 2012).

In contrast, Experiments 5-7 all used simultaneous onsets of targets, distractors, and surface context. Furthermore, although these displays were sparse, the objects to which observers executed saccades appear somewhat more integrated with the surfaces on which they are drawn.

As such, the most parsimonious explanation of the pattern of results is that fine-grained dynamics of the saccade trajectory are sensitive to object surfaces, provided a strong object-based representation.

Conclusion 2: High task engagement is not required for object-based processing.

Saccade distractor-related deviations were modulated by the context on which the saccade target and distractor appeared in one low-engagement experiment, in which observers simply executed orienting saccades toward a target that appeared above or below fixation, and in one high-engagement experiment, in which observers used a surface cue to search for a target among distractors (and then manually report decisions about the target features) in an additional singleton paradigm. High task engagement has been previously understood to be a precondition for object-based effects, but the present work suggests this distinction is not rigid. This is consistent with the hypothesis that object surface encoding arises early in the visual system and is fed forward to the visual map used to plan a saccade, even in a simple orienting task for which scene context is irrelevant.

Conclusion 3: Surface structure and distractor processing.

In the additional singleton paradigm task in Experiments 5 and 6, surface context did not seem to guide orienting toward the target nor did it enhance capture when the singleton was on the cued surface relative to a no-surface baseline. As such, there was no evidence for attentional spreading throughout the cued object. Surface structure did allow a reduction of distractor-related costs in manual response time and in oculomotor capture. Singletons that appeared on cued surfaces (same as the target) produced effects of distraction, and these effects were mitigated when the same singleton was on an uncued surface (different from the target). It is possible that surface information allowed the programming of a top-down suppression of the salient singleton (Gaspelin et al., 2016; Gaspelin, Leonard, & Luck, 2015) such that its activity was reduced in the map used to inform manual and saccadic responses.

However, in Experiment 7, saccades curved more toward distractors on the same surface (relative to a no-surface baseline), with no evidence that saccades curved less to distractors on a different surface (relative to a no-surface baseline). This finding *is* consistent with attentional spreading: when a surface was present in the display, attention spread throughout it such that the distractor-related activity was enhanced. There was no evidence of active suppression of a distractor when it was on a different surface. A speculative hypothesis about this difference is that because the singleton in Experiment 6 is more salient than the target, observers benefit more from adopting a top-down strategy of singleton suppression such that attentional spreading throughout the surface is overwhelmed. Reconciling the differences between Experiments 6 (evidence for signal suppression) and 7 (evidence for attentional spreading) is difficult without experiments that systematically explore the space between the high-engagement task of Experiment 6 and the low-engagement task in Experiment 7.

Notes of caution

Three characteristics of this dissertation are worth brief cautionary notes.

First, the null effects of surface structure in Chapters 2-4 may have arisen due to low statistical power rather than a theoretical distinction between Chapters 2-4 and 5-6. Although each experiment's number of subjects was based on the number of subjects in earlier findings using similar paradigms, it's possible that object surface effects are weaker than the manipulations that have been previously used in these paradigms. As such, it is my hope that further work can use the effect sizes published in these experiments to calculate the number of participants required for .80 power.

Second, in most of the present work, the saccade target was always or frequently on an object surface that was in the closest apparent depth plane to the observer. When a surface was or surfaces were present, the target appeared on the front-most surface 100% of the time in Experiments 3, 6, and 7, 66% of the time in Experiment 1, and 50% of the time in Experiments 2 and 4. Note that evidence of object-based effects were found in Experiments 6 and 7, in which a front-most surface always contained the target. Depth ordering is known to affect attentional selection (Atchley et al., 1997b; Reppa, Fougnie, & Schmidt, 2010) such that attention is biased to select nearby surfaces (West, Pratt, & Peterson, 2013), and as such may have been an unexplored interaction in this work. Nonetheless, depth ordering requires as a precondition the establishment of object surfaces, so it is possible that future work may reveal a more precise description object surface-based processing as a function of depth ordering in the saccade map.

