THE INTERACTION BETWEEN FEATURE- AND SPACE-BASED ATTENTION

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A DISSERTATION

Submitted to
Michigan State University
in partial fulfillment of the requirements
for the degree of

Psychology — Doctor of Philosophy

2019

ABSTRACT

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Although the separate effects of feature- and space-based attention are relatively well established, the conjoint effects of attending to both a location and a feature are under-investigated. I analyzed the literature and extracted three approaches that explain such conjoint effects, namely the independence, sensory gating, and boosting approaches. The three approaches have substantial supports and shortcomings, and the current study will investigate which of the three approaches provide the best prediction of behavioral performance. I conducted two experiments to investigate whether the interplay between feature- and space-based attention varied as a function of the elapsed time between the cue and the target onset. A space-feature combination cue directed attention to a target on which participants discriminated small changes in color saturation. Both the spatial and feature cues were partially valid, making it possible to assess the cueing effect. The time difference between the cue and the saturation change onsets was manipulated in fine steps. Experiment 1 showed that space- and feature-based attention had an interactive effect on performance, such that feature-based attention did not influence performance outside the focus of space-based attention regardless of the temporal asynchrony between the cue and target onset. Experiment 2 was conducted to determine which of the three approaches provided the best account for the interaction pattern by adding a spatially neutral condition. It showed that feature- and space-based attention influenced performance, yet feature-based attention could not influence the performance outside the focus of spatial attention regardless of the temporal asynchrony between the cue and target onset. Moreover, the effectiveness of feature-based attention was equivalent at the spatially valid

and neutral locations. In conclusion, the findings resemble with the predictions of the sensory gating approach. While feature-based attention could operate at the attended location or under diffused spatial attention equally well, its effectiveness diminished outside the focus of spatial attention. Moreover, the spatial filter imposed on feature-based attention is more permeable than originally proposed by the sensory gating approach. Lastly, feature-based attention does not fully spread to an unattended location regardless of the time difference between the cue and target onsets.

This work is dedicated to my family,
Thank you for your endless support in my journey, beyond Ocean and further.

ACKNOWLEDGEMENTS

I am beyond thankful to my family, who helped me actualize myself in my life. I was blessed to take my first baby steps and my steps to the marriage altar with your endless support and understanding. I am grateful to the Life because we have been destined to be, yet I always feel the bitterness of losing my grandpa every day. As he carried me on his shoulders when I was a kid, I feel his supporting hands on my shoulder. Though you are beyond oceans, I will be walking proudly to defend my work for your undying love and honor.

I am thankful for all my mentors for being the light on the path when it was dark. I am especially grateful to my primary school teacher, Kudret Bayraktaroğlu, who kindled my love for learning and reading. I have not always been the exemplary student, and I am grateful to my high school teachers who sometimes corrected my unaligned compass.

My journey has started in the suburbs of Istanbul, continued through Germany to the United States. Michigan State University has become my home in the last five years. It has been more than a terminal, rather my haven. Without my colleagues, mentors, and husband, I could not withstand the demands of graduate school and the winters of Michigan. Thank you for making Michigan State University my home.

I thank my dissertation committee members, Drs. Mark Becker, Jan Brascamp, and Erik Altmann, for their support and criticisms in my dissertation work. Last, but not least, I thank my advisor, Dr. Taosheng Liu. He has been the guiding energy in my research while nourishing my intellectual freedom and ownership. He has always praised and criticized aptly. He never gave up on me even when I faltered.

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CHAPTER 1

INTRODUCTION

The visual environment is full of wonders and richness, yet it seems impossibly arduous to process each and every visual stimulus. Therefore, humans attend to certain aspects of the visual environment to select important or interesting information for further processing at the expense of the rest. What is selected and how it is selected depends on what the observer chooses to attend. One can attend to a particular location (space-based attention), a specific feature (feature-based attention), or the combination of both. There is some consensus regarding how a location or a feature is selected, yet the consequence of attending to both is less clear. The current project aims to reveal the behavioral outcomes and the underlying mechanisms of attending to a location and a feature simultaneously and how temporal factors may affect their influences. In this pursuit, I will first briefly explain the mechanisms of space- and feature-based attention as they inform the approaches to study their combined effects. Then, I will delve into three approaches that explain the combined effect of feature- and space-based attention. The goal of this study is to provide an explicit test of these different approaches.

Space-Based Attention

Space-based attention selects a subset of the items in the visual environment due to their locations. Space-based attention can be exogenous, as when salient items capture attention, or it can be endogenous, as when the observer voluntarily chooses to attend to a location to accomplish a goal. For the purpose of the current study, space-based attention will refer to endogenous spatial attention, as I will focus on the consequence of voluntarily attending to a feature and a location in order to select task-relevant information.

Earlier theories used “spotlight” (Posner, Snyder, & Davidson, 1980), “gradient” (Mangun

& Hillyard, 1988; LaBerge & Brown, 1989), "zoom lens" (Eriksen & James, 1986; Eriksen & Yeh, 1985) or "Mexican hat" (Müller, Mollenhauer, Rösler, & Kleinschmidt, 2005) as metaphors to depict the functioning of space-based attention. While there are some nuances among these metaphors, they all communicate the core idea that items in an attended location enjoy enhanced processing at the expense of items outside the attended location. For example, a target in an attended location is detected faster than that in a neutral location, and a target in a neural location is, in turn, detected faster than that in an unattended location (Posner, 1980; Posner et al., 1980). In addition to effects on reaction time, accuracy also improves for spatially attended items compared to unattended items (Downing, 1988; Müller & Findlay, 1987). These effects are generally believed to be a consequence of enhanced signal to noise ratio due to attention, which can be realized by noise reduction (Dosher & Lu, 2000a, 2000b) and/or signal enhancement mechanisms (Carrasco, Penpeci-Talgar, & Eckstein, 2000; Ling & Carrasco, 2006; Liu, Abrams, & Carrasco, 2009).

In terms of neural mechanisms, spatial attention is believed to be controlled by the frontoparietal network and actualized by early visual cortical areas (for a review, Beck & Kastner, 2016). The target appearing at the attended location elicit a higher BOLD response in the visual cortex (e.g. Martinez et al., 1999) and the frontoparietal network (for a review, Corbetta & Shulman, 2002), as well as larger ERP components such as P1, N1, and N2pc (for a review, Luck, 2005). In conclusion, it is evident that space-based attention prioritizes information at the attended location (for an excellent review, see Carrasco, 2011).

Feature-Based Attention

Imagine that you are looking for your friend among a sea of people. As people move and shift around, it is impossible to predict where your friend will be. Suppose your friend is a Spartan, who wears a basil green hat among people with various fashion choices. You can utilize this information to detect your friend by attending to items with basil-green color in the environment. This example illustrates a commonly used laboratory task—visual search, a situation where knowledge of visual features guides attentional selection (e.g. Wolfe, 1994; Treisman & Gelade, 1980).

Attending to the feature of a target makes visual search easier (Egeth, Virzi, & Garbart, 1984). Feature-based attention increases the signal of the target and attenuates the external noise (e.g., Ling, Liu, & Carrasco, 2009). In general, feature-based attention increases perceptual salience of the attended feature (for a review, see Carrasco, 2011). The visual cortical areas that are specialized for processing certain features will be more responsive when that feature is attended (for a review, Maunsell & Treue, 2006). As in space-based attention, it is believed that the frontoparietal network generates the control signals for feature-based attention (Egner et al., 2008, Liu, Hospadaruk, Zhu & Gardner, 2011; Liu & Hou, 2013).

Attending to a Feature and a Location

We not only attend to specific locations or features in our daily lives, but certain task demands entail attending to a combination of a feature and a location. For example, I have lost my golden pen somewhere on my desk. To find it, I voluntarily choose to attend to my portion of the space in the shared office space and golden color. Intuitively, the questions that arise in this situation, and investigated in this study, are as follows. Will any golden item on my desk or my coworkers' desk be processed efficiently in my brain? As my task goal dictates attending to a specific combination of color and location, will I be more efficient in processing a gold item on my desk than anywhere else? Will the golden ring on my coworkers' desk still grab my attention even when I know it is not my goal item?

A handful of existing studies have investigated the consequences of attending to both a location. The experimental tasks typically entailed detecting or discriminating a visual target. An informative cue regarding the location and feature of the target preceded the target display. The attentional effects were measured for a visual stimulus as a function of whether it was attended due to its location or feature. A variety of measures have been used in the previous research, including physiological measures, such ERP patterns (Andersen, Fuchs, & Muller, 2011; Anllo-Vento & Hillyard, 1996; Eimer, 1995; Hillyard & Münte, 1984) and neuronal firing rate (Hayden & Gallant, 2005, 2009; Ibos & Freedman, 2016), and behavioral measures such as the reaction time or accuracy (Kingstone, 1992; Lambert & Hockey, 1986; White, Rolfs, & Carrasco, 2015). In this study, I will focus on the conjoint impact of space- and feature-based attention on behavioral performance.

A few studies have investigated this question, but the findings are divergent (see Kingstone, 1992; Lambert & Hockey, 1986; White et al., 2015). The current study aims to fill this gap in the literature. I have conducted an extensive literature review of the effects of feature- and space-based attention on both behavioral and neurophysiological measures. I propose that the diverse findings from this broad background can be categorized into three different approaches, namely the sensory gating, independence, and boosting. In the following chapters, I will first outline a simple model to distinguish these three approaches, followed by a review of the empirical findings supporting each approach and their limitations. Lastly, I will introduce a potential factor that may influence the interplay between space-based and feature-based attention, which is the time available to utilize the informative cue to deploy the two types of attention.

CHAPTER 2

SIMPLE MODELS FOR THE THREE APPROACHES

The independence, sensory gating, and boosting approaches provide descriptive accounts about the relationship between feature- and space-based attention. Using simple equations, I will depict the predicted influence of space- and feature-based attention on an outcome measure, namely behavior. The model is based on *a priori* considerations of possible patterns of interaction between the two types of attentional effect. It is meant to be a descriptive one to synthesize empirical findings and not as a quantitative model to fit actual behavioral performance.

Here is an overview of the terms and definitions. We will use P to denote the performance outcome (dependent variable) where a larger value means better performance (higher accuracy or lower reaction time). The terms C, A_S, A_F, are common variables across all approaches. C is the baseline performance under passive viewing. A_S and A_F denote the impacts of space- and feature-based attention on performance, respectively. A_S has three levels: attended (target appearing at the expected location), neutral (target appearing at any location under spatially diffused attention), and unattended locations (target appearing at the opposite of the expected location). Under diffused feature-based attention, P at the attended location is expected to be higher than neutral location. P is expected to be higher at the neutral location compared to an unattended location (e.g. Downing, 1988; Müller & Findlay, 1987; Posner, 1980; Posner et al., 1980). A_F has two levels: attended (target possessing the expected feature) and unattended feature (target possessing opposite of the expected feature). Under diffused space-based attention, P for the attended feature is expected to be higher than an unattended feature (e.g. Hillyard & Munte, 1984; Ling et al., 2009; Liu et al., 2007; White et al., 2015).

The three approaches make distinct predictions regarding the P as a combination of space-and feature-based attention. Now, I will depict the predictions of three approaches from simple to more complex interactions.

The Independence Approach

The independence model is easiest to quantify. According to the independence model, feature- and space-based attention have independent impact on performance. Hence, it can be captured by a simple formulation as $P = C + A_S + A_F$. P denotes an outcome performance score (Figure 1a). Deployment of space-based attention increases A_S, where the performance at the attended, neutral, and unattended locations is differentiated. Deployment of feature-based attention increases A_F, where the performance for attended features becomes larger in comparison to unattended features. The main prediction of this equation is that the efficacy of the feature-based attention, that is the performance difference for the targets with the attended and unattended features does not vary between attended, neutral, and unattended locations.

The Sensory Gating Approach.

The sensory gating approach posits that space-based attention gates feature-based attention. Hence, the formula becomes: $P = C + A_S + G^* A_F$ (Figure 1b). G is the parameter that denotes the gating term. According to the sensory gating approach, the gating terms operates only at the unattended location on A_F. When space-based attention is not differentiated across space, all locations can be categorized as neutral hence G does not operated on A_F. When space-based attention is deployed, G assumes the value of 1 at the attended and neutral locations (see Hillyard & Munte, 1984). Hence, the efficacy of feature-based attention (the performance difference between attended and unattended feature) is identical for the attended and neutral locations. For the unattended location: $G < 1$, which attenuates the performance difference between the target with the attended and unattended feature. Crucially, the efficacy of feature-based attention at the unattended location is smaller than its efficacy at the attended or neutral locations. The exact value of G is unknown but previous work has shown that the gate can eliminate (Anllo-Vento & Hillyard, 1996; Hillyard & Münte, 1984; Kingstone, 1992; Stoppel et al., 2007) or just reduce (Eimer, 1995; Leonard et al., 2015; Vierck & Miller, 2008) the efficacy of feature-based attention at the unattended location.

The Boosting Approach

The boosting approach assumes an interaction between space- and feature-based attention, such as $P = C + A_S + A_F + \beta * A_S * A_F$ (Hayden & Gallant, 2005, 2009) (Figure 1c). β is the interaction parameter that integrates the impact of feature- and space-based attention (the competition term in White et al., 2015). If the feature- (Lambert & Hockey, 1986) or space-based (Kingstone, 1992; White et al., 2015) attention is very weak (i.e., A_F or A_S approaches zero), the interaction term's impact on performance would disappear. If the observer attends to a location and a feature, an interactive pattern of results emerges: the efficacy of feature-based attention at the attended location becomes larger than at the neutral location, because the multiplication $\beta * A_S * A_F$ ends up greater at the attended location (with higher performance score for A_S) than the neutral location (with lower performance score for A_S) (Hayden & Gallant, 2005, 2009; Ibos & Freedman, 2016).

