Neuronal Tuning and Its Role in Attention

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Abstract

The activity of sensory neurons can be modulated by both external stimuli and an animal's internal state. Characterizing the role of these bottom-up and top-down factors as well as the way in which they interact is critical for an understanding of how the activity of sensory neurons contributes to perception. To this end, we recorded from the middle temporal area (MT) in awake-behaving primates in order to measure the joint tuning properties of these neurons for two commonly studied feature dimensions, direction of motion and binocular disparity. Additionally, we set out to determine whether attention directed to these two features can modulate the responses of MT neurons. We showed that MT neurons have fixed tuning preferences for direction of motion and binocular disparity and thus represent these features in a separable manner. Further, we have demonstrated that MT neurons can be modulated by feature attention for both direction of motion and binocular disparity and that the amount of this modulation depends on a neuron's tuning strength. These results further our understanding of how stimulus features are jointly represented in the brain and how the attentional system interacts with these representations in order to facilitate perception.

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INTRODUCTION

Attention and the brain

At any given moment, our sensory epithelia are inundated by stimuli. In order to deal with this bewildering amount of information, we have the ability to direct our focus to whatever aspect of our sensory environment, or internal thoughts, that we determine is of behavioral relevance. This process is referred to as selective attention and has been of great interest to neuroscientists since the time of William James. Relying on introspection, James famously wrote in the *Principles of Psychology* (1890):

> *"Everyone knows what attention is. It is the taking possession by the mind, in clear and vivid form, of one out of what seem several simultaneously possible objects or trains of thought… It implies withdrawal from some things in order to deal effectively with others."*

With this quote, James identified the components that make the study of attention so compelling and ushered in the start of psychological and, eventually, neuroscientific investigations into the study of attention. There is a rich history of more than a century's worth of psychological and psychophysical studies into the cognitive properties of attention but an in-depth treatment of these topics is beyond the scope of what can be covered here. Instead, this section will focus on the neurophysiological study of attention, which, in many ways, began with studies performed by Hernández-Peón and colleagues during the 1950s. These authors performed several seminal experiments investigating how attention to one sensory

modality affected the neural responses to a different modality. In the first of these experiments, they measured evoked responses in the dorsal cochlear nucleus of the awake cat using subdural electrodes. The authors presented auditory stimuli that were sometimes paired with a visual stimulus, a mouse, to attract the cat's attention (Hernández-Peón, Scherrer, & Jouvet, 1956). The authors found a decreased evoked response to auditory stimuli when the cat 'attended' visually to the mouse and concluded that:

> "If this sensory inhibition during attentive behaviour, as demonstrated in the auditory pathway, occurs in all other sensory paths, except the ones concerned with the object of attention, such an inhibitory mechanism might lead to the favouring of the attended object by the selective exclusion of incoming signals."

A similar, albeit better controlled, experiment was later performed by Gabriel Horn (Horn, 1960). Horn also attracted a cat's attention using a live mouse and while the cat exhibited "positive orientational behaviour" toward the mouse, he flashed unattended spots of light elsewhere in the visual field. Similarly to Hernandez-Peon, he observed a decreased response to the flashes of light when the animals attended to the mouse compared to when they were unengaged. Both of these studies provided early physiological evidence of selective attention decreasing the response of neurons to unattended stimuli. The first example of selective attention leading to an increase in the response of sensory neurons came in 1959 when David Hubel and colleagues demonstrated an enhancement in the response of single neurons in auditory cortex when cats seemed to direct their attention to certain auditory stimuli (Hubel et al., 1959).

Later, Michael Goldberg and Robert Wurtz published the first observations of attentional effects in the macaque (*Macaca mulatta*). These authors trained monkeys to either ignore or saccade towards a spot of light while performing extracellular recordings in the superior colliculus. They found that a large proportion of neurons in the superior colliculus demonstrated increased firing when the spot of light in the receptive field was a saccade target versus when it was ignored. These results suggested that behavioral context can strongly modulate the responses of these neurons and that the observed firing rate enhancement may be the mechanism that underlies selective attention (Goldberg & Wurtz, 1972).