Finally, in the introduction I reviewed existing models of saccade programming that represent visual space as features without any object-based organization. Although there is now data to suggest that these models are incomplete without surface-based representations, there is only one experiment here (Experiment 7) that is consistent with surface-based processing. There may be task demands or display characteristics I have not examined that contributed to the finding of surface-based encoding in the saccade. As such, replication and extension will be necessary before any consideration of the idea of a serious revision of models of saccade planning.

Together, these findings suggest that the visual coordinates used to inform a saccade can reflect object surface context (albeit possibly not one informed by amodal completion). Saccade distractor-related effects such as capture and trajectory deviation were affected by the surface context on which the target and distractor appeared, independently of task engagement.

The priority map used to program a saccade integrates over bottom-up visual information, top-down goal-related signals, and selection history. Each of these signals contributes to a competitive interaction between items, such that the winner of this competitive process is selected as the first location for a shift of covert and overt attention (Meeter, Van der Stigchel, & Theeuwes, 2010; Wolfe, 2007). In this map framework, my findings are that surface context can inform relatively reflexive shifts of attention because it is encoded in the feed-forward visual information used to program a saccade.

REFERENCES

Anderson, B. A., & Yantis, S. (2013). Persistence of value-driven attentional capture. *Journal of Experimental Psychology: Human Perception and Performance*, *39*(1), 6–9. http://doi.org/10.1037/a0030860

Atchley, P., Kramer, A. F., & Andersen, G. J. (1997a). Spatial cuing in a stereoscopic display: Evidence for a "depth-aware" attentional focus. *Psychonomic Bulletin & …*, *4*(4), 524–529. http://doi.org/10.3758/BF03214343

Atchley, P., Kramer, A. F., Andersen, G. J., & Theeuwes, J. (1997b). Spatial cuing in a stereoscopic display: Evidence for a "depth-aware" attentional focus. *Psychonomic Bulletin & Review*, *4*(4), 524–529. http://doi.org/10.3758/BF03214343

Awh, E., Belopolsky, A. V., & Theeuwes, J. (2012). Top-down versus bottom-up attentional control: a failed theoretical dichotomy. *Trends in Cognitive Sciences*, *16*(8), 437–443. http://doi.org/10.1016/j.tics.2012.06.010

Bacon, W. F., & Egeth, H. E. (1994). Overriding stimulus-driven attentional capture. *Perception & Psychophysics*, *55*(5), 485–496.

Behrmann, M., Zemel, R. S., & Mozer, M. C. (1998). Object-based attention and occlusion: Evidence from normal participants and a computational model. *Journal of Experimental Psychology: Human Perception and Performance*, *24*(4), 1011–1036.

Bompas, A., Hedge, C., & Sumner, P. (2017). Speeded saccadic and manual visuo-motor decisions: Distinct processes but same principles. *Cognitive Psychology*, *94*, 26–52. http://doi.org/10.1016/j.cogpsych.2017.02.002

Borji, A., Sihite, D. N., & Itti, L. (2013). Quantitative analysis of human-model agreement in visual saliency modeling: a comparative study. *IEEE Transactions on Image Processing : a Publication of the IEEE Signal Processing Society*, *22*(1), 55–69. http://doi.org/10.1109/TIP.2012.2210727

Brainard, D. H. (1997). The psychophysics toolbox. *Spatial Vision*, *10*(4), 433–436. http://doi.org/10.1163/156856897x00357

Brown, J. M., & Denney, H. I. (2007). Shifting attention into and out of objects: evaluating the processes underlying the object advantage. *Perception & Psychophysics*, *69*(4), 606–618.