The predictions of the boosting and the sensory gating approach seems hard to differentiate at the first glance, as both predict some kind of overall interaction between space- and feature-based attention (figures 1c and 1b). Both predict that the efficacy of feature-based attention at the unattended location should be smaller than at the attended and neutral locations, due to the filtering term G attenuating A_F according to the sensory gating approach or due to $\beta * A_S * A_F$ getting smaller according to the boosting approach. However, according to the boosting approach, the feature-based effect at the unattended location can never completely disappear as long as feature-based attention is operational due to the additive term for the feature-based attention, A_F, that applies homogenously to all locations. On the other hand, according to the sensory gating approach, the performance difference between the attended and unattended features at the unattended location may totally disappear depending on the permeability of the filter, G. Most importantly, how the efficacy of the feature-based attention differs between the neutral and attended location is the main distinction between the sensory gating and the boosting approaches. According to the sensory gating approach, there should be no such difference between those two locations as the filtering term G are identical for both. On the other hand, the difference should be larger at the attended location than the neutral locations due to the $\beta * A_S * A_F$, as according to the boosting approach.

The behavioral predictions of the three approaches are simple and straightforward. Next, I will provide empirical findings supporting these approaches in the chronological order and discuss the evidence and shortcomings.

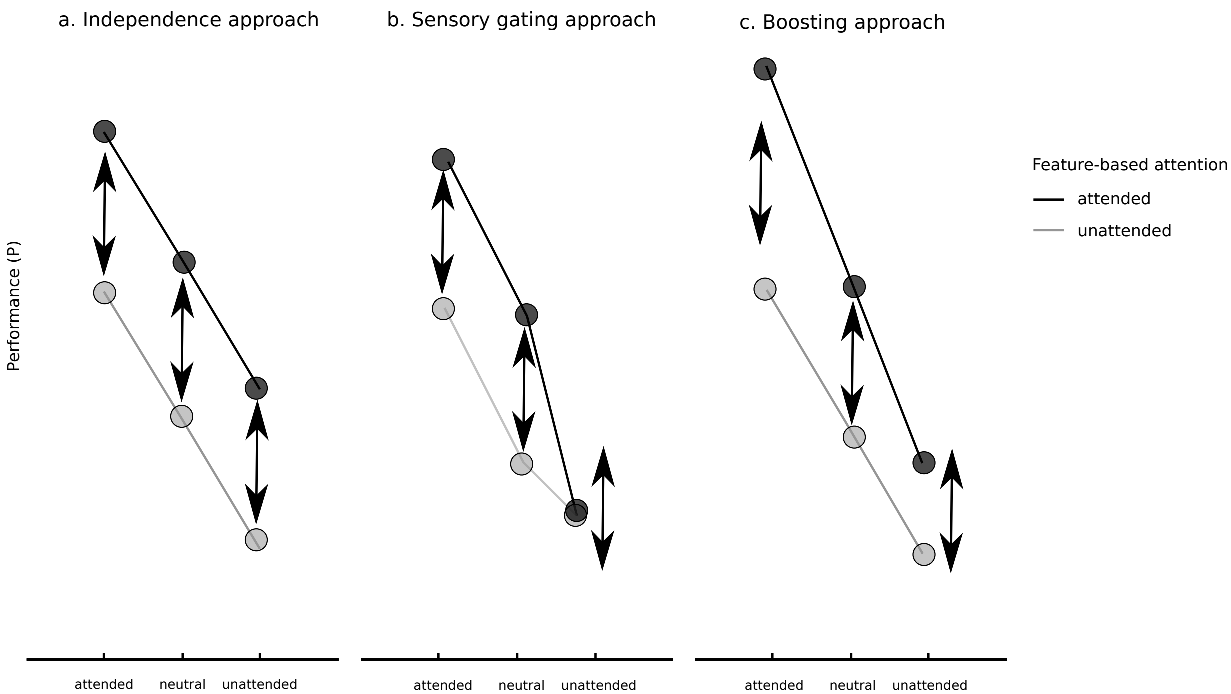

Figure 1. The predicted performances as outcomes of attending to a location and a feature, according to the a. independence approach, b. sensory gating approach, c. boosting approach. The bidirectional arrows depict the effectiveness of feature-based attention (performance difference between attended and unattended feature) in different locations. Notice that the two lines (depicting attended and unattended features) are parallel for the independence approach (a), the two lines are parallel except at the unattended location for the sensory gating approach (b), and the lines gradually get closer from attended, to neutral and to unattended location in the boosting approach (c).

CHAPTER 3

EMPIRICAL EVIDENCE FOR THE THREE APPROACHES

THE SENSORY GATING APPROACH

The sensory gating approach was the earliest attempt to explain the interplay between space- and feature-based attention and was highly influenced by predecessor filtering theories (see Hillyard & Münte, 1984). The filtering theories were originally developed in the dichoptic listening paradigm where the observer's goal was attending to one stream of incoming information in one ear while ignoring the other one (Cherry, 1953). Though the detailed property of the filter was under debate, all agreed that the unattended channel was attenuated (Broadbent, 1958; Cherry, 1953; Moray, 1959). As the extension of the filtering theories from the auditory domain to the visual domain, what could be the filter in the visual domain?

Space- and feature-based attention were both logical candidates for the filter. Spatial attention was likened to a "zoom lens" (Eriksen & James, 1986) or "searchlight" (Broadbent, 1982). However, simple visual features were believed to be processed pre-attentively and could also serve as a filter (Treisman, 1985). The first premise is that it should operate relatively earlier than other candidate. Therefore, comparing their relative time courses could be informative about which one could act upon the other one (see Hillyard & Münte, 1984). Thus, early studies used ERP to investigate this question and have found that spatially attended items elicited earlier or stronger ERP components than spatially non-attended items around 100 msecs after the stimulus onset (i.e., P1 and N1, Anllo-Vento & Hillyard, 1996; Eimer, 1994; Mangun & Hillyard, 1991). Feature-based attention was found to have a later impact than space-based attention, i.e., items having attended features elicited stronger or earlier ERP components in comparison to unattended features about 300 msecs after the stimulus onset (Anllo-Vento & Hillyard, 1996). Similarly, a later behavioral study investigating the impact of cue-target asynchrony on the utilization of feature and spatial cues found that feature-based attention was utilized at later cue-target asynchronies than space-based attention (Liu, Stevens, & Carrasco, 2007). Therefore, space-based attention could potentially be the early filtering mechanism due to its earlier operation than feature-based attention (Hillyard & Anllo-Vento, 1998).

Space-Based Attention as the Filter

Additional studies investigated the relationship between space- and feature-based attention in factorial designs. Participants were asked to respond when the specific object with a specific feature appeared at the specific location. Then, the ERPs elicited by non-target objects at the attended/unattended location with attended/unattended feature were measured. If both feature- and space-based attention are deployed in conjunction, which one operates earlier, and which one qualifies the other one?

The filter was identified by conjointly manipulating space- and feature-based attention and comparing how the interplay between the two influences ERP components. In a go, no-go task (Eimer, 1995), subjects were asked to report whether a circle with the precued color appeared at the precued location. In some trials, a monocolored rectangle (probe) with attended or unattended color appeared at the cued or uncued location. The probes at the validly cued location elicited larger P1 (around 100 msecs after the probe onset) than at the invalidly cued location, regardless of the feature properties of the probe. The feature validity effect was also observed, but later than the spatial validity effect, which was about 150 msec after the probe onset. Most importantly, the markers of feature-based attention was observed only when the probe appeared within the attended location. In a similar study (Anllo-Vento & Hillyard, 1996), probes at the attended location elicited stronger P1 and N1 than probes at the unattended location. Most importantly, probes with attended features elicited higher SN, which is an index of feature-based attention, only when they appeared at the attended location. Earlier emergence of space-based attention effects than feature-based attention and the modulation of feature-based attention by space-based attention support the sensory gating approach.

Another study using the steady-state-visual –evoked potential (SSVEP) also provides behavioral and physiological evidence for the sensory gating approach (Andersen et al. 2011). In terms of physiological evidence, they have found that P3 amplitude that was locked to the probe onset, which is a marker of late-stage attentional processes, was low at the uncued location regardless of whether the change occurred at the attended color. On the attended location, the P3 amplitude was larger for changes in the attended color than in the unattended color. Behavioral results mirrored the P3 pattern: people made quite a lot of false alarms when non-target change appeared at the attended location. However, people did not commit as many false alarms when the non-target change occurred at the unattended location regardless of on whichever color it occurred. Andersen et al.'s study (2011) may be interpreted against the independence approach (see next section), as not all aspects of feature-based attention operate independently from space-based attention.

Even though the sensory gating approach claimed that feature-based attention can operate within the range of spatially attended location, it was not clear whether feature-based attention could operate under diffused space-based attention. Hillyard and Münte (1984) tested the predictions of the sensory gating approach under focused and diffused spatial attention conditions. They have confirmed that P1 was an index of space-based attention, as the probes at the attended location elicited higher P1 than at the unattended location. However, the P1 amplitude in the diffused space-based attention condition was lower than in the focused space-based attention condition. Probes with the attended features, in comparison to unattended feature, elicited enhanced ERP components that were later than P1. Most importantly, feature-based attention elicited a larger ERP components for the probes at the attended location than at the unattended location only in the focused attention condition. In the diffused attention condition, feature-based attention elicited equal-sized ERP components at the attended and unattended location. Hence, feature-based attention can spread globally across space in the absence of spatial focus of attention. However, when spatial attention is deployed to a specific location, feature-based attention can only operate within the boundary of the spatial attention.

Behavioral Evidence for the Sensory Gating Approach

In a series of experiments, Kingstone (1992) simultaneously presented a predictive feature and spatial cue before the presentation of the target to be discriminated. In the first version, the feature cue was 80% predictive of the target shape, while the spatial cue was either 70% or 90% predictive of the target location. In the second version, the spatial cue's predictivity was 80% while the feature cue was 70% or 90% predictive. It was clear that subjects were sensitive to the predictivity of the cues: the cost of the invalid spatial cue and the benefit of the valid spatial cue (in comparison to the neutral spatial cue) increased as the predictivity of the spatial cue increased. As for the feature cue, the cost of the invalid cue and the benefit of the valid cue increased as the feature cue's predictivity increased. Interestingly, the interaction between space and the feature cue emerged when the predictivity of the spatial cue was 80% or 90%. The benefit of the feature cue diminished at the uncued location, yet the benefit of the valid feature increased at the cued location. According to Kingstone, the findings supported the hypothesis that space-based attention was available earlier than feature-based attention; therefore the former modulated the latter.

In addition, a few studies have investigated the effectiveness of feature-based attention at the unattended location, while varying distance between the attended location and the target. Consistent with the sensory gating approach, it was found that the effectiveness of feature-based attention could spread as far as within the attended location and to its vicinity, but it waned outside the reaches of space-based attention (Leonard et al., 2015; Vierck & Miller, 2008).

Limitations of the Sensory Gating Approach

The sensory gating approach is internally consistent, yet it is not devoid of shortcomings. Almost all the supporting studies (except Kingstone, 1992) were conducted on the ERP domain, and the few behavioral studies supportive of sensory gating did not explicitly manipulate space-based attention (Leonard et al., 2015; Vierck & Miller, 2008). Therefore, the generalizability of the sensory gating approach to the behavioral performance has been unknown.

The sensory gating approach has been mostly concerned about the gating aspect of space-based attention (e.g. Eimer, 1995; Anllo-Vento & Hillyard, 1996; Hillyard & Munte, 1984). Except for Kingstone (1992), the impact of space-based attention on feature-based attention at the attended location as opposed to diffused space-based attention was not extensively investigated. It has been known that space-based attention not only decreases the sensitivity at the unattended location (e.g. Desimone & Duncan, 1995; Pestilli, Viera, & Carrasco, 2007; Pestilli & Carrasco, 2005), visual sensitivity increases at the attended location (Carrasco et al., 2000; Dosher & Lu, 2000a, 2000b; Ling & Carrasco, 2006; Liu et al., 2009). The 'filter' (Broadbent, 1958) concept can account for the role of space-based attention in the sensory gating approach. However, this approach did not consider the enhancing role of space-based attention at the attended location. Therefore, one of the main shortcomings of the sensory gating approach is its lack of consideration of the fate of space-based attention at the unattended location compared to the feature-based attention under diffused spatial attention.

It also seems that the sensory gating approach has fallen out of favor due to the advent of a newer perspective on feature-based attention, which suggests that feature-based attention can spread to an unattended location. This view has given rise to the independence approach, to which I now turn.

THE INDEPENDENCE APPROACH

According to the independent approach (Figure 1a), which seems the most prominent approach currently, the consequence of the conjoint manipulation of space- and feature-based attention is equivalent to manipulating each only and then additively summing up their effects. The independence approach has two implicit premises that lead to the additive effect of space- and feature-based attention: Space-based attention is not inherently feature-selective (Martinez-Trujillo & Treue, 2004; Reynolds & Heeger, 2009; Treue & Martinez-Trujillo, 1999) and feature-based based can spread globally under diffused space-based attention (Liu & Mance, 2011; Liu & Hou, 2011; Saenz, Buracas, & Boynton, 2002, 2003; Zhang & Luck, 2009; Serences & Boynton, 2007).