Goldberg and Wurtz's investigations into spatial attention have been extremely influential both in terms of the experimental paradigm that they developed and the animal model that they employed. Because the macaque brain is relatively similar to that of a human and because monkeys are readily trained, they have become an invaluable model for investigations into the effects of attention on the responses of neurons. The focus of this attentional research has primarily been to characterize the way in which attention selectively alters the processing of sensory information in order to confer the perceptual advantages that paying attention is known to provide (Treue, 2001). Even though many early investigations into attention focused on the auditory system, the visual system has become the most common model for studying attentional effects in cortex. This is largely because of the ease of both presenting well-controlled visual stimuli and training non-human primates, which are inherently visual animals, on visual tasks. Despite this focus on the visual system, the larger aim of all of these investigations has been to use attention as a tool for understanding how

the internal state of an animal affects neural processing, and more generally, how cortical activity subserves the bevy of complicated, goal directed behaviors that are the hallmark of animals with a complex nervous system.

In the hands of different researchers, visual attention has been shown to lead to multiplicative gain changes in the responses of sensory neurons (Lee & Maunsell, 2010; McAdams & Maunsell, 2000; Spitzer, Desimone, & Moran, 1988; Treue & Martinez-Trujillo, 1999; Treue & Maunsell, 1999), or increases in effective contrast gain (Li & Basso, 2008; Martinez-Trujillo & Treue, 2002; Reynolds, Pasternak, & Desimone, 2000). Additionally, attention has been shown to sharpen the response of a population of neurons (Martinez-Trujillo & Treue, 2004). Attentional effect sizes have been shown to increase, on average, in areas that are further along in the visual cortical hierarchy (Maunsell & Cook, 2002). Recent work has shown that attention can affect the correlation structure of populations of neurons (Cohen & Kohn, 2011; Cohen & Maunsell, 2009, 2011; Mitchell, Sundberg, & Reynolds, 2009). Most studies of visual attention in primates have focused on the allocation of attention to a particular location in space or a particular feature contained in a stimulus, but attention has also been shown to alter neuronal firing in response to complex object properties (Mitchell, Stoner, & Reynolds, 2004; Qiu, Sugihara, & von der Heydt, 2007; Wannig, Rodríguez, & Freiwald, 2007) (for a different interpretation of these effects, see (Treue & Katzner, 2007)).

There is some evidence that suggests the frontal eye fields (Moore & Armstrong, 2003; Moore & Fallah, 2001; Rossi et al., 2007; Zhou & Desimone, 2011), parietal cortex (Cutrell & Marrocco, 2002) and the superior colliculus

(Cavanaugh & Wurtz, 2004; Müller, Philiastides, & Newsome, 2005) may contribute to the creation of attentional effects. Additionally, it has been shown that small amounts of acetylcholine can enhance spatial attention effects in V1 while a muscarinic antagonist (scopolamine), but not a nicotinic antagonist (mecamylamine), can reduce attentional modulation (Herrero et al., 2008). A promising hypothesis has suggested that normalization mechanisms, which play a role in adjusting sensory responses to the presence of multiple stimuli, may also play a role in attentional effects (Reynolds & Heeger, 2009). In support of this hypothesis, a very strong relationship, within single neurons, was observed between normalization and spatial attention effects in area MT (Lee & Maunsell, 2009).

Feature attention

Of particular importance in this thesis is feature-based attention, where attention to a specific feature creates a spatially independent enhancement or decrement in neuronal responses. It is postulated that feature attention could aid in visual search or otherwise enhance behavioral performance by selectively modifying the neuronal representation of complex visual scenes. For example, by selectively enhancing the activity of neurons that are tuned to the color red, feature attention could facilitate the detection of a red car in a crowded parking lot. Evidence from both psychophysical (Busse, Katzner, & Treue, 2006; Cohen & Magen, 1999; Katzner, Busse, & Treue, 2006; Maljkovic & Nakayama, 1994, 1996; Rossi & Paradiso, 1995; Sàenz, Buraĉas, & Boynton, 2003) and neuronal (Bichot, Rossi, & Desimone, 2005; Chelazzi et al., 1993; Haenny, Maunsell, & Schiller, 1988; Martinez-Trujillo & Treue,

2004; Maunsell et al., 1991; McAdams & Maunsell, 2000; Motter, 1994; Treue & Martinez-Trujillo, 1999; Zhou & Desimone, 2011) investigations support this hypothesis.