Bucker, B., Silvis, J. D., Donk, M., & Theeuwes, J. (2015). Reward modulates oculomotor competition between differently valued stimuli. *Vision Research*, *108*(C), 103–112. http://doi.org/10.1016/j.visres.2015.01.020

Carrasco, M. (2011). Visual attention: The past 25 years. *Vision Research*, 1–42. http://doi.org/10.1016/j.visres.2011.04.012

Chen, Z. (2012). Object-based attention: A tutorial review. *Attention, Perception, & Psychophysics*. http://doi.org/10.3758/s13414-012-0322-z

Davis, G., & Driver, J. (1994). Parallel Detection of Kanizsa Subjective Figures in the Human Visual-System. *Nature*, *371*(6500), 791–793. http://doi.org/10.1038/371791a0

Davis, G., & Driver, J. (1998). Kanizsa subjective figures can act as occluding surfaces at parallel stages of visual search. *Journal of Experimental Psychology: Human Perception and Performance*, *24*(1), 169–184.

Desimone, R., & Duncan, J. (1995). Neural mechanisms of selective visual attention. *Annual Review of Neuroscience*.

Doyle, M., & Walker, R. (2001). Curved saccade trajectories: Voluntary and reflexive saccades curve away from irrelevant distractors. *Experimental Brain Research*, *139*(3), 333–344. http://doi.org/10.1007/s002210100742

Duncan, J. (1984). Selective attention and the organization of visual information. *Journal of Experimental Psychology: General*, *113*(4), 501–517.

Duncan, J., & Humphreys, G. W. (1989). Visual search and stimulus similarity. *Psychological Review*, *96*, 433–458.

Egly, R., Driver, J., & Rafal, R. D. (1994). Shifting visual attention between objects and locations: evidence from normal and parietal lesion subjects. *Journal of Experimental Psychology: General*, *123*(2), 161–177.

Engel, S. A., Glover, G. H., & Wandell, B. A. (1997). Retinotopic organization in human visual cortex and the spatial precision of functional MRI. *Cerebral Cortex*, *7*(2), 181–192.

Eriksen, C. W., & Hoffman, J. E. (1973). The extent of processing of noise elements during selective encoding from visual displays. *Perception & Psychophysics*.

Ernst, Z. R., Palmer, J., & Boynton, G. M. (2012). Dividing attention between two transparent motion surfaces results in a failure of selective attention. *Journal of Vision*, *12*(12), 6–6. http://doi.org/10.1167/12.12.6

Findlay, J. M. (1982). Global Visual Processing for Saccadic Eye-Movements. *Vision Research*, *22*(8), 1033–1045.

Gaspelin, N., Leonard, C. J., & Luck, S. J. (2015). Direct Evidence for Active Suppression of Salient-but-Irrelevant Sensory Inputs. *Psychological Science*, 1–11. http://doi.org/10.1177/0956797615597913

Gaspelin, N., Leonard, C. J., & Luck, S. J. (2016). Suppression of overt attentional capture by salient-but-irrelevant color singletons. *Attention, Perception, & Psychophysics*, 1–18. http://doi.org/10.3758/s13414-016-1209-1

Godijn, R., & Theeuwes, J. (2002). Programming of endogenous and exogenous saccades: Evidence for a competitive integration model. *Journal of Experimental Psychology: Human Perception and Performance*, *28*(5), 1039–1054. http://doi.org/10.1037//0096-1523.28.5.1039

Godijn, R., & Theeuwes, J. (2004). The Relationship Between Inhibition of Return and Saccade Trajectory Deviations. *Journal of Experimental Psychology: Human Perception and Performance*, *30*(3), 538–554. http://doi.org/10.1037/0096-1523.30.3.538

He, Z. J., & Nakayama, K. (1992). Surfaces Versus Features in Visual-Search. *Nature*, *359*(6392), 231–233. http://doi.org/10.1038/359231a0

He, Z. J., & Nakayama, K. (1994). Apparent motion determined by surface layout not by disparity or three-dimensional distance. *Nature*, *367*(6459), 173–175. http://doi.org/10.1038/367173a0

Henderson, J. M., & Hollingworth, A. (1999). High-level scene perception. *Annu. Rev. Psychol.*, *50*(1), 243–271. http://doi.org/10.1146/annurev.psych.50.1.243

Henderson, J. M., & Macquistan, A. D. (1993). The spatial distribution of attention following an exogenous cue. *Perception & Psychophysics*, *53*(2), 221–230.