The feature-similarity gain model proposes that feature- and space- are independent dimensions. Space-based attention's influence was not altered with the feature of a visual item. The gain function was evident within and outside the feature-relevant location (Martinez-Trujillo & Treue, 2002, 2004; Treue & Martinez-Trujillo, 1999). Such independence is also manifested in computation models of attention, such as the influential normalization model of attention, which posits that the impact of space- and feature-based attention on neuronal firing is implemented independently from each other, and feature-gain is assumed to be constant across all locations (Reynolds & Heeger, 2009).

An important corollary of the independence approach is that feature-based attention can spread globally in space. A plethora of studies investigated how feature-based attention behaves across two attended locations or outside the focus of an attended, task-relevant location. I refer to the former as "dual attention foci" and the latter as "single task studies". Below, the two types of studies are presented and discussed separately.

Dual Attention Foci Studies

"Dual attention foci" studies urge participants to engage in two different tasks. Each task, even though they may not seem equally important, requires attending to different locations. Those studies can be roughly grouped into three categories.

In the first group of studies, the same feature or two opposing features were attended across two equally relevant locations. Those studies have found that attending to one feature across two locations was easier than attending to two different features across two locations (Andersen, Hillyard, & Müller, 2013; Becker, Ravizza, & Peltier, 2015; Saenz et al., 2003). Attending to the same feature across two locations comes easy because the attended feature becomes prioritized globally by default. On the other hand, trying to attend opposing features at two different locations decreases the signal to noise ratio of the two features, because when attending to a feature at a location, one cannot help attending the same feature at the opposite location, which constitutes the wrong feature in that location (Andersen et al., 2013)

However, the findings above can be accommodated by an alternative explanation, based on object-based attention. The division between an object and a group is somewhat blurry. It is generally recognized that visual stimuli can be grouped due to shared features. Thus, attending to the same feature across visual field could be akin to attending to a grouped item due to shared feature and attending to the different features across visual field could be akin to attending to the parts of two different groups. It has been well established that it is easier to attend one object than two objects, and attending to one part of an object obligatorily spreads to other parts of the object (Duncan, 1984, Egly, Driver, & Rafal, 1994; see Chen, 2012 for a review). As a possibility, observers could have grouped two features across space into two groups. When asked to attend to a feature across space, they might have grouped the same feature from different locations into an object and attended to one object only. When asked to attend to two different features across two different locations, they might have divided their attention across two locations into two different objects (Festman & Braun, 2010, 2012).

The second group of studies also required attending to a feature at a location. Different than the previous group, one location contains the primary task while the other one contains the secondary task. The primary task explicitly entails attending to a feature, while the target in the secondary task may or may not possess the attended feature. Here, the interesting variable was the secondary task performance as a function of whether the secondary target possessed the target feature of the primary task. This category of studies with a primary task and a secondary task across two different locations are less amenable to the object-based account above, as the stimuli at two locations are very distinctive.

It was found that even when the attended feature in the primary task did not predict the target in the secondary task, it was easier to detect the secondary target when it possessed the attended feature in comparison to when it did not (Rossi & Paradiso, 1995; White & Carrasco, 2011). Those studies concluded that feature-based attention spread across locations and tasks, as any stimulus possessing the attended feature became visually more prominent. However, note this paradigm does entail two task-relevant locations, one primary and one secondary. Importantly, these studies did not test the spread of feature-based attention at a location that was never task-relevant.

The third variation of the dual-task design investigated the spread of aftereffect due to feature-based attention. In those studies, the primary task is to attend to an adapter in one location, and the secondary task is to perform a discrimination task on a test stimulus in a different location to measure the strength of the aftereffect. It is known that perceiving a feature for an extended period causes adaptation, which is manifested as decreased sensitivity to the adapted feature and perceptual aftereffect (for a review, Kohn, 2007). Critically, attending to one of the features among two opposing and spatially superimposed features leads to adaptation to the attended feature. Alais and Blake (1999) found that after attending to a motion direction among two superimposed, opposite-moving fields, participants perceived a static patch appearing at the same location as moving in the opposite direction of the attended direction. Moreover, later studies found that the feature-based attention induced aftereffect could be reliably measured at a remote location (Boynton, Ciaramitaro, & Arman 2006; Sohn, Chong, Papathomas, & Vidnyanszky, 2005), even as far as 15° away from the adaptor (Liu & Hou, 2011; Liu & Mance, 2011). The explanation is that attending to a feature increases the activity of the feature detectors that process the attended feature, therefore leading to feature-selective adaptation. Most importantly, all the feature detectors, even the remote ones from the adapting stimulus, modulate their activity and hence become adapted. However, the alternative explanation of the dual-task studies with a primary and a secondary task also applies to the aftereffect studies. Here, the primary task is attending to a feature in the adaptor, and the secondary task is the measure of adaptation. The test stimulus for measuring the adaptation strength was partially task-relevant and could potentially be attended to some degree by the participants. Therefore, a more conservative conclusion is that feature-based attention induced aftereffect can spread to task-relevant locations.

In general, "dual attention foci" shows that processing a feature at a specific location necessitates the spread of feature-based attention to a distal location that is not relevant for the attended feature. However, the spread of feature-based attention was not measured outside the focus of spatial attention because the distal location was still within the focus of spatial attention, albeit for another task. Indeed, the foci of space-based attention were not explicitly manipulated in these studies, thus precluding a definitive conclusion regarding the global spread of feature-based attention under all variations of spatial attention. Instead, single-task studies can provide a more definitive answer regarding the spread of feature-based attention to an unattended location.

Single Task Studies

The experiments with a single task used similar designs to dual-task studies. The task was to attend to a feature among two spatially superimposed items with opposite feature values. Meanwhile, a task-irrelevant item appeared at the opposite hemifield, which may or may not possess the attended feature. Crucially, the response to the task-irrelevant distant distractor as a function of its similarity to the attended feature was the main dependent variable. In order to claim that feature-based attention spreads globally, the distractor with the attended feature should be able to enjoy enhanced processing in comparison to a distractor without the attended feature. Unlike dual-task studies, the single-task studies provided solely physiological evidence for the support of the independence approach. It was found that the distant distractor with the attended feature elicited higher ERP markers of attention, such as P1, in comparison to a distant distractor without the attended feature (Zhang & Luck, 2009). A distractor with an attended color also elicited a higher BOLD response in color-processing visual areas, such as V1 and V4 in comparison to a distractor without the attended color (Saenz et al., 2002), and the same was found in the motion domain where the effects were observed in the motion-processing brain regions such as V1, V3a and MT+ (Saenz et al, 2002; Serences & Boynton, 2007). The spread of feature-based attention is not bound to the presence of a stimulus. The attended motion can be decoded from the visual cortex contralateral to the task-irrelevant distractor location even in the absence of the physical distractor (Serences & Boynton, 2007).

In general, abovementioned single-task studies show that our brains are not idle for the attended feature at the task-irrelevant locations. Attending to a feature increases the activity of the brain regions that are responsible for the processing of that feature throughout the space, even outside the focus of spatial attention. Detecting the neuronal correlate of feature-based attention at an unattended location, I think, is major counter-evidence against the sensory gating approach which would claim that feature-based attention should disappear at the task-irrelevant location. However, the task-irrelevant location in the single-task studies may not be completely devoid of spatial attention. Space-based attention might occasionally have visited the task-irrelevant location in long, block designs (e.g. Saenz et al, 2002; Zhang & Luck, 2009). From the perspective of the sensory gating approach, some 'leakage' of space-based attention to a task-irrelevant location might possibly have attenuated the rigidity of the spatial filter (e.g. Lachter, Forster, & Ruthruff, 2004).

The 'dual attention foci' and 'single-task' studies incentivize the independence approach. Those designs serve well to investigate the spatial bounds of the spread of feature-based attention, yet conjoint manipulation of space- and feature-based attention can provide a more global picture about whether feature-based attention does not alter under various strengths of space-based attention. Now, I will turn to studies that have found support to the independence approach by conjointly manipulating the space- and feature-based attention.

Conjoint Manipulation of Space- and Feature-Based Attention

Two behavioral studies also support the claim of the independence approach. Lambert and Hockey (1986) presented conjoint spatial and feature cues that were each 60% predictive of the upcoming target's location and form, respectively. They asked participants to utilize both cues (session 1 & session 2), space-cue only (session 3), or feature-cue only (session 4). When asked to utilize both cues, attended locations were prioritized over unattended locations, and attended features over the unattended ones. However, feature- and space-based attention did not interact; they did not affect each other's effectiveness, suggesting an independent effect. White et al. (2015) used a similar design and factorial cue regimen, but the cue predictivities were increased to 75% and neutral space and feature cues were introduced. Their study consisted of two experiments, differing in the amount of competition, defined by the number of potential targets (one target: low competition, three targets: high competition experiment). In the low competition experiment, they found that subjects were more sensitive to changes in the attended color than in the neutral and unattended color. It was also easier to detect the target at the cued location in comparison to uncued location, but not in comparison to a neutral location. Most importantly, feature-based attention's impact was constant across all location. Hence, they concluded that space- and feature-based attention influenced the signal to noise ratio, yet they did not influence one another under low competition.

In terms of the EEG measurements, Andersen et al. (2011) has found that the early ERP measures reflected both the attended feature and location. The SSVEP improvement evoked by feature-based attention did not differ within and outside the attended location, so did the SSVEP improvement evoked by space-based attention as a function of the attended or unattended feature.

The Limitations of the Independence Approach

I think that the limitations of the independence approach are three-fold: relatively weak attentional manipulations, contradictory findings within the same studies, and the possible over-generalization of the some of the single-task studies.

Recall that Kingstone (1992) has conducted a target discrimination study by conjointly manipulating space- and feature-based attention in a similar regimen to White et al. (2015) and Lambert and Hockey (1986). Even though the experimental designs were similar, Kingstone (1992) has found support for the sensory gating approach, yet White et al. (2015) (under low competition) and Lambert and Hockey (1986) provide support for the independence approach. A close inspection of the experimental design reveals that Kingstone (1992) found the interaction with highly predictive cues of location (80% and 90%) and feature (70%, 80%, 90%) of the target, while White et al. (2015) and Lambert and Hockey (1986) used less predictive cues, respectively with 75% and 60% predictive values. Reflecting the cue predictivities, Kingstone (1992) found reliable main effects of feature- and space-based attention, yet the main effect of space-based attention in White et al. (2015) and the feature-based attention in Lambert and Hockey (1986) were relatively weaker. Therefore, the absence of the interaction between space- and feature-based attention in White et al. (2015) and Lambert and Hockey (1986) could possibly be explained by the weak main effects of attention. The importance of obtaining sizable main effects in order to capture any interaction can be explained by the model terms of Chapter 2. For example, G does not operate under diffused spatial (neutral location) (Figure 1b). Therefore G might not have operated on feature-based attention in White et al. (2015). With the same logic, G could possibly be not operative Lambert and Hockey (1986) because feature-based attention was almost absent. In terms of $\beta * A_S * A_F$, β was multiplied with relatively undifferentiated A_S or A_F hence the interaction term was virtually undetectable.

Another shortcoming of the supporting studies is the contradictions within the studies. For example, even though Andersen et al. (2011) did not find any evidence of interaction in the low-level visual processes, their behavioral data and late ERP markers of attention reveal that space- and feature-based attention interact in later stages, such that feature-based attention's effects were observed only within the attended location. Though Andersen et al. (2011)'s main argument for the independence approach is the early ERP markers, I think that the late ERP markers are no less important because they seem to be a better correlate of the behavioral false alarm results.

White et al. (2015) has found that the impact of space- and feature-based attention were independent only when the competition was low. Under high competition, the effectiveness of space-based attention depended on feature-based attention. It is hard to determine was it the 'default setting' of the relationship between space- and feature-based attention by looking at their results. Though competition could be potentially important for the relationship between space- and feature-based attention (e.g., White et al., 2015), the term itself is hard to quantify. Moreover, the 'competition' in their study was possibly confounded with the strength of space-based attention and working memory load. Space-based attention seemed to be stronger under high competition than low competition, which could possibly make the interaction term to become more detectable. Additionally, the participants were asked to monitor for one event under low competition while they were asked to monitor for three events under high competition. Given that monitoring and remembering three events are almost at the limit of the working memory capacity (e.g., Luck & Vogel, 1997; Zhang & Luck, 2008), the low and high competition conditions could respectively correspond to low and high working memory load. Therefore, the interpretation of White et al. (2015) in favor of any approach can be challenging.

Even though the studies with the conjoint manipulation of space- and feature-based attention fall short to provide concrete evidence in favor of the independence framework, the independence framework rings a familiar tone and it is seems to be widely accepted. I speculate the independence approach possibly owes its popularity to single-task studies that have found feature-based attention can spread to an unattended location (e.g. Saenz et al, 2002; Saenz & Boynton, 2007; Zhang & Luck, 2009). Though establishing feature-based attention *can* spread globally, they were not designed to elaborate on the profile of the space- and feature-based attention.

Lastly, the boosting approach can be a potential alternative to the sensory gating and independence approaches. Considering that feature- and space-based attention can at least partially independent, the boosting approach may potentially account for the interaction between space- and feature-based attention.