Because feature attention modifies the firing rate of sensory neurons independently of spatial representations, these findings beg the question of whether feature and spatial attention are distinct. Both spatial and feature attention effects have been shown to be present in the same neurons (Hayden & Gallant, 2005; McAdams & Maunsell, 2000; Treue & Martinez-Trujillo, 1999) and combine additively (Treue & Martinez-Trujillo, 1999) (but see (Hayden & Gallant, 2009)). Several studies have attempted to highlight differences between spatial and feature attention. For example, Hayden and Gallant have argued that the time course of spatial and feature attention differ and that this suggests that the two effects depend on different mechanisms and may play different roles in active vision (Hayden & Gallant, 2005). Others have suggested that space may simply be one aspect of a stimulus's feature set and that the similarities between spatial and feature attention argue in favor of a unified attentional system (Duncan, 1980; Maunsell & Treue, 2006). This latter proposal still allows for the idea that space may be a somewhat special feature. Spatial representations are extremely important for orienting and navigating and this fact could have led to increased selective pressure on the evolution of mechanisms devoted to emphasizing these representations. Further, many parts of the visual system are organized spatiotopically and this organization has been proposed to be a factor that could greatly simplify the wiring of attentional modulation (Maunsell & Treue, 2006). In fact, there is some psychophysical evidence that spatial attention may be uniquely

important during attentional conditions that require the linking of multiple stimulus attributes (Nissen, 1985). While this is an interesting issue, it is beyond the scope of the research described in this thesis.

The seminal investigations into feature attention in the primate brain have been performed in 'mid-level' visual processing areas like the middle temporal area (MT) and V4. These regions have typically been selected because of the combination of their robust visual responses, relatively well understood tuning properties and readily observable attentional effects. In one study, McAdams and Maunsell recorded from V4 while monkeys performed a delayed match to sample task (McAdams & Maunsell, 2000). The animals either attended into or out of the spatial receptive field of the neuron under study. When the animals attended outside of the receptive field, there were two possible stimuli that could be presented: an oriented Gabor that was similar to the stimulus in the receptive field, or a colored Gaussian patch. The authors found that, on average, when an animal attended to a Gabor whose orientation matched the Gabor that was in the receptive field of the neuron, the neuron's exhibited an increased firing rate as compared to when the animal attended to a colored Gaussian outside the receptive field. It was argued that this enhancement was the result of the features contained in the attended stimulus and that this effect was spatially independent.

Another way of studying feature attention effects has been to use visual search tasks. Bichot and colleagues trained monkeys to search for a stimulus of a specific color or shape among a set of distractors while recording neuronal responses during the short fixational periods between saccades that occurred during the animal's active search (Bichot et al., 2005). The authors found that V4 neurons responded more

vigorously when the stimulus in the receptive field matched the feature that the animal was searching for compared to conditions when the same stimulus appeared in the neuron's receptive field as a distractor.

The neurophysiological studies mentioned above involved recording neuronal activity from area V4, and while these studies have shed important light on feature attention effects in visual cortex, studies in area MT have given the clearest picture of how feature attention acts to selectively modulate the activity of sensory neurons. The experiments described in this volume were performed in area MT, therefore, the following sections will focus on details about MT and the feature attention effects that have been observed there.

The middle temporal area

The middle temporal area (V5/MT) is among the most studied of cortical sensory areas and because of this, there exists a relatively strong understanding of its anatomical connections and functional properties. MT is located in the posterior bank of the superior temporal sulcus in the macaque brain. It receives cortical input from two primary sources: as direct projections from V1 and as indirect projections that originate in V1 and arrive via projections from areas V2 and V3 (for review, see (Roe et al., 2007)). MT also receives subcortical input from the lateral geniculate nucleus (Sincich et al., 2004) as well as the lateral and inferior pulvinar (Glickstein et al., 1980; Maunsell & Van Essen, 1983; Stepniewska, Qi, & Kaas, 1999) which conveys information from the superior colliculus (Berman & Wurtz, 2010, 2011; Rodman, Gross, & Albright, 1990). Visual responsiveness in area MT has been shown to

depend on the presence of input from either V1 or the Superior Colliculus (Girard, Salin, & Bullier, 1992; Rodman, Gross, & Albright, 1989, 1990). MT sends feed-forward projections to a large swath of cortical and subcortical regions as well as feed-back projections into areas earlier in the visual hierarchy (Maunsell & Van Essen, 1983; Ungerleider & Desimone, 1986). MT is part of the dorsal, or 'where' pathway (Ungerleider & Mishkin, 1982) and consistent with its position in the dorsal pathway, neurons in MT encode information about the location and movement of visual stimuli but are relatively invariant to stimulus shape and color (Born & Bradley, 2005).