Hoffman, J. E., & Subramaniam, B. (1995). The role of visual attention in saccadic eye movements. *Perception & Psychophysics*, *57*(6), 787–795.

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. http://doi.org/10.1080/13506280802193367

Hollingworth, A., Maxcey-Richard, A. M., & Vecera, S. P. (2012). The spatial distribution of attention within and across objects. *Journal of Experimental Psychology: Human Perception and Performance*, *38*(1), 135–151. http://doi.org/10.1037/a0024463

Hubel, D. H., & Wiesel, T. N. (1968). Receptive fields and functional architecture of monkey striate cortex. *The Journal of Physiology*, *195*(1), 215–243.

Hunt, A. R., Mühlenen, von, A., & Kingstone, A. (2007). The time course of attentional and oculomotor capture reveals a common cause. *Journal of Experimental Psychology: Human Perception and Performance*, *33*(2), 271–284. http://doi.org/10.1037/0096-1523.33.2.271

Itti, L., & Koch, C. (2000). A saliency-based search mechanism for overt and covert shifts of visual attention. *Vision Research*.

Jiang, Y., Chun, M. M., & Marks, L. E. (2002a). Visual marking: Selective attention to asynchronous temporal groups. *Journal of Experimental Psychology: Human Perception and Performance*, *28*(3), 717–730. http://doi.org/10.1037//0096-1523.28.3.717
Jiang, Y., Chun, M. M., & Marks, L. E. (2002b). Visual marking: Selective attention to asynchronous temporal groups. *Journal of Experimental Psychology: Human Perception and Performance*, *28*(3), 717–730. http://doi.org/10.1037//0096-1523.28.3.717
Juan, C.-H., Shorter-Jacobi, S. M., & Schall, J. D. (2004). Dissociation of spatial attention and saccade preparation. *Proceedings of the National Academy of Sciences*, *101*(43), 15541–15544. http://doi.org/10.1073/pnas.0403507101
Kerzel, D., Born, S., & Schönhammer, J. (2012). Perceptual grouping allows for attention to cover noncontiguous locations and suppress capture from nearby locations. *Journal of Experimental Psychology: Human Perception and Performance*, *38*(6), 1362–1370. http://doi.org/10.1037/a0027780
Kimchi, R., & Peterson, M. A. (2008). Figure-Ground Segmentation Can Occur Without Attention. *Psychological Science*, *19*(7), 660–668. http://doi.org/10.1111/j.1467-9280.2008.02140.x
Kimchi, R., Yeshurun, Y., & Cohen-Savransky, A. (2007). Automatic, stimulus-driven attentional capture by objecthood. *Psychonomic Bulletin & Review*, *14*(1), 166–172.
Knierim, J. J., & Van Essen, D. C. (1992). Neuronal responses to static texture patterns in area V1 of the alert macaque monkey. *Journal of Neurophysiology*.
Koch, C., & Ullman, S. (1985). Shifts in Selective Visual Attention: Towards the Underlying Neural Circuitry. *Human Neurobiology*, *4*(4), 219–227.
Kowler, E. (2011). Eye movements: The past 25 years. *Vision Research*, *51*(13), 1457–1483. http://doi.org/10.1016/j.visres.2010.12.014
Kruijne, W., Van der Stigchel, S., & Meeter, M. (2014). A model of curved saccade trajectories: Spike rate adaptation in the brainstem as the cause of deviation away. *Brain and Cognition*, *85*(C), 259–270. http://doi.org/10.1016/j.bandc.2014.01.005
Lamy, D., & Egeth, H. (2002). Object-based selection: the role of attentional shifts. *Perception & Psychophysics*, *64*(1), 52–66.
Lee, T. S., Mumford, D., Romero, R., & Lamme, V. (1998). The role of the primary visual cortex in higher level vision. *Vision Research*, *38*(15-16), 2429–2454. http://doi.org/10.1016/S0042-6989(97)00464-1
Ludwig, C. J. H., & Gilchrist, I. D. (2003). Goal-driven modulation of oculomotor capture. *Perception & Psychophysics*, *65*(8), 1243–1251.
McCarley, J. S., Kramer, A. F., & Peterson, M. S. (2002). Overt and covert object-based attention. *Psychonomic Bulletin & Review*, *9*(4), 751–758.
McCormick, P. A., & Klein, R. (1990). The spatial distribution of attention during covert visual orienting. *Acta Psychologica*.
McPeek, R. M., Han, J. H., & Keller, E. L. (2003). Competition between saccade goals in the superior colliculus produces saccade curvature. *Journal of Neurophysiology*, *89*(5), 2577–2590. http://doi.org/10.1152/jn.00657.2002
McSorley, E., Haggard, P., & Walker, R. (2004). Distractor modulation of saccade trajectories: spatial separation and symmetry effects. *Experimental Brain Research*, *155*(3), 320–333. http://doi.org/10.1007/s00221-003-1729-5
Meeter, M., Van der Stigchel, S., & Theeuwes, J. (2010). A competitive integration model of exogenous and endogenous eye movements. *Biological Cybernetics*, *102*(4), 271–291. http://doi.org/10.1007/s00422-010-0365-y
Melcher, D., & Kowler, E. (1999). Shapes, surfaces and saccades. *Vision Research*, *39*(17), 2929–2946. http://doi.org/10.1016/S0042-6989(99)00029-2