THE BOOSTING APPROACH

The boosting approach is the newest and the least well-known among all approaches. The studies that constitute the basis of this approach did not explicitly propose a theory of "boosting", the term was used to describe the effectiveness of feature-based attention at the attended location (White et al., 2015). However, given the commonality among this group of studies, I believe that the term "boosting approach" would be an apt title to describe the particular kind of interaction pattern between space- and feature-based attention.

Physiological Evidence for the Boosting Approach

Because the boosting approach is mostly supported by the physiological research, the physiological relationship between the markers of feature- and space-based attention is informative (e.g., Freedman & Ibos, 2018; Ibos & Freedman, 2016). Feature- and space-based are governed by overlapping brain regions in the frontoparietal network (Egner et al., 2008; Liu et al., 2011). Some studies claim that space- and feature-based attention are governed by independent neuronal signals from each other (Greenberg et al., 2010; Liu & Hou, 2013; Schenkluhn, Ruff, Heinen, & Chambers, 2008), yet there is also evidence that feature- and space-based attention signals are generated by the same neuronal populations (Patzwahl & Treue, 2009). Therefore, the neuronal hardware of the feature- and space-based attention may not be perfectly identical, yet the overlap is substantial.

The boosting approach stems from physiological evidence from nonhuman primates. Their (Hayden & Gallant, 2005, 2009; Ibos & Freedman, 2016) methodologies are similar: a visual neuron was recorded while the monkey subject was instructed to give a response when a specific feature appeared at a specific location. In such an experiment, Hayden and Gallant (2005) recorded neurons in V4 in a delayed match-to-sample task. The firing rate to the sample items was influenced by the sample's location and feature in relation to the attended location and feature, respectively. While attending to the preferred feature of the neurons caused a higher firing rate than attending to another feature, the samples within the attended location caused a higher firing rate than samples at the unattended location. Though the influence of feature- and space-based attention were also independent, a super-additive interaction was detected in 42% of V4 neurons. In these neurons, the combination of the benefits feature- and space-based attention were greater than their independent effects. In a subsequent study (Hayden & Gallant, 2009), they acknowledged the super-additivity and suggested that the attentional effects were synergistic even though they were controlled by relatively independent mechanisms. A more compelling experiment later put more emphasis on the interaction term. In a similar experimental design, Ibos and Freedman (2016) measured the response of the posterior parietal cortex neurons. The neurons' response for any visual stimulus was stronger when spatial attention was directed in the receptive field of the neuron than outside the receptive field. Most importantly, the impact of feature-based attention (that is, the firing rate difference between attended and unattended feature) was larger at the attended location than the unattended location. Even though space- and feature-based attention effects could be both observed from the neurons' firing patterns, the super-addictive effect indicated that the feature- and space-based attention co-benefitted each other.

According to Ibos and Freedman (2016), the feature-based attention signals that arise in visual cortex are multiplied with the retinotopic space-based attention signals before being transmitted to the posterior parietal cortex. Given that the posterior parietal cortex is thought to be a candidate for the 'priority map'(see Fecteau & Munoz, 2006), the items that happen to appear at the attended location and possessing the attended feature are given more attention than the sum of the attention given to an item appearing at the attended location or possessing the attended feature. In simpler terms, the item that happens to appear at the attended location and possess the attended feature signifies a match with the target template and put on a pedestal, and anything else is a mismatch (Freedman & Ibos, 2018).

Behavioral Evidence and Limitations for the Boosting Approach

There are no behavioral studies that solely support the boosting approach. Only one study seemingly provide behavioral evidence in favor of the boosting approach. The reader is familiarized with White et al.'s (2015) study under the independence approach section. In high competition condition, White et al. (2015) have also found a super-additive term as the sensitivity was boosted for the target at the attended locations that appeared in the attended feature in comparison to the unattended feature. They have updated the normalization model (Reynolds & Heeger, 2009) by adding a super-additive term. The shortcoming of the only behavioral evidence

(White et al., 2015) was explained under the independence approach. In summary, the strength of competition was confounded with the strength of space-based attention and working memory load. Therefore, the interaction between space- and feature-based attention under high competition could potentially reflect factors other than attentional effects. Overall, better behavioral evidence is needed to support the boosting approach.

CHAPTER 4

THE POSSIBLE INFLUENCE OF TIME ON THE RELATIONSHIP BETWEEN FEATURE- AND SPACE-BASED ATTENTION

Previous studies investigated the time courses of the feature- (Liu et al., 2007) and space-based attention (e.g., Dosher & Lu, 2000a, 2000b; Müller & Rabbitt, 1989), yet the time courses of space- and feature-based attention under conjoint manipulation has not been a theoretical concern in any of the approaches. I propose that capturing the snapshots of the interplay between space- and feature-based attention in various SOAs between the cue and target onsets may potentially reveal a dynamic relationship between the two.

Firstly, attention takes time to evolve. When people are asked to utilize a space or feature cue, they cannot immediately allocate attentional resources to the most likely location or feature. A predictive spatial cue can be utilized as early as 150 msec after the cue onset (Dosher & Lu, 2000a, 2000b; Müller & Rabbitt, 1989) and space-based attention can be sustained for a long time (Müller & Rabbitt, 1989). On the other hand, it could take 500 msec after the cue onset to utilize a predictive feature cue for motion direction (Liu et al., 2007). Among the studies that concurrently manipulate space- and feature-based attention, only Hilyard and Münte (1984) used the shortest SOAs (350 msec and 500 msec). They found that feature-based attention operated, yet only at the attended location. However, they have collapsed the results across SOAs. Hence their study cannot inform us about how early the initial feature-based attention signals can be detected when people attended to both a location and a feature. Therefore, space-based attention is likely to operate earlier than feature-based attention after the cue onset. With short SOAs, possibly only space-based attention can influence performance. In terms of the models, the equation will reduce to $P = C + A_S$, which will yield identical predictions for all three models with higher performance when the target appears at the attend location in comparison to a neutral location, and higher performance when the target appears at the neutral location compared to unattended location.

What happens when SOA is sufficiently long to engage in feature-based attention? Due to the long lifetime of space-based attention, we can assume that space-based attention is still operational (Liu et al., 2007; Müller & Rabbitt, 1989). The previous experiments hint that about 500 msecs of SOA is sufficient for feature-based attention to be utilized (Hillyard & Münte, 1984; Liu et al., 2007). Now, the P will depend on both A_S and A_F. However, the global spread of feature-based attention to the task-irrelevant locations also takes time. The ERP measures show that the spread of the feature-based attention to an unattended location takes about 100 msec to 200 msec after attending to the feature at the attended location (Stoppel et al., 2012). Thus, feature-based attention is likely to be bound at the attended location between the SOAs of about 500ms and 600ms. However, the exact timing of the emergence of the spread, or whether it can spread, is not known. The previous studies that used SOAs of 700 msec (Anderson et al., 2011) and 800msec (Lambert & Hockey, 1986) also used longer SOAs up to 3.7 secs (Anderson et al., 2011) and 1600 msec (Lambert & Hockey, 1986). Andersen et al. (2011) did not find the interaction between space- and feature-based attention in early EEG patterns, yet have found an interaction resembling the sensory gating in late ERP markers. Thus, 700 msecs could be sufficient for sampling the initial arise of feature-based attention, therefore revealing limited access of feature-based attention within the attended location. However, 3.7 secs SOA could potentially allow for the spread of space-based attention, hence revealing a pattern supporting the independence approach. Lambert and Hockey (1986) did not find the main effect of feature-based attention in their results with SOAs ranging from 800 to 1200 msecs, let alone a significant interaction term. However, it remains a possibility that the strength of feature-based attention, and the interaction pattern could have revealed different results for the earlier and later SOAs. The earlier SOAs could potentially yield in a weaker spread of feature-based attention compared to later SOAs. In both studies, not factoring in the SOA into the analysis might have masked the interaction term that emerged as a result of localized feature-based attention within the locus of attention.

Many experiments that manipulated the feature- and space-based attention in factorial designs choose SOAs that are longer than 800 msec. The studies that provided support for the sensory gating approach used SOAs of 900 msec (Eimer, 1995) or manipulated attention in a block design (Anllo-Vento & Hillyard, 1996). The supporting studies of the boosting approach used SOAs ranging from 900 msec (Ibos & Freedman, 2016), and 1 sec (Hayden & Gallant, 2005, 2009). Some of the studies provided partial support for both the sensory gating and the boosting approaches using SOAs of 1 sec (White et al., 2015), 1.5 sec (Kingstone, 1992), and 1.8 sec (Ibos & Freedman, 2016). In terms of the spread of feature-based attention to an unattended location at longer than 800 msecs SOA, it may fully spread (e.g., White et al., 2015), it may spread but not as effective as neutral spatial location (e.g., Ibos & Freedman, 2016; Hayden & Gallant, 2005, 2009), or it may never spread (Anllo-Vento & Hillyard, 1996; Eimer, 1995; Kingstone, 1992).

Thus, it is evident that some kind of interaction between space- and feature-based attention can be detected as early as 900 ms in terms of the effectiveness of feature-based attention at the unattended location in relation to the neutral location. Additionally, the literature is not clear about how the interaction emerges over time and whether there is an interplay between the boosting and the sensory gating. I speculate that the initial interaction between the space- and feature-based attention will resemble the predictions of the sensory gating approach. However, it is unknown whether the boosting could develop over time, such that the feature-based attention may potentially become even stronger at the attended location as the time passes. As the previous studies did not systematically investigate the time course of attentional effect, another unknown is whether only the boosting or sensory gating can operate at a given time or they can co-occur. Using the model predictions, I intend to investigate how the interaction between space- and feature-based attention evolves over time.

SOA and Behavioral Outcomes

It is likely that only space-based attention operates in a short SOA. Hence, only space-based attention is expected to be evident in short SOAs (see Liu et al., 2007). In that case, the only main effect of the validity of the spatial cue is expected to be significant on behavior. According to all models, the performance for the target at the attended locations should be better than the neutral location, and the neutral location should be better than the unattended location. Here, the efficiency of feature-based attention is uniformly zero across all locations.

If the SOA is longer, the observer may have sufficient time to engage with the feature cue (Liu et al., 2007). However, the global spread of feature-based attention to an unattended location may take even longer time (Stoppel et al., 2012). Therefore, feature-based attention is not expected to operate at the unattended location at this phase. However, feature-based attention is expected to influence attention within the attended location or neutral location. Furthermore, regardless of feature-based attention, the impact of space-based attention is expected to be evident.

There are two possible outcomes regarding the fate of feature-based attention at the unattended location. Time may possibly be a remedy for the spread of feature-based attention. Then, feature-based attention can spread globally though it may be less effective compared to diffused spatial attention (e.g., Hayden & Gallant, 2005, 2009; Ibos & Freedman, 2016). Another possibility is that feature-based attention may never be effective at the unattended location regardless of the SOA (Eimer, 1995; Anllo-Vento & Hillyard, 1996; Kingstone, 1992).

The effectiveness of feature-based attention is expected to be observed at the attended and neutral locations. Feature-based attention may be more effective at the attended location in comparison to the neutral location as expected by the boosting approach (e.g., Hayden & Gallant, 2005, 2009; Ibos & Freedman, 2016), or it might be equally effective at attended and neutral locations as expected by the sensory gating approach (e.g., Hillyard & Munte, 1984). Regardless, space-based attention is expected to exert influence on behavior.

In general, the short SOAs will not be highly diagnostic of the different approaches. In a longer SOA where feature-based attention is initially effective, the behavior is expected to follow the predictions of the sensory gating approach (Figure 1b). In longer SOAs, the interaction pattern is expected to follow the boosting approach (Figure 1c) or remain unchanged from the sensory gating approach (Figure 1c).

The Current Experiments: The Interaction Between Feature- and Space-Based Attention

The aim of the current study is to examine the behavioral consequences of conjointly attending to a location and feature in various SOAs. Experiment 1 was designed to detect the emergence and the lifetime of the interaction between space- and feature-based attention. In Experiment 1, the SOA between the cue and the target onsets was manipulated in the fine steps of 300, 400, 500, 600, 700, and 1200 msecs in a task where the likely location and the feature of a target were cued. The short SOAs were selected to capture the initial emergence of feature-based attention at around at least 400 msecs (see Liu et al., 2007) and its spread in about 100 msecs (Stoppel et al., 2012). Because Experiment 1 aims to investigate the bounds of the interaction, the finely tuned mid-level SOAs were used to investigate the first signs of feature-based attention (which is expected to be around 500 msecs or slightly earlier) and its rise (about 700 msecs), and the longevity of the interaction. The longest SOA was 1200 msecs, because this was within the range of SOAs used in studies that have found the homogenous spread of feature-based attention all locations (e.g., Lambert & Hockey, 1986; Anderson et al., 2011). If feature-based attention *can* spread globally even to the unattended location as claimed by previous studies (e.g., Hayden & Gallant, 2005, 2009; Lambert & Hockey, 1986; Anderson et al., 2011; White et al., 2015), then 1200 msecs should be sufficient to detect it (e.g., Stoppel et al., 2012).

If an interaction pattern is found such that the effectiveness of feature-based attention is diminished in spatially unattended location, this could possibly be explained by two approaches: boosting (Figure 1c) and sensory gating (Figure 1b). To determine which approach better explain the performance, a spatially neutral location is necessary. The original version of the sensory gating approach predicts that the effectiveness of feature-based attention should not differ between attended and neutral locations due to space-based attention's gating property. However, in the light of recent research (e.g. Carrasco et al., 2000; Dosher & Lu, 2000a, 2000b; Ling & Carrasco, 2006; Liu et al., 2009), the gating of feature-based attention could possibly be accompanied by enhanced "filtering in" at the attended location in comparison to neutral location—this is captured by the boosting approach, which predicts that the effectiveness of feature-based attention should be larger at the attended location compared to a neutral location. Therefore, Experiment 2 was conducted to determine the best approach by using a coarse sample of the shortest, longest, and a mid-level SOA from the Experiment 1 where interaction was observed while introducing an additional spatially neutral location.