MT tuning properties

MT is thought to play a role in motion perception, the integration of local motion signals and the guidance of some eye movements (Born & Bradley, 2005). For the purposes of the research presented in this thesis, focus will be placed on the visual response properties of these neurons and their relationship to behavior. Neurons in area MT are selective for the location, direction, speed, size and binocular disparity of moving visual stimuli (Born & Bradley, 2005; Maunsell & Van Essen, 1983a, 1983b; Zeki, 1974a, 1974b). MT is organized retinotopically and contains strong columnar organization for direction (Albright, Desimone, & Gross, 1984) and binocular disparity tuning preferences (DeAngelis & Newsome, 1999), and clustering, but not columnar organization, for speed preferences (Liu & Newsome, 2003).

The hallmark of electrophysiological recording in area MT is the remarkably strong tuning for direction of motion that is encountered in most cells (Dubner & Zeki, 1971; Maunsell & Van Essen, 1983b). A stimulus moving in the preferred direction of

an MT neuron can elicit spiking activity above 100 Hz, while motion in the opposite

direction can silence the neuron, eliminating even the paltry background spontaneous

activity. Direction tuning for single neurons in MT is well characterized by a circular

Gaussian function with a population average bandwidth of approximately 90°

(Albright, 1984; Price et al., 2005). Because of MT neurons' strong tuning for the

direction and speed of moving stimuli, they are likely involved in velocity

computations (Born & Bradley, 2005).

      MT neurons are also strongly modulated by the binocular disparity of a visual

stimulus. Binocular disparity is the difference in position between the left and right

retinal images that results from the horizontal separation of the two eyes (Figure 1).

The visual system uses binocular disparity, along with other visual cues, to estimate

depth. Several visual brain areas contain neurons that are tuned for binocular disparity

(Cumming & DeAngelis, 2001; Ponce & Born, 2008; Roe et al., 2007). In MT, it has

been shown that more than two-thirds of neurons exhibit strong selectivity for

binocular disparity (DeAngelis & Uka, 2003; Maunsell & Van Essen, 1983a).
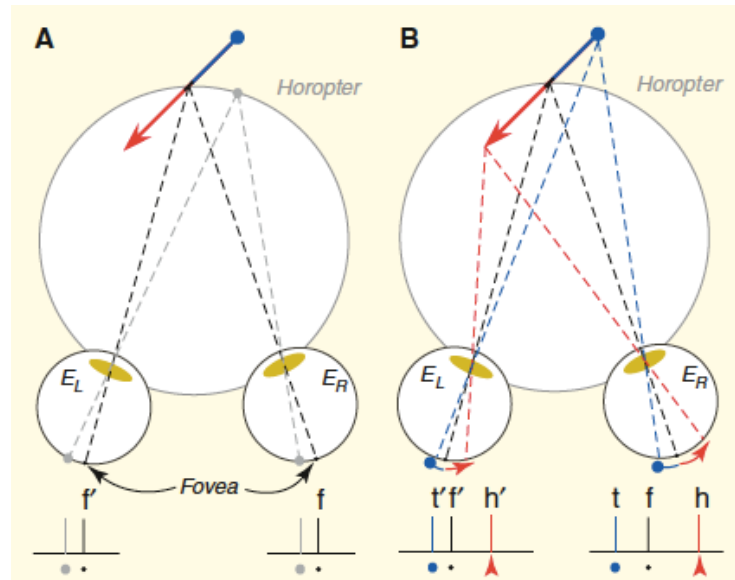
Figure 1 - The geometry of stereopsis. Each diagram represents a section through the horizontal equator of the eye as viewed from above. (A) Points along the horopter produce images on corresponding points of the two retinas. (B) Points on the arrow at different distances from the observer produce images at different distances from the fovea on the two retinas. These differences are referred to as 'binocular disparity.' Figure and caption modified from (Ponce and Born, 2008).