Moore, C. M., & Egeth, H. (1997). Perception without attention: evidence of grouping under conditions of inattention. *Journal of Experimental Psychology: Human Perception and Performance*, *23*(2), 339–352.
Moore, C. M., & Fulton, C. (2005). The spread of attention to hidden portions of occluded surfaces. *Psychonomic Bulletin & Review*, *12*(2), 301–306.
Moore, C. M., Yantis, S., & Vaughan, B. (1998). Object-based visual selection: Evidence from perceptual completion. *Psychological Science*, 1–8.
Moore, C., Grosjean, M., & Lleras, A. (2003). Using inattentional blindness as an operational definition of unattended: The case of surface completion. *Visual Cognition*. http://doi.org/10.1080/13506280143000041
Mulckhuyse, M., Van der Stigchel, S., & Theeuwes, J. (2009). Early and Late Modulation of Saccade Deviations by Target Distractor Similarity. *Journal of Neurophysiology*, *102*(3), 1451–1458. http://doi.org/10.1152/jn.00068.2009
Munoz, D. P., & Wurtz, R. H. (1993). Fixation cells in monkey superior colliculus. II. Reversible activation and deactivation. *Journal of Neurophysiology*, *70*(2), 576–589.
Nakayama, K., He, Z. J., & Shimojo, S. (1995). Visual surface representation: A critical link between lower-level and higher-level vision (Vol. 2, pp. 1–70). MIT Press Cambridge, MA.
Oliva, A., & Torralba, A. (2007). The role of context in object recognition. *Trends in Cognitive Sciences*, *11*(12), 520–527. http://doi.org/10.1016/j.tics.2007.09.009
Pelli, D. G. (1997). The VideoToolbox software for visual psychophysics: Transforming numbers into movies. *Spatial Vision*.
Port, N. L., & Wurtz, R. H. (2003). Sequential activity of simultaneously recorded neurons in the superior colliculus during curved saccades. *Journal of Neurophysiology*, *90*(3), 1887–1903. http://doi.org/10.1152/jn.01151.2002
Posner, M. I. (1980). Orienting of attention. *Quarterly Journal of Experimental Psychology*, *32*, 3–25.
Rensink, R. A., & Enns, J. T. (1995). Preemption effects in visual search: evidence for low-level grouping. *Psychological Review*, *102*(1), 101–130.
Rensink, R. A., & Enns, J. T. (1998). Early completion of occluded objects. *Vision Research*, *38*, 2489–2505.
Reppa, I., Fougnie, D., & Schmidt, W. C. (2010). How does attention spread across objects oriented in depth? *Attention, Perception, & Psychophysics*, *72*(4), 912–925. http://doi.org/10.3758/APP.72.4.912
Reynolds, J. H., & Desimone, R. (1999). The role of neural mechanisms of attention in solving the binding problem. *Neuron*, *24*(1), 19–29. http://doi.org/10.1016/S0896-6273(00)80819-3
Ringach, D. L., & Shapley, R. (1996). Spatial and temporal properties of illusory contours and amodal boundary completion. *Vision Research*, *36*(19), 3037–3050.
Robinson, D. A. (1972). Eye movements evoked by collicular stimulation in the alert monkey. *Vision Research*, *12*(11), 1795–1808.
Roelfsema, P. R., Lamme, V., & Spekreijse, H. (1998). Object-based attention in the primary visual cortex of the macaque monkey. *Nature*, *395*(6700), 376–381. http://doi.org/10.1038/26475
Rosenholtz, R., Li, Y., & Nakano, L. (2007). Measuring visual clutter. *Journal of Vision*, *7*(2), 17–17. http://doi.org/10.1167/7.2.17
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 & Review*, *16*(2), 225–237. http://doi.org/10.3758/PBR.16.2.225
Russell, A. F., Mihalaş, S., Heydt, von der, R., Niebur, E., & Etienne-Cummings, R. (2014). A model of proto-object based saliency. *Vision Research*, *94*(C), 1–15. http://doi.org/10.1016/j.visres.2013.10.005