CHAPTER 5

EXPERIMENT 1

The aim of Experiment 1 is to investigate the time course of the initial engagement with feature-based attention and its interaction with space-based attention. For this purpose, the time difference between the conjoint space and feature cue onset and the target onset was manipulated in the fine steps of 300, 400, 500, 600, 700, and 1200 msecs.

Methods

Participants

Twenty-four Michigan State University students (gender: 11 female, 13 male; mean ± SD age: 23.58 ± 3.57; author included) who were older than 18, had no neurological disorder and had normal or corrected-to-normal vision participated in the experiment. The participants were compensated with 5 dollars per 30 minute of participation. The study was approved by the Institutional Review Board at Michigan State University.

Materials and Stimuli

A LCD monitor (1600 x 674 pixels, 60 Hz) was positioned 55 cm away from the participants. The experiment was programmed in MatLab (MathWorks, MA) using MGL functions (http://gru.stanford.edu/mgl/). An EyeTribe eye tracker (http://theeyetribe.com) was used in the main experiment to ensure that participants fixated at the center of the screen.

The display background was black. A gray fixation dot (diameter: .15º) was located at the center of the screen. The central cue's circular aperture (diameter: .15º) was located at the center of the screen. The tail of the cue, which indicated the cued direction, was extended .75º toward the cued hemifield on the horizontal axis. The cue and baseline dot field colors were red and green. The probe consisted of four dot clouds: each side of the screen (left and right) contained two superimposed red and green dot fields. Each dot field contained 84 randomly located dots (diameter: .15°) within a circular aperture (diameter: 10°). The center of the circular apertures were 10° away from the center of the screen.

The chromatic properties of the color stimuli were defined on the HSV space (H; hue, S: saturation, V: luminance). The luminance of all dots was set at 50%, half the maximum luminance value of the monitor. The baseline saturation was set at 50%.

Procedures - Thresholding Task

A thresholding block preceded the main experiment. The aim of the thresholding block was to determine the amount of saturation change in red and green dot fields that approximately yielded 75% correct discrimination performance.

A fixation dot remained on the screen throughout a trial. After an interval of 400, 500, 600, 700, 800, or 1300 msecs, the probe was presented for 300ms. A saturation increase or decrease for 100 msecs in one of the four dot fields occurred in the middle of the probe's 300 msecs duration. The task was to indicate the direction of the saturation change once the probe disappeared. Participants were instructed to press up and down arrow keys to report saturation increase and decrease, respectively. They were told that accuracy was the most important while asked not to delay their responses. They were also instructed to keep fixating at the center of the screen throughout a trial. The next trial started immediately after the keypress response.

The thresholding block consisted of 160 trials, where equal numbers of saturation changes occurred in one of the red and green dot fields. The location (left or right), color (green red), and the direction of the saturation change (increase or decrease) were randomized.

The intensity of the saturation changes in red and green dot fields were controlled by separate QUEST staircases (Watson & Pelli, 1983) to converge to 75% accuracy level. The

QUEST procedure assumed a Weibull psychometric function, with the prior guess rates and lapse rates set at .5 and .02, respectively. The prior alpha values ranged from 5% to 45% in a uniform distribution. The mean of the posterior alpha values was used to update the staircase. The saturation change intensities in red and green dot fields corresponding to 75% correct were used in the main experiment, which followed the thresholding block.

Procedures - Main Task

The task and the properties of the stimuli in the main experiment were identical to the task in the thresholding session with a few exceptions. A fixation dot remained on the screen throughout a trial. After 500ms from the trial onset, a cue appeared for 200 msecs. The cue was either red or green, and pointing toward either right or left side of the screen. After 0, 100, 200, 300, 400, or 900 msecs from the cue offset, the dot fields appeared for 300 msecs. A saturation change in one of the four dot fields occurred in the middle of probe's duration for 100 msecs. After the disappearance of the dot fields, participants pressed up and down arrow keys to indicate perceived saturation change increase or decrease, respectively (figure 2).

The spatial cue was valid in 80% of the trials, where the saturation change occurred at the side pointed by the cue, and it was invalid in 20% of the trials, where the saturation changed occurred at the opposite side to the cued location. Similarly, the feature cue was valid in 80% of the trials, where the saturation change occurred in the cued color, and it was invalid in 20% of the trials, where the saturation change occurred in the uncued color. Each block had 150 trials, and the experiment consisted of 24 blocks. The SOA between the cue onset and the saturation change onset (300, 400, 500, 600, 700, or 1200 msec) and the location, color, and direction of the saturation change were randomized within blocks.

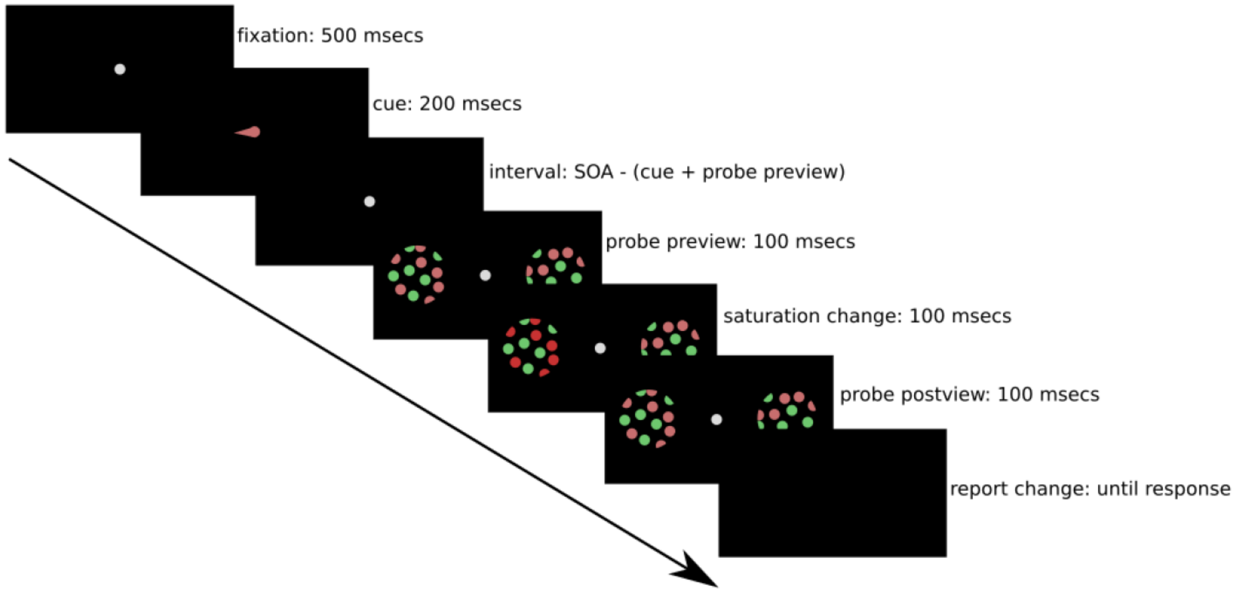

Figure 2. The trial sequence in Experiments 1 and 2. The SOA levels were 300, 400, 500, 600, 700, and 1200 msecs in Experiment 1 while they were 300, 750, and 1200 msecs in Experiment 2. In this trial sequence, both space and feature cues were valid as the saturation change appeared respectively at the cued location and in the cued color.

Data Analysis

The independent variables were the SOA (300, 400, 500, 600, 700, and 1200 msecs), the validity of the spatial cue (valid and invalid), and the validity of the feature cue (valid and invalid). The dependent variables were the mean reaction time (RT in msecs) from the onset of the saturation change and the accuracy rate in saturation change discrimination.

Trials in which the reaction time of a participant exceeded 2.5 standard deviations from the mean of the respective condition (the combination of SOA, spatial validity, and feature validity) were excluded from the analysis (M = 3.32 %, SD = .56 %). Furthermore, trials in which the gaze fell more than 2° from the fixation dot during the probe and cue displays were excluded from the analysis (M = .15 %, SD = .17 %). Reaction time of the correct trials were analyzed.

Results

Accuracy Rate

A 6 (SOA) × 2 (spatial validity) × 2 (feature validity) repeated-measures ANOVA was conducted on the accuracy rate (Figures 3 and 4). The main effect of the spatial validity was significant, $F(1, 23) = 28.85$, $p < .001$, $\eta^2 = .56$. The accuracy was higher when the space cue was valid (M = 85.54, SE = 1.24) compared to invalid ($M = 77.94$, $SE = 2.21$). The main effect of the feature validity was significant, $F(1, 23) = 11.04$, $p = .003$, $\eta^2 = .32$. The accuracy was higher when the feature cue was valid ($M = 83.40$, $SE = 1.38$) compared to invalid ($M = 80.08$, $SE = 2.00$).

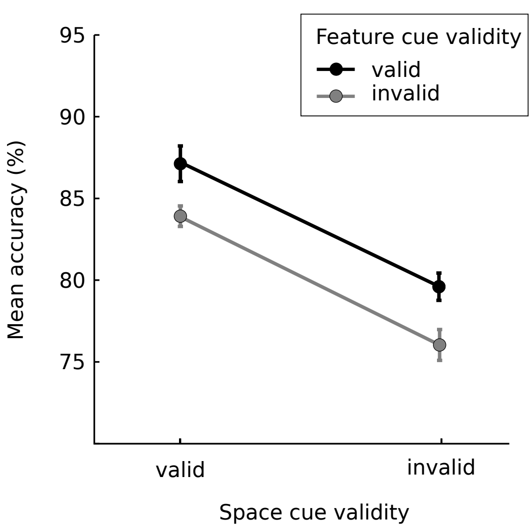

Figure 3. Accuracy rate as the function of the space and feature cues' validities in Experiment 1. The error bars in all figures are within-subject confidence intervals as suggested by Cousineau (2005).

The main effect of the SOA [$F(5, 115) = .77$, $p = .576$, $\eta^2 = .03$] and the rest of the interactions (spatial and feature validities [$F(1, 23) = .02$, $p = .901$, $\eta^2 < .01$]; SOA and spatial validity [$F(5, 115) = .99$, $p = .425$, $\eta^2 = .04$]; SOA and feature validity [$F(5, 115) = .67$, $p = .647$, $\eta^2 = .03$]; SOA, feature and spatial validities [$F(5, 115) =.27$, $p = .930$, $\eta^2 = .01$]) were not significant.

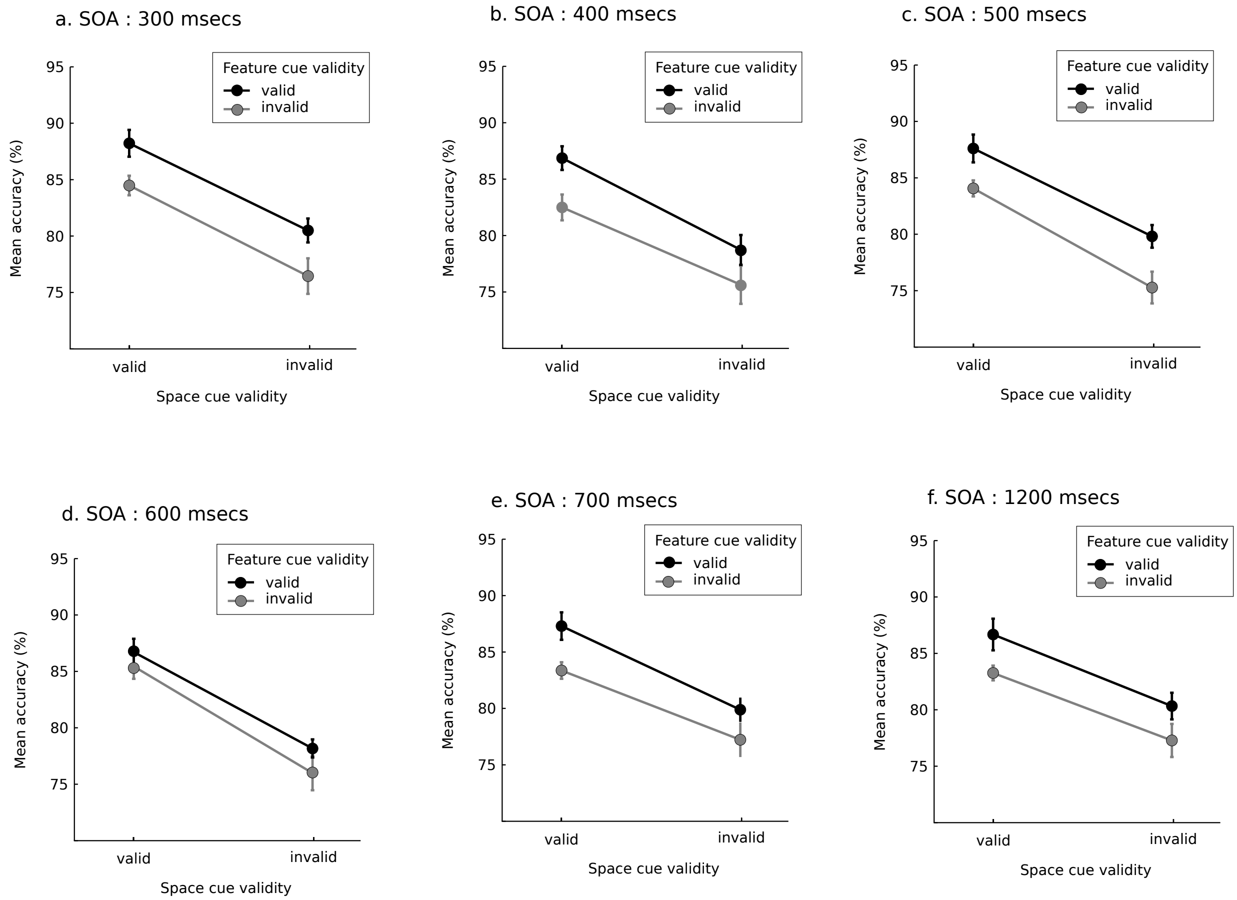

Figure 4. Accuracy rate as the function of the space and feature cues' validities across 300 (a), 400 (b), 500 (c), 600 (d), 700 (e), and 1200 (f) msecs SOAs in Experiment 1.