It is thought that information about direction of motion and binocular disparity arrives in MT via two distinct pathways. As mentioned previously, the direct pathway arrives in MT from primary visual cortex while the indirect pathway proceeds from primary visual cortex through the thick stripes of V2 before arriving in MT. Several lines of evidence suggest that each pathway carries a distinct type of information to MT. The direct pathway is thought to primarily carry information about direction of motion. Movshon and Newsome antidromically identified V1 neurons that directly projected to MT and showed that these neurons were highly direction selective

(Movshon & Newsome, 1996). Unfortunately, they did not test for binocular disparity

tuning in these neurons. The indirect pathway, which passes through the thick stripes

of V2, by contrast, is thought to carry information about binocular disparity to MT.

The thick stripes have been shown to contain a high percentage of neurons that are

tuned for binocular disparity (Chen, Lu, & Roe, 2008; Hubel & Livingstone, 1987;

Peterhans & von der Heydt, 1993; Roe & Ts'o, 1995). Further, on the basis of their

response properties, V2 neurons, rather than V1 neurons, are likely the primary

provider of disparity information to MT: V1 neurons have even-symmetric responses

to binocular disparity, while V2 neurons and MT neurons have odd-symmetric

disparity responses and respond to disparities of comparable sizes (Cumming &

DeAngelis, 2001; Thomas, Cumming, & Parker, 2002). Additionally, MT neurons

respond to larger binocular disparity values than do neurons in V1 (DeAngelis & Uka,

2003). Perhaps the strongest evidence for the segregation of information in these

pathways came from the Born lab when it was demonstrated that reversible

inactivation of the indirect pathway diminished tuning for binocular disparity in MT

while leaving direction tuning strength unaltered (Ponce, Lomber, & Born, 2008;

Smolyanskaya, Lomber, & Born, 2011).

Are direction and binocular disparity tuning in MT separable?

The arrival of direction and binocular disparity tuning information into MT via

different pathways raises many interesting questions about how stimulus information

is integrated in the region. Of primary concern for this thesis is whether the tuning

preferences for each of these features are mathematically separable within single

neurons. By separable, it is meant that the response of an MT neuron to a stimulus made up of a certain direction of motion and binocular disparity can be predicted as a linear combination of the neuron's tuning for each of those features. In other words, does a neuron have a fixed tuning preference for each of these features or does the preference for one feature vary as the other changes? For example, it may be said that a neuron in MT "prefers" upward motion, but typically, while making this determination, other features to which the neuron may be tuned, like the binocular disparity, speed, or size of the stimulus, would have been left fixed. This is usually done for practical purposes: the combinatorial explosion that results from including multiple values of each of these features would quickly become overwhelming. The practical decision to leave other variables fixed while testing for the tuning of another feature rests on the assumption that a neuron's tuning for each feature is independent. Explicitly, this means that the tuning preferences of a neuron for a certain feature do not depend on the values of other features. Whether this assumption is true or not has practical implications for the experimental design that will be discussed in chapter 2 as well as conceptual implications for models of read-out and attentional mechanisms.

Priebe and colleagues have demonstrated that MT neurons exhibit speed tuning for grating stimuli and thus have inseparable spatial and temporal frequency tuning. This is in contrast to V1, where most neurons studied have exhibited separable tuning for spatial and temporal frequency (Priebe, Lisberger, & Movshon, 2006). While many groups have studied direction of motion and binocular disparity tuning in MT, it remains unknown whether the tuning for these features is separable. Roy and Wurtz have shown that these features are not separable in some neurons in MST (Roy &

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Wurtz, 1990), a region that receives projections from MT (Maunsell & Van Essen, 1983; Ungerleider & Desimone, 1986). While it is not a formal requirement for neurons that represent two variables independently to receive input about those variables in a segregated manner, the hypothesis that direction and binocular disparity information might reach MT via two distinct pathways is suggestive that these two features may be represented separably in MT. This issue will be examined in detail in chapter 1.