Sheliga, B., Riggio, L., & Rizzolatti, G. (1994). Orienting of attention and eye movements. *Experimental Brain Research*, *98*(3), 507–522.
Shomstein, S., & Yantis, S. (2002). Object-based attention: sensory modulation or priority setting? *Perception & Psychophysics*, *64*(1), 41–51.
Sommer, M. A., & Wurtz, R. H. (2000). Composition and topographic organization of signals sent from the frontal eye field to the superior colliculus. *Journal of Neurophysiology*, *83*(4), 1979–2001.
Sparks, D. L. (2002). The brainstem control of saccadic eye movements. *Nature Reviews Neuroscience*, *3*(12), 952–964. http://doi.org/10.1038/nrn986
Theeuwes, J. (1992). Perceptual selectivity for color and form. *Perception & Psychophysics*, *51*(6), 599–606.
Theeuwes, J., & Godljn, R. (2002). Irrelevant singletons capture attention: evidence from inhibition of return. *Perception & Psychophysics*, *64*(5), 764–770.
Theeuwes, J., De Vries, G.-J., & Godijn, R. (2003). Attentional and oculomotor capture with static singletons. *Perception & Psychophysics*, *65*(5), 735–746.
Theeuwes, J., Kramer, A. F., Hahn, S., Irwin, D. E., & Zelinsky, G. J. (1999). Influence of attentional capture on oculomotor control. *Journal of Experimental Psychology: Human Perception and Performance*, *25*(6), 1595–1608.
Tipper, S. P., Howard, L. A., & Jackson, S. R. (1997). Selective Reaching to Grasp: Evidence for Distractor Interference Effects. *Visual Cognition*, *4*(1), 1–38. http://doi.org/10.1080/713756749
Torralba, A., Oliva, A., Castelhano, M. S., & Henderson, J. M. (2006). Contextual guidance of eye movements and attention in real-world scenes: The role of global features in object search. *Psychological Review*, *113*(4), 766–786. http://doi.org/10.1037/0033-295X.113.4.766
Treisman, A. M., & Gelade, G. (1980). A feature-integration theory of attention. *Cognitive Psychology*, *12*(1), 97–136.
Valdes-Sosa, M., Cobo, A., & Pinilla, T. (2000). Attention to object files defined by transparent motion. *Journal of Experimental Psychology: Human Perception and Performance*, *26*(2), 488–505. http://doi.org/10.1037//0096-1523.26.2.488
Van der Stigchel, S. (2010). Recent advances in the study of saccade trajectory deviations. *Vision Research*, *50*(17), 1619–1627. http://doi.org/10.1016/j.visres.2010.05.028
Van der Stigchel, S., & de Vries, J. P. (2015). There is no attentional global effect: Attentional shifts are independent of the saccade endpoint. *Journal of Vision*, *15*(15), 17–12. http://doi.org/10.1167/15.15.17
Van der Stigchel, S., Meeter, M., & Theeuwes, J. (2006). Eye movement trajectories and what they tell us. *Neuroscience & Biobehavioral Reviews*, *30*(5), 666–679. http://doi.org/10.1016/j.neubiorev.2005.12.001
Vatterott, D. B., & Vecera, S. P. (2015). The attentional window configures to object and surface boundaries. *Visual Cognition*, *23*(5), 561–576. http://doi.org/10.1080/13506285.2015.1054454
Walton, M. M. G., Sparks, D. L., & Gandhi, N. J. (2005). Simulations of saccade curvature by models that place superior colliculus upstream from the local feedback loop. *Journal of Neurophysiology*, *93*(4), 2354–2358. http://doi.org/10.1152/jn.01199.2004
West, G. L., Pratt, J., & Peterson, M. A. (2013). Attention is biased to near surfaces. *Psychonomic Bulletin & Review*, *20*(6), 1213–1220. http://doi.org/10.3758/s13423-013-0455-7
White, B. J., Theeuwes, J., & Munoz, D. P. (2012). Interaction between visual-and goal-related neuronal signals on the trajectories of saccadic eye movements. *Journal of Cognitive Neuroscience*, (Early Access), 1–11.
Wilder, M. H., Mozer, M. C., & Wickens, C. D. (2009). A Unified Theory of Attentional Control.
Wilder, M. H., Mozer, M. C., & Wickens, C. D. (2011). An integrative, experience-based theory of attentional control. *Journal of Vision*, *11*(2), 8–8. http://doi.org/10.1167/11.2.8