Reaction Time

A 6 (SOA) ×2 (spatial validity) x 2 (feature validity) repeated-measures ANOVA was conducted on the mean RT (Figures 5 and 6). The main effect of the spatial validity was significant, $F(1, 23) = 28.62$, $p < .001$, $\eta^2 = .55$. The mean RT was faster when the space cue was valid (M = 1097.71, SE = 30.88) compared to invalid (M = 1146.69, SE = 35.16). The main effect of the feature validity was significant, $F(1, 23) = 7.85$, $p = .010$, $\eta^2 = .25$. The mean RT was faster when the feature cue was valid (M = 1108.31, SE = 30.30) compared to invalid (M = 1136.09, SE = 36.76). The main effect of the SOA was significant, $F(5, 115) = 6.35$, $p = .001$, $\eta^2 = .22$. Post-hoc pairwise comparisons showed that the mean RT was slower in 300 msecs SOA (M = 1153.34, SE = 31.09) compared to the 400 (M = 1120.14, SE = 33.31), 500 (M = 1111.99, SE = 33.11), 600 (M = 114.76, SE = 35.52), 700 (M = 1113.14, SE = 33.95), and 1200 (M = 1119.86, SE = 32.40) msec SOAs.

The interaction between the spatial and feature validities was significant, $F(1,23) = 4.31$, $p = .049$, η^2=.16. The rest of the interaction effects were not significant (the SOA and spatial validity [$F(5, 115) = .14$, $p = .943$, $\eta^2 = .01$]; the SOA and feature validity [$F(5, 115) = .58$, $p = .645$, $\eta^2 = .03$]; the SOA, feature and spatial validities [$F(5, 115) = .15$, $p = .932$, $\eta^2 = .01$]).

The reaction times were collapsed across SOA to investigate the source of the interaction between spatial and feature validity. Two repeated-measures ANOVAs were conducted on the mean reaction time for valid and invalid space cues to determine whether the impact of feature validity depended on the spatial validity. The tests revealed that the mean RT was faster for validly cued feature (M = 1078.07, SE = 27.51) than invalidly cued feature (M = 1117.94, SE = 35.24) only when the space cue was valid [$F(1, 23) = 8.75$, $p = .007$, $\eta^2 = .28$]. When the space cue was invalid, the mean RT difference between valid (M = 1138.73, SE = 33.50) and invalid feature (M = 1154.11, SE = 37.34) cues were not statistically significant [$F(1, 23) = 2.67$, $p = .116$, $\eta^2 = .10$]. As an alternative, two repeated-measures ANOVAs were conducted on the mean RT separately in valid and invalid features to determine whether the impact of spatial cue's validity depend on feature cue's validity. The tests revealed that RT in valid space cue condition was faster than invalid space cue condition when the feature cue was valid [$F(1, 23) = 35.29$, $p < .001$, $\eta^2 = .61$] or invalid [$F(1, 23) = 11.75$, $p = .002$, $\eta^2 = .34$].

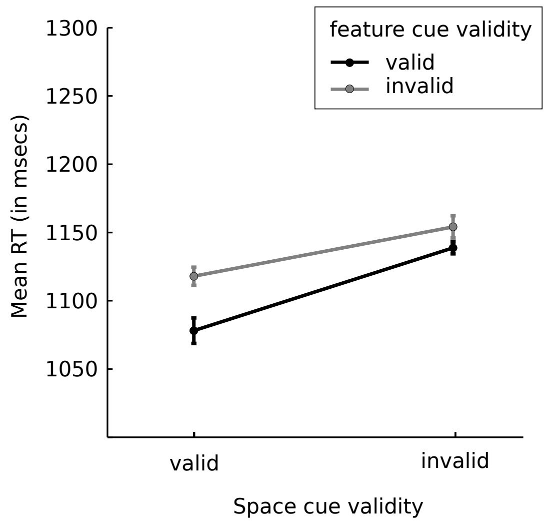

Figure 5. The mean reaction time as a function of space and feature cues' validities in Experiment 1.

Additionally, one-sample t-test was conducted on the mean accuracy of the valid feature at the unattended location to determine whether the accuracy in the condition with the worse performance was above the 50% chance level. The test revealed that the overall accuracy at the unattended location in invalid feature was above 50 % chance level, $t(23) = 10.69$, $p<.001$.

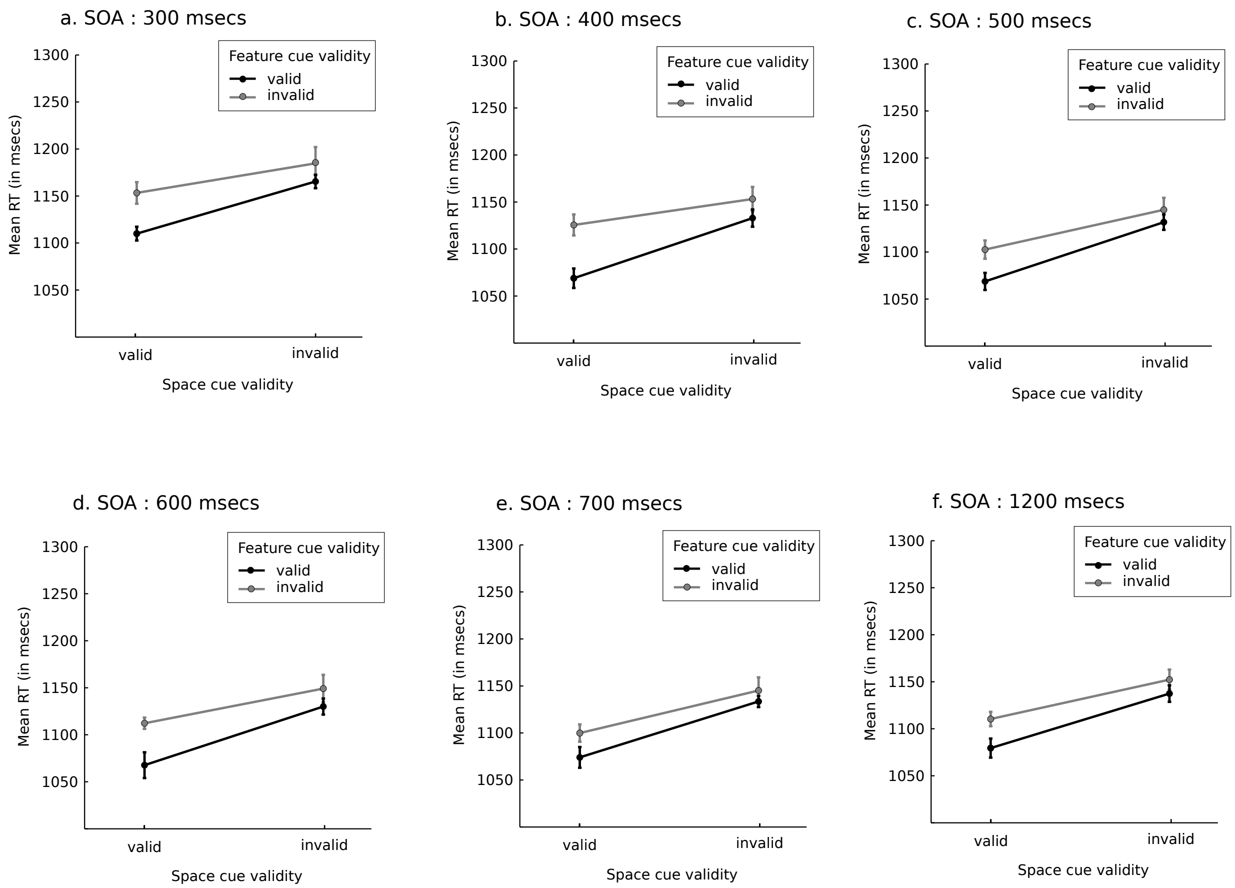

Figure 6. The mean reaction time as the function of the space and feature cues' validities across 300 (a), 400 (b), 500 (c), 600 (d), 700 (e), and 1200 (f) msecs SOAs in Experiment 1.

Discussion

Feature and space cues were indeed utilized to facilitate performance on the saturation discrimination task. Feature-based attention improved the sensitivity and speed for visual targets with the attended feature as opposed to an unattended feature. The same pattern was also evident for space-based attention, that space-based attention improved both sensitivity and speed for visual targets at the attended location as opposed to unattended location. Most importantly, feature-based attention's benefit was greater at the attended location as opposed to unattended location. While feature-based attention improved the discrimination speed at the attended location, feature-based attention did not influence the speed at the unattended location.

The absence of an interaction between feature validity and SOA indicates that feature cue was uniformly utilized across all SOAs. Moreover, the absence of the interaction between feature validity, space validity, and SOA shows that the interaction between space- and feature-based attention on reaction time is ubiquitous across SOA. The current study possibly has sampled from relatively longer SOAs for capturing the initial utilization of the feature cue. If the current experiment had sampled from even shorter SOAs, we could have captured the initial deployment of feature-based attention. Nevertheless, I was more speculative about the fate of feature-based attention in later SOAs than in the earliest SOAs. Therefore, I believe that sampling from even shorter SOAs would not change the findings, that feature-based attention would still not fully visit the unattended location.

The initial question of whether space- and feature-based attention interacts progressed into investigating the interaction pattern, such as how the effectiveness of feature-based attention was influenced at the attended location in comparison to under homogenously diffused space-based attention. Introducing this spatially neutral condition will inform us about the overall shape of the interaction, and help us determine whether the effectiveness of feature-based attention is improved at the attended location in comparison to unattended location. With the global profile of the effectiveness of feature-based attention across various levels of spatial attention, we can determine whether the sensory gating (Figure 1b) or boosting approach (Figure 1c) is more predictive of the behavioral data. For this purpose, Experiment 2 manipulated the SOAs coarsely but added a spatially diffused attention condition. The earliest, latest, and an in-between SOAs in which the interaction was observed were extracted from Experiment 1. Given that the SOA did not alter the interaction in Experiment 1, the interaction was ubiquitous across various SOAs. The shortest, longest, and the average of the former two SOAs in Experiment 1 was used in Experiment 2.

CHAPTER 6

EXPERIMENT 2

The aim of Experiment 2 was to determine the overall spatial profile of the interaction between the feature- and space-based attention at attended, neutral, and unattended locations. The spatial profile of the interaction pattern was measured in early, late, and mid-range SOAs to investigate whether the profile evolved over the lifetime of the interaction.

Methods

Participants

Twenty-four Michigan State University students (16 participated in Experiment 1, gender: 12 female, 12 male; mean ± SD age: 23.67 ± 3.91; author included) participated under the identical recruitment criteria in Experiment 1.

Materials and Stimuli

The properties of the visual stimuli and the apparatus were identical to Experiment 1. A neutral cue was introduced which was a bidirectional cue.

Procedures

A thresholding block preceded the main experiment, as explained in Experiment 1. The properties and durations of the visual stimuli were identical to Experiment 1 with a few exceptions. Unlike experiment 1, the interval between the trial onset and the probe onset ranged from 400, 850, and 1300 msecs. The saturation change was adjusted as explained in Experiment 1, except that the prior alpha range was uniformly distributed between 20% and 40% saturation changes. The thresholding block consisted of 160 trials, where equal numbers of saturation changes occurred in one of the red and green dot fields. The location, color, and the direction of the saturation change were randomized. Separate saturation thresholds were obtained for red and green color, which were used in the main experiment.

The task and stimuli in the main experiment were identical to those of Experiment 1. Unlike in Experiment 1, the central cue was bidirectional in 1/6 of trials and unidirectional in 5/6 of trials. The bidirectional cues were spatially neutral because they were not predictive of the location of the saturation change. Among the trials that the cue was unidirectional, space cue was valid in 80% and invalid in 20% of the trials. Three SOA levels were used: 300, 750, and 1200 msecs. Each block had 180 trials, and the experiment consisted of 12 blocks. The SOA and the location, color, and direction of the saturation change were randomized within blocks.

Data Analysis

The independent variables were the SOA (300, 750, and 1200 msecs), space cue's validity (valid, neutral, and invalid), and the feature cue's validity (valid and invalid). The dependent variables were the RT and accuracy rate as defined in Experiment 1.

Trials in which the reaction time of a participant exceeded 2.5 standard deviations from the mean of the respective condition (the combination of SOA, space cue's validity, and feature cue's validity) were excluded from the analysis (M = 3.10 %, SD = .75 %). Furthermore, trials in which the gaze deviated more than 2° from the fixation dot during the probe and cue displays were excluded from the analysis (M = .11 %, SD = .14 %). Reaction time on correct trials were analyzed.