The relationship of activity in MT to behavior and attention

Because there exists a relatively strong understanding of the anatomical connectivity and receptive field properties of MT, neurons in MT have often been used as a substrate for investigating the relationship between neuronal activity and behavior. It was first established that individual MT neurons are roughly as sensitive as a monkey's psychophysical performance during judgments about the direction of motion of moving dot stimuli (Newsome, Britten, & Movshon, 1989). It has subsequently been shown that pools of tens to hundreds of MT neurons are sufficient to account for monkey's behavioral performance during these tasks (Cohen & Newsome, 2009). It has also been shown that the activity of single MT neurons correlates weakly with perceptual decisions during a variety of direction and disparity discrimination and detection tasks (Bosking & Maunsell, 2011; Bradley, Chang, & Andersen, 1998; Britten et al., 1992, 1996; Cook & Maunsell, 2002; Sasaki & Uka, 2009; Uka & DeAngelis, 2004). Further, microstimulation in MT has been shown to bias decisions about these same features (DeAngelis & Newsome, 2004; Salzman et

al., 1992; Uka & DeAngelis, 2006). These results suggest that the responses of MT neurons have a causal relationship with an animals' behavioral choice during judgments about both direction of motion and binocular disparity.

In addition to these decision related signals, attention effects in primate MT are relatively large and have been well described (Cook & Maunsell, 2002, 2004; Dodd et al. 2001; Ferrera & Lisberger 1997; Lee & Maunsell, 2010; Martinez-Trujillo & Treue, 2004; Recanzone & Wurtz, 2000; Seidemann & Newsome, 1999; Treue and Martinez-Trujillo 1999; Treue & Maunsell, 1996, 1999; Wannig, Rodriguez, & Freiwald, 2007; Zaksas & Pasternak, 2005). Many of these attention studies have taken advantage of MT neurons' tuning properties for direction of motion and used motion stimuli to either drive these neurons during a spatial attention task or have animals specifically attend to motion to investigate non-spatial, or feature-based, forms of attention.

The feature similarity gain model

In a seminal series of experiments, Treue and Martinez-Trujillo investigated feature attention effects in MT by training monkeys to attend to a distant moving stimulus while recording the activity of an MT neuron in response to an unattended, stimulus in its receptive field (Martinez-Trujillo & Treue, 2004; Treue & Martinez-Trujillo, 1999). They observed that when the animal attended to a distant stimulus moving in the neuron's preferred direction, the neuron from which they were recording exhibited increased firing relative to when the animal attended to a distant stimulus moving in the neuron's null direction (Treue & Martinez-Trujillo, 1999). In a

subsequent experiment, these authors systematically changed the direction of the distant attended stimulus and found that attention created a "push-pull" effect on the responses of MT neurons (Figure 2). When the animal attended to the preferred direction of the neuron under study, the neuron's firing rate increased relative to its response when the animal performed a motion irrelevant task at fixation. When the animal attended to the null direction of the neuron under study, the neuron's firing rate decreased relative to the response during the fixation task. The authors concluded that feature attention sharpens the response of a population of neurons in order to highlight the activity of neurons that are tuned for the attended feature (Martinez-Trujillo & Treue, 2004).
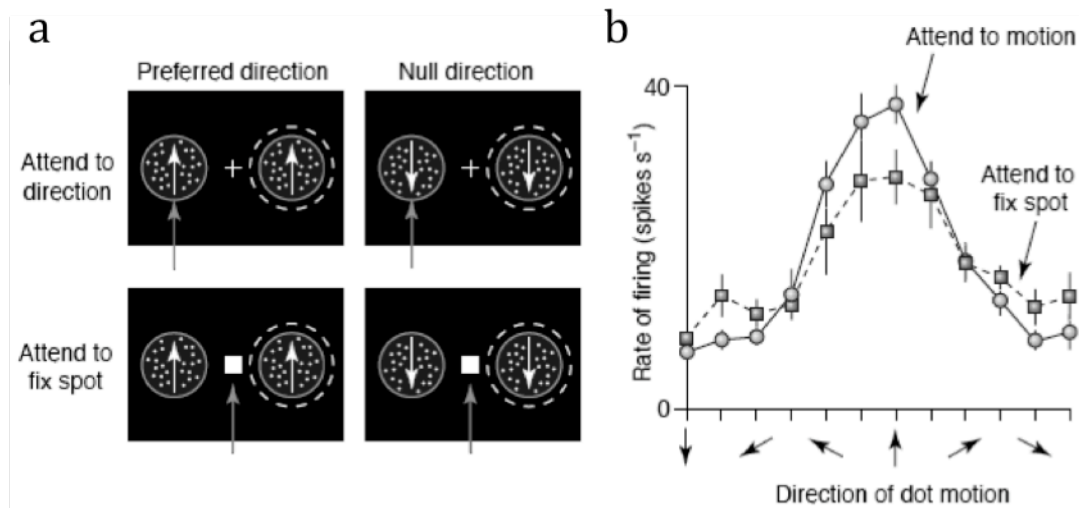
Figure 2 – Task and results from Martinez-Trujillo and Treue (2004). (A) The task and stimuli used. The animals attended to either a moving dot stimulus outside of the receptive field of a neuron or the fixation spot. The direction of the stimuli inside and outside of the receptive field were yoked together but changed on a trial-by-trial basis. (B) The responses from an example neuron whose preferred direction of motion was up. Attention outside of the receptive field selectively enhanced the firing rate of the neuron relative to attention to the fixation spot when the attended stimulus was at or near the preferred direction of the neuron whereas the response was suppressed when the attended stimulus moved in the anti-preferred direction. Figure from Maunsell and Treue, 2006, based off of Martinez-Trujillo and Treue 2004.