Wolfe, J. M. (1994). Guided search 2.0 A revised model of visual search. *Psychonomic Bulletin & Review*, *1*(2), 202–238.
Wolfe, J. M. (2007). Guided search 4.0: Current progress with a model of visual search. In W. Gray (Ed.), *Integrated models of cognitive systems* (pp. 99–119). New York: Integrated models of cognitive systems.
Wong, E., & Mack, A. (1981). Saccadic programming and perceived location. *Acta Psychologica*, *48*(1-3), 123–131.
Yantis, S. (1992). Multielement visual tracking: attention and perceptual organization. *Cognitive Psychology*, *24*(3), 295–340.
Yeshurun, Y., & Rashal, E. (2016). The Typical Advantage of Object-Based Attention Reflects Reduced Spatial Cost. *Journal of Experimental Psychology: Human Perception and Performance*, 1–10. http://doi.org/10.1037/xhp0000308
Zhao, M., Gersch, T. M., Schnitzer, B. S., Dosher, B. A., & Kowler, E. (2012). Eye movements and attention: The role of pre-saccadic shifts of attention in perception, memory and the control of saccades. *Vision Research*, *74*(C), 40–60. http://doi.org/10.1016/j.visres.2012.06.017
Zhou, H., Friedman, H. S., & Heydt, von der, R. (2000). Coding of border ownership in monkey visual cortex. *Journal of Neuroscience*, *20*(17), 6594–6611.