Results

Accuracy Rate

A 3 (SOA) × 3 (spatial validity) × 2 (feature validity) repeated-measures ANOVA was conducted on the accuracy rate (Figures 7 and 8). The main effect of the spatial validity was significant, $F(2, 46) = 12.23$, $p = .001$, η^2=.35. Post-hoc pairwise comparisons revealed that the accuracy rate was higher when the space cue was valid (M = 83.47, SE = 1.30) compared to neutral

(M = 80.84, SE = 1.20), and the accuracy rate was lower for invalid space cue than the other two conditions (M = 77.06, SE = 1.99)(*both p's*<.05). The main effect of the feature validity was significant, $F(1, 23) = 15.01, p = .001, \eta^2 = .40$. The accuracy was higher when the feature cue was valid (M = 82.36, SE = 1.26) compared to invalid (M = 78.55, SE = 1.58). The main effect of the SOA [$F(2, 46) = .50$, $p = .612$, $\eta^2 = .02$] was not significant.

The interaction between the spatial and feature validities was significant, $F(2, 46) = 4.61$, $p = .015$, $\eta^2 = .17$. The rest of the interaction effects (SOA and spatial validity [$F(4, 92) = .75$, $p = .562$, $\eta^2 = .03$]; SOA and feature validity [$F(2, 46) = 1.78$, $p = .181$, $\eta^2 = .07$]; SOA, feature and spatial validities [$F(4, 92) = .94$, $p = .448$, $\eta^2 = .04$]) were not significant.

The accuracy rates were collapsed across SOA to investigate the source of the interaction between space- and feature-based attention. Three repeated-measures ANOVAs were conducted on the accuracy rate for valid, neutral, and invalid space cues to determine whether the impact of feature validity depended on the spatial validity. The tests revealed that the accuracy rate was higher for validly cued feature (M = 85.83, SE = 1.11) than invalidly cued feature (M = 81.09, SE = 1.69) when the space cue was also valid [$F(1, 23) = 15.30, p = .001, \eta^2 = .40$]. When the space cue was neutral, the accuracy rate was also higher for valid feature (M = 83.69, SE = 1.23) than invalid feature (M = 78.15, SE = 1.61), [$F(1, 23) = 11.31, p = .003, \eta^2 = .33$]. When the space cue was invalid, the accuracy rate statistically did not differ between valid (M=77.65, SE=2.05) and invalid feature cues (M =76.64, SE = 2.09), [$F(1, 23) = .94, p = .343, \eta^2 = .04$]. The accuracy difference between valid and invalid features were collapsed across SOAs, and it was compared among attended and neutral space cue conditions to investigate whether the effectiveness of the feature-based attention was boosted at the attended location in comparison to the neutral location. A paired-samples t-test showed that the validity effect of the feature cue did not significantly differ between attended (*M* = 4.74, *SE* = 1.21) and neutral (*M* = 5.54, *SE* = 1.65) locations, $t(23) = .56$, $p = .581$.

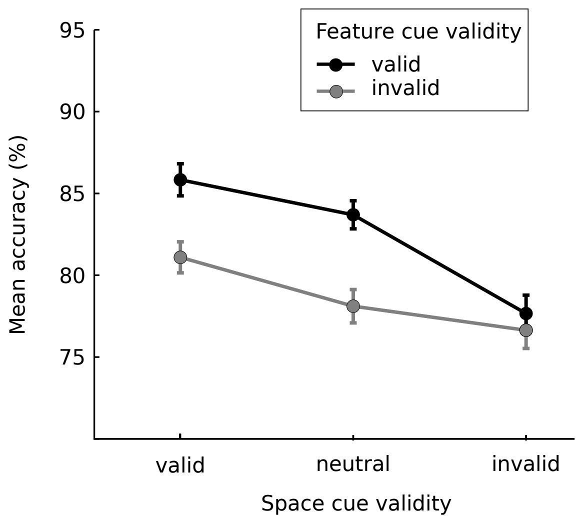

Figure 7. Accuracy rate as the function of the space and feature cues' validities in Experiment 2.

As an alternative interpretation, a repeated-measures ANOVA was conducted on the accuracy rate separately for valid and invalid feature cue conditions to determine whether the impact of spatial validity depend on feature validity. When the feature cue was valid, the accuracy rate was higher in the valid space cue (*M* = 85.83, *SE* = 1.11) than neutral space cue (*M* = 83.69, *SE* = 1.25) condition, and it was lower than the former two conditions in the invalid space cue condition (*M* = 77.65, *SE* = 2.05) (all pairwise p's< .005), [$F(2, 46) = 16.23$, $p < .001$, $\eta^2 = .42$]. When the feature cue was invalid, the accuracy rate was higher in the valid space cue condition (*M* = 81.10, *SE* = 1.69) compared to neutral (*M* = 78.15, *SE* = 1.61) and invalid (*M* = 76.64, S*E* = 2.09) space cue conditions (pairwise p's<.05), and it did not differ between neutral and invalid spatial cues [$F(2, 46) = 4.22$, $p = .021$, $\eta^2 = .16$].

Additionally, one-sample t-test was conducted on the mean accuracy of the valid and invalid feature cues at the unattended location to determine whether the accuracy was above the 50% chance level. The test revealed that the overall accuracy at the unattended location was above chance level, $t(23) = 13.58$, $p<.001$.

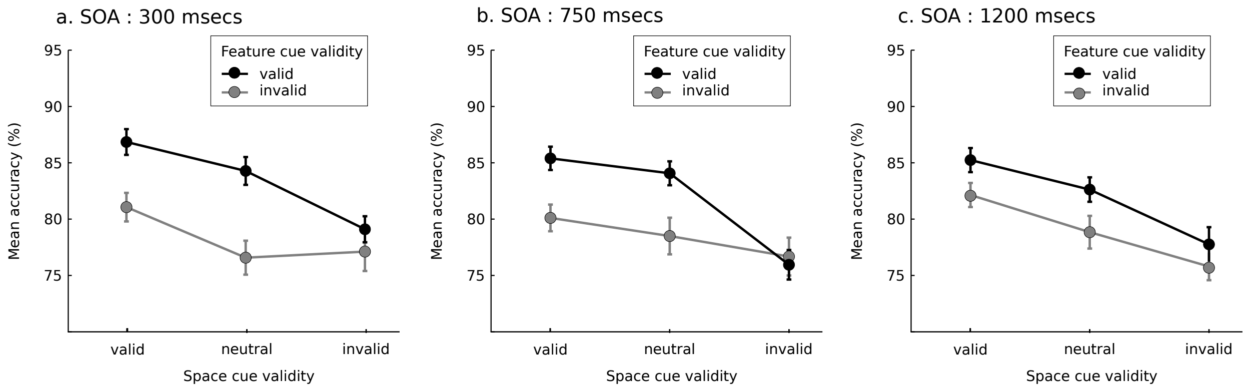

Figure 8. Accuracy rate as the function of the space and feature cues' validities across 300 (a), 750 (b), and 1200 (c) msecs SOAs in Experiment 2.

Reaction Time

A 3 (SOA) × 3 (spatial validity) × 2 (spatial validity) repeated-measures ANOVA was conducted on the mean RT (Figures 9 and 10). The main effect of the spatial validity was significant, $F(2, 46) = 21.47$, $p < .001$, $\eta^2 = .48$. Post-hoc pairwise comparisons showed that the mean RT was faster when the space cue was valid ($M = 1125.34$, $SE = 45.76$) compared to neutral ($M = 1139.72$, $SE = 44.40$), and it was also higher when the spatial cue was neutral compared to invalid ($M = 1178.88$, $SE = 52.13$). The main effect of the feature validity was significant, $F(1, 23) = 9.11$, $p = .006$, $\eta^2 = .28$. The RT was faster when the feature cue was valid ($M = 1130.43$, $SE = 44.06$) compared to invalid ($M = 1165.52$, $SE = 50.99$). The main effect of SOA was significant, $F(2, 46) = 18.91$, $p < .001$, $\eta^2 = .45$. Post-hoc pairwise comparisons showed that the RT was slower in 300 msecs SOA ($M = 1174.21$, $SE = 46.87$) compared to the 750 (M=1136.21, SE=47.32) and

1200 (*M* = 1133.54, *SE* = 48.26) msec SOAs.

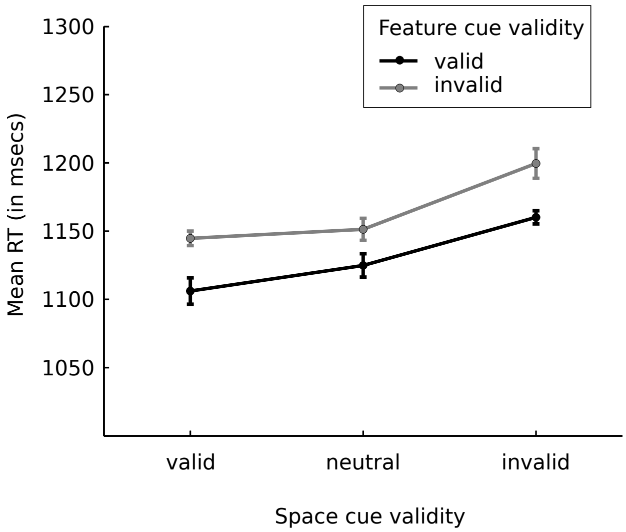

Figure 9. Reaction time as the function of the space and feature cues' validities in Experiment 2.

The rest of the interaction effects were not significant (spatial and feature validities [$F(2, 46) = .52$, $p = .597$, $\eta^2 = .02$]; SOA and spatial validity [$F(4, 92) = 1.53$, $p = .221$, $\eta^2 = .06$]; SOA and feature validity [$F(2, 46) = .31$, $p = .734$, $\eta^2 = .01$]; SOA, feature and spatial validities [$F(4, 92) = .50$, $p = .649$, $\eta^2 = .02$]).

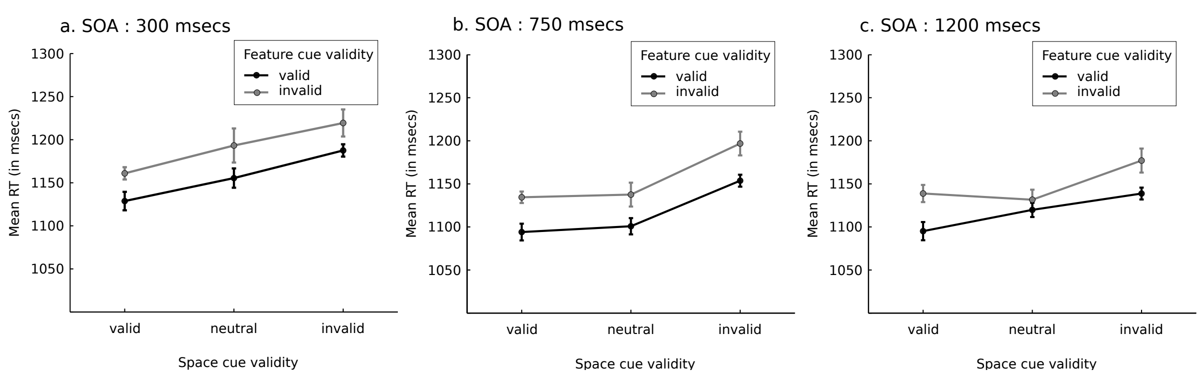

Figure 10: Reaction time as the function of the space and feature cues' validities 300 (a), 760 (b), and 1200 (c) msecs SOAs in Experiment 2.

Discussion

Feature and space cues were indeed utilized in speed and accuracy of behavioral response in Experiment 2. Due to space-based attention, the accuracy and speed of discrimination were improved at the attended location in comparison to a neutral location while the accuracy and discrimination speed suffered at the unattended location in comparison to a neutral location. Feature-based attention also improved the speed and accuracy of the discrimination of the target with the attended feature in comparison to an unattended feature.

Most importantly, space- and feature-based based attention's influences interacted on behavior. While feature-based attention could benefit the accuracy at the attended and spatially neutral locations, it did not influence accuracy in the unattended location. Furthermore, space-based attention did not particularly improve the effectiveness of feature-based attention at the attended location as compared to a spatially neutral location. Space-based attention simply filtered out the impact of feature-based attention at the unattended location. This pattern was also ubiquitous across all SOAs. Henceforth, the current conclusion resembled mostly to the sensory gating approach (Figure 1c). However, the unattended location was not completely eliminated from visual perception, as the participants could still complete the task at the unattended location with accuracy rates above the chance level.

CHAPTER 7

GENERAL DISCUSSION

The aim of the current study was to understand the impact of conjointly attending to a feature and location on behavioral performance. By manipulating the SOA between the cue and target onsets, the current study investigated the temporal dynamics of the interaction between space- and feature-based attention. The SOA was manipulated in fine steps to capture the emergence of the interaction and its time course in Experiment 1. In Experiment 2, the SOA was coarsely sampled at the earliest and latest time points of the interaction while the strength of feature-based attention was measured under varying degrees of strength of space-based attention to determine which of the existing approaches, namely the independence, sensory gating, or boosting determine the behavioral performance.