These observations led to the proposal of the feature similarity-gain (FSG) model, which describes how feature attention may enhance the selectivity of a population of neurons in a way that leads to an emphasis of attended features (Martinez-Trujillo & Treue, 2004; Maunsell & Treue, 2006). The FSG model emphasizes the importance of the role of sensory neurons' tuning preferences for the allocation of attentional effects. Specifically, the critical factor is the match between a neuron's tuning preference for a feature and the currently attended feature value. Because a neuron's tuning preferences are the important variable, the FSG model

posits that the stimulus that is in a neuron's receptive field is unimportant for attentional modulation. The model's predictions have been verified by several experiments using either fixation-based discriminations or free viewing visual search tasks (Bichot, Rossi, & Desimone, 2005; Cohen & Maunsell, 2011; Martinez-Trujillo & Treue, 2004), but see (David et al., 2008; Zhou & Desimone, 2011) for examples of studies that do not provide support for this model.

Because the FSG model is built upon the premise that the attentional system can account for a neuron's tuning preferences, it prompts us to ask interesting questions about how these effects are created. Ranking among the most important of these questions are: How are attentional effects applied to neurons that represent all parts of visual space? How does the attentional system account for a neuron's tuning preferences? What aspect of a neuron's tuning properties determine whether it will exhibit feature attention effects? Can single neurons exhibit feature attention effects for multiple features at the same time?

As mentioned above, it has been suggested that cortical organization for a feature may be important for the presence of feature attention effects (Maunsell & Treue, 2006). While there is not strong empirical evidence for this suggestion, the wiring of spatial attention is easier to envision because of the strong topographical organization that is present in visual cortex, thus simplifying the required connectivity map. Similarly, the presence of columnar organization for other features, like direction of motion and binocular disparity in area MT, could greatly simplify the anatomical requirements of wiring feature attention. Feature attention effects have, however, been described for spatial frequency, orientation, color and shape in V4 without there

being strong evidence of columnar organization for these features (Bichot, Rossi, & Desimone, 2005; Cohen & Maunsell, 2011; McAdams & Maunsell, 2000; Zhou & Desimone, 2011). Further, while the limit of the types of stimuli to which attention can modulate neuronal responses is currently unknown, it is unlikely that this limit is restricted to the space of features that have strong cortical organization.

Instead of relying on columnar organization, feature attention effects could depend on lateral connectivity. There is some suggestion that similarly tuned sensory neurons may have preferential lateral connectivity across distances larger than a cortical column (Bosking et al., 1997), but this issue is far from settled. Further, the ranges of these connections are thought to cover relatively small distances, especially when compared to the scale of feature attention effects, which have been demonstrated across large portions of visual space – including across hemispheres (Cohen & Maunsell, 2011; Martinez-Trujillo & Treue, 2004; McAdams & Maunsell, 2000; Treue & Martinez-Trujillo, 1999). The way that the attentional system can create these types of coordinated effects across cortical hemispheres is currently unknown.