The impact of space-based attention was evident in both experiments of the current study. In Experiment 1, discrimination speed and accuracy for a target at the attended location was improved in comparison to the unattended location. Adding the diffused spatial attention condition in Experiment 2, we have replicated Experiment 1 and the previous findings of a benefit of space-based attention at the attended location relative to a neutral location and the cost of space-based attention at the unattended location relative to a neutral location (Mangun & Hillyard, 1990; Muller & Rabbitt, 1989; Pestilli et al., 2007; Pestilli & Carrasco, 2005; Posner, 1980; Posner et al., 1980). This finding is predicted by all the three approaches, which is modeled by A_S assuming different values for attended, neutral, and unattended location (Figure 1).

From the perspective of the filtering theories (e.g., Broadbent, 1958; see Lachter et al., 2004), I have checked whether the visual information at the unattended location was completely lost from the perception. The accuracy at the unattended location in unattended feature (which had the worst overall accuracy) in Experiment 1 and the mean accuracy at the unattended location in Experiment 2 were better than the chance. Therefore, the unattended location was not completely forsaken from visual processing (as in Broadbent, 1958, Duncan & Desimone, 1995).

As in line with the previous studies, space-based attention indeed was evident as early as 300 msecs after the cue onset (Dosher & Lu, 2000a, 2000b; Muller & Rabbitt, 1989) and it had a long-lasting impact (Muller & Rabbitt, 1989; Rafal, Calabresi, Brennan, & Sciolto, 1989). Unlike White et al. (2015)'s study where the absence of the interaction between space-based and feature-based attention could potentially be explained by a weak space-based attention effect, the current study does not suffer from the same weakness to interpret any potential absence of the interaction. In terms of the modeling, the term A_S had a large range of values.

The impact of feature-based attention was also evident in both experiments. Both in Experiment 1 and 2, discrimination speed (see Moore & Egeth, 1998; Shih & Sperling, 1996) and accuracy (see Baldassi & Verghese, 2005; Davis & Graham, 1981; Ball & Sekuler, 1981; Liu et al., 2007) for a target with the attended feature was improved in comparison to a target with the opposite feature. Henceforth, the current study has detected a decent feature-based attention effect. Unlike Lambert and Hockey's (1986) study where a weak feature-based attention effect could potentially explain the absence of the interaction between space-based and feature-based attention, the current study does not suffer from the same weakness to interpret any potential absence of the interaction. In terms of the modeling, A_F was not null.

Additionally, none of the statistical analysis showed a hint of the interaction between SOA and attentional conditions. Therefore, the impact of feature-based attention was ubiquitous across all SOAs, ranging from 300 to 1200 msecs from the cue onset. This shows that feature-based attention is utilized earlier than previously thought (e.g., Liu et al, 2007), at least as early as 300 msecs SOA. Most importantly, the current study has found that the effectiveness of feature-based attention depended on space-based attention. Therefore, the effectiveness of feature-based attention under diffused spatial attention, within and outside the attended location shall be inspected separately under the lenses of the three existing approaches.

Feature-Based Attention Under Diffused Spatial Attention

The independence, sensory gating, and boosting approaches all agree that feature-based attention can spread globally under diffused spatial attention where A_F was effective at the spatially neutral location. Though most of the evidence comes from the studies that provide support to the independence approach (Liu & Mance, 2011; Liu & Hou, 2011; Saenz et al., 2002; Serences & Boynton, 2007; White et al., 2015; Zhang & Luck, 2009) even the sensory gating approach accepts that the late ERP components elicited by feature-based attention can be observed across multiple locations (Hillyard & Munte, 1984). Therefore, the diffusion of space-based attention is not diagnostic of the explanatory approaches. However, it provides a reality check and comparison standard for the effectiveness of feature-based attention within and outside the attended location.

The current study has found that feature-based attention improved the discrimination speed (see Moore & Egeth, 1998; Shih & Sperling, 1996) and accuracy (see Baldassi & Verghese, 2005; Davis & Graham, 1981; Ball & Sekuler, 1981; Liu et al., 2007) at the neutral location. By varying the SOA from 300 msecs to 1200 msecs, we have found that 300 msecs is sufficient to engage with a feature, and it has long-lasting effects, and it does not suffer from the inhibition-of-return (for reviews, Klein, 2000; Lupiáñez, Klein, & Bartolomeo, 2006) similar to endogenous space-based attention.

Our study concludes that feature-based attention can spread early and remain for a long time under diffused spatial attention. The main diagnostic conditions, however, is the effectiveness of feature-based attention outside and within the attended location.

Feature-Based Attention at the Unattended Location

The three approaches make different predictions regarding the fate of feature-based attention outside the attended location. According to the independence approach, the effectiveness of feature-based attention remains constant under varying strength of space-based attention. In Experiment 2, a bidirectional (neutral) spatial cue was used to diffuse space-based attention across two possible target locations. Therefore, feature-based attention outside the focus of spatial attention should be as effective as under diffused space-based attention. In contrast, the sensory gating approach claims that space-based attention works akin to a filter, and feature-based attention cannot influence performance outside the attended location. In between those two extremes, the boosting approach predicts that the effectiveness of feature-based attention becomes smaller than under diffused space-based attention, but it does not disappear.

In Experiment 1, feature-based attention influenced the accuracy rate constantly across attended and unattended locations, but it affected the reaction time only within the attended location. The opposite pattern emerged in Experiment 2, feature-based attention influenced the reaction time constantly across attended, unattended, and neutral locations, yet feature-based attention could not affect the accuracy rate at the unattended location. The accuracy in Experiment 1 and reaction time in Experiment 2 supports the independence approach, yet the reaction time in Experiment 1 and accuracy in Experiment 2 supports the sensory gating approach. In term of the models, the accuracy rate in Experiment 1 and the reaction time in Experiment 2 resembles the right-side of the independence approach's prediction (Figure 1a), while the reaction time in

Experiment 1 and the accuracy rate in Experiment 2 resembles the right-side of the independence approach's prediction (Figure 1b), such that a strict *G* filtered out the impact of A_F at the unattended location on the reaction time (Experiment 1) or accuracy (Experiment 2).

Then, what aspect of behavior should be conceptualized as 'the performance'? Both accuracy and reaction time are important measures of performance, and they reflect the different aspects of performance. For example, the reaction time mainly indicates the speed of information processing, whereas accuracy is the reflection of the signal representation (Prinzmetal, McCool, & Parks, 2005). In some cases, the improvement of one aspect of behavior is achieved by sacrificing another aspect of behavior (see Heitz, 2014). However, this did not seem to be the case regarding the effectiveness of feature-based attention at the unattended location on accuracy and reaction time. In Experiment 1, the diminished effectiveness of feature-based attention on reaction time is not accompanied by the improved effectiveness of feature-based attention on accuracy. The same logic can be applied to Experiment 2, where the diminished effectiveness of feature-based attention on accuracy did not improve its effectiveness on the reaction time. Thus, there was no apparent speed-accuracy trade-off in the performance data. Overall, the results suggest that feature-based attention could not fully operate at the unattended location.

The task and the instructions in the experiments were identical so were the properties of the visual stimuli. The current study cannot provide an answer to why reaction time in Experiment 1 and accuracy in Experiment 2 could not be influenced by feature-based attention outside the focus of spatial attention. However, ours is not the only one among the experiments that conjointly manipulated space- and feature-based attention that has found divergence within the same experiment. For example, Anderson et al.'s (2011) results in early SSVEP provides the basis of the supporting evidence for the independence approach, yet the later ERP data and the signal detection scores instead support the sensory gating approach. Because the primary performance measure in Anderson et al. (2011) was the early SSVEP pattern, the structure of their research puts less emphasis on the evidence for the sensory gating approach. In the current study, both reaction time and accuracy were equally important to assess behavioral performance. Therefore, the combination of the behavioral data indicates that the effectiveness of feature-based attention was compromised at the unattended location. White et al. (2015) have also measured behavioral performance, though they have found converging patterns in reaction time and accuracy. However, White et al. (2015) found supporting evidence both for the boosting and independence approaches from subtle manipulations of visual competition or possibly due to confounds such as the difference between their two experiments in possibly working memory demand and spatial attention strength. Though the current study was conducted diligently without intentions of manipulating competition or task demand, we currently do not have an explanation about why the interaction emerged in different aspects of behavior in the current study.

The decrease in the overall effectiveness of feature-based attention at the unattended location resonates well with the boosting approach (Figure 1c), yet it may also be compatible with the sensory gating approach. Performance is multi-dimensional, and each dimension of performance may be subjective to filtering. In Experiment 1, the filter *G* operated on the reaction time, made feature-based attention inaccessible at the unattended location. However, the filter *G* rendered the accuracy rates inaccessible to feature-based attention at the unattended location. Given that performance is a combination of accuracy and reaction time, the overall performance dropped in either case. The attenuation of the overall impact of feature-based attention on performance at the unattended location is, therefore, the result of the elimination of the impact of feature-based attention on an aspect of behavior at the unattended location.

The current study acknowledged that feature-based attention could not spread globally in early SOAs, yet entertained the possibility that it could spread to the unattended location eventually (e.g., Stoppel et al., 2012). Feature-based attention was attenuated at the unattended location throughout short (300 msec) and longer (1200 msec) SOAs in both experiments. The ineffective spread of feature-based attention outside the focus of spatial attention does not appear to be due to a lack of time. Otherwise, it would have fully spread in a few hundred milliseconds after the initial engagement with the feature-based attention (e.g., Stoppel et al., 2012).

Feature-Based Attention at the Attended Location

All the approaches agree that feature-based attention can operate at the attended location. However, how effectively it operates at the attended location compared to under diffused space-based attention has been debated. Though due to different underlying mechanisms, both the sensory gating and independence approaches agree that the effectiveness of feature-based attention should be equivalent across attended and neutral locations. According to the independence approach, space-based attention is irrelevant to the spread of feature-based attention. In contrast to the independence approach, space-based attention is thought to filter out feature-based attention at the unattended location according to the sensory gating approach. In contrast, the boosting approach predicts that the effectiveness of feature-based attention should be more pronounced at the attended location compared to the neutral location. Experiment 2, henceforth, was designed to investigate whether the effectiveness of feature-based attention was improved due to space-based attention compared to diffused spatial attention. It was found the impact of feature-based attention on both accuracy and reaction time is equivalent within the attended location and under diffused spatial attention. There is no hint of improvement of feature-based attention's effectiveness at the attended location in comparison to under diffused spatial attention. Though space-based attention alters the visual sensitivity at the attended location (e.g., Carrasco et al., 2000; Dosher & Lu, 2000a, 2000b; Ling & Carrasco, 2006; Liu et al., 2009), it does not improve the effectiveness of feature-based attention.

In terms of the three approaches, the constant influence of feature-based attention across attended and neutral locations partially resembles the predictions of the independence (Figure 1a) and sensory gating (Figure 1b) approaches. Finally, we can determine what approach can explain the overall behavioral performance.

The Overall Spatial Profile of Feature-Based Attention

The current study has shown that space-based attention's impact on behavior is ubiquitous across attended and unattended features. However, the effectiveness of feature-based attention depends on where the target with the attended feature appears in relation to the attended location. Experiment 1 and 2 showed that feature-based attention can be fully utilized to improve target discrimination accuracy and speed within the focus of spatial attention. On the other hand, feature-based attention cannot benefit the discrimination speed (Experiment 1) or accuracy (Experiment 2) outside the focus of spatial attention. Overall, feature-based attention loses its effectiveness outside the focus of spatial attention. Additionally, Experiment 2 showed that space-based attention does not alter the relative effectiveness of feature-based attention in the attended and neutral locations. Additionally, the inability of feature-based attention's spread is not a matter of time. Using short (300 msec) and long SOAs (1200 msec) in both Experiments did not change the fate of feature-based attention.

Our findings resemble mostly the predictions of the sensory gating approach. In line with one premise of the sensory gating approach, space-based attention influenced feature-based attention. We could not support the other premise of the sensory gating approach, which claims that space-based attention operates earlier than feature-based attention. Though we used a wide range of SOAs, our choices of SOAs might have been longer than the initial deployment of feature-based attention. However, the possibility remains that feature-based attention could possibly operate later than space-based attention, but likely under even shorter SOAs than the current study. Most importantly, space-based attention operated akin to a filter.

The current study proposes an update to the properties of the filter in the original sensory gating approach. The original sensory gating approach emphasized only one aspect of performance as the main measure (e.g., Anllo-Vento & Hillyard, 1996; Eimer, 1995; Hillyard & Münte, 1984; Kingstone, 1992), yet the current study gave importance to both accuracy and reaction time. In agreement with the sensory gating approach, feature-based attention influenced behavioral performance at the attended (Experiments 1 and 2) and neutral (Experiment 2) locations. Because reaction time (in Experiment 1) or accuracy (Experiment 2) were not influenced by feature-based attention outside the focus of spatial attention, it is clear that space-based attention imposes some restrictions on feature-based attention. In terms of the overall performance, the filter at the unattended location was not totally impermeable. The effectiveness of feature-based attention diminished outside the attended location, but it did not disappear. The filter also did not filter out all visual information at the unattended location, as the participants could still perform the task at the unattended location. Hence, the overall performance is similar to an output of a 'permeable' (e.g., Treisman, 1985) filter rather than an absolute, rigid filter (e.g. Broadbent, 1958)

In conclusion, the sensory gating approach is the most plausible approach to explain the conjoint influence of feature- and space-based attention on behavioral performance. Space-based attention worked akin to a filter at the unattended location (Figure 1b), that decreased the effectiveness of feature-based attention by eliminating its influence on the speed (Experiment 1) or accuracy (Experiment 2) of response. Once passed beyond the filter within the attended and unattended location, space-based attention did not impose further control over feature-based attention.

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