The functional properties of neurons that exhibit feature attention effects are also largely unknown. For example, it is unknown whether sensory neurons can exhibit feature attention effects for features to which they are only weakly tuned. One way to begin to address this question would be to study feature attention for multiple features within single neurons, preferably using features that evoke a range of different tuning strengths. Furthermore, given that most neurons are tuned for multiple features, it is not clear how the attentional system highlights the activity of neurons with relevant tuning. The FSG model predicts that the amount of attentional modulation

observed in a single neuron is a function of the similarity of a feature in an attended stimulus to the cell's preference for that feature. Can this model be extended to encompass the suite of tuning properties to which a neuron is tuned? Typically, when multiple types of attention have been studied in single neurons, one of the features studied has been spatial (Hayden & Gallant, 2005, 2009; Treue and Martinez-Trujillo 1999; McAdams & Maunsell, 2000) or the task demands have been changed from trial to trial in order to test whether these demands will lead to feature attention effects for different task related features (Bichot, Rossi, & Desimone, 2005; Cohen and Maunsell 2011; Katzner, Busse, & Treue 2009). Thus it is currently unknown whether feature attention can be present in the same neuron to multiple non-spatial features in the same experimental context. More generally, the limits of the precision of attentional allocation in terms of a neuron's feature preferences are unknown.

While MT neurons' tuning preferences for motion stimuli have been exploited in studies of attention, few electrophysiological studies have looked specifically at attention to stimuli of varying binocular disparities. There is some evidence from psychophysical studies for the existence of attentional effects in three-dimensional space, including those that can emphasize an attended surface across varying depths (He & Nakayama, 1995, 1992). Further, an ERP study has found modulation in early evoked potentials as a function of attending to stimuli at different depths (Kasai et al., 2003). It is an important question to ask whether attentional effects in MT are present for other features to which MT neurons are tuned. The answer will help shed light on the question of what aspects of a neuron's tuning are important for feature attention modulation. These issues will be addressed in chapter 2.

Summary

The neurophysiological study of attention has shown how the responses of sensory neurons are altered in order to highlight behaviorally relevant information. However, much about this process remains unknown. We are particularly ignorant of the mechanisms of feature attention, where the attentional system highlights the activity of neurons whose tuning preferences make them most relevant for the task at hand. Because primate MT has well understood tuning properties, it is an ideal brain region in which to investigate what aspects of a neuron's tuning play a role in feature attention. The work presented in this thesis will attempt to gain a better understanding of how MT neurons represent direction of motion and binocular disparity information and whether this representation is mathematically separable, in order to determine whether MT neurons have fixed tuning preferences for these features. Further, it will be tested whether MT neurons exhibit feature attention for binocular disparity in addition to previously described effects for direction of motion. It is hoped that by establishing the presence of feature attention effects for multiple features within the same neurons that we can address what aspects of a neuron's tuning properties play a role in the allocation of feature attention effects. It is hypothesized that because the attentional system can account for a neuron's tuning preferences, as we will discuss in chapter 2, that it will be sensitive to a neuron's tuning strength.

CHAPTER ONE

The Separability of Tuning For

Direction of Motion and Binocular Disparity

in Single Neurons in Primate Area MT

The work in this chapter was performed in collaboration with Alexandra Smolyanskaya, a fellow graduate student in the Born lab. Alex and I planned the experiments, I collected the data, and Alex performed the data analyses. I have prepared this text.

Introduction

Visual processing is a massively parallel process that begins with the breaking down of a visual scene into a fragmented representation, where neurons with different receptive field properties encode different aspects of the scene. A simplistic view of this process involves early stages of processing representing the basic, low-level components of a scene while the higher stages encode increasingly more complex features. A cost associated with the increasingly complicated stimulus selectivity that develops at higher stages of processing is the loss of information about the low-level stimulus attributes. The way in which these transformations are made, as well as the brain areas where they happen, give us insight into which stimulus attributes are best represented in a given area and, accordingly, which areas are best suited to represent information about a particular feature.

Complicating matters is the fact that even at the earliest of stages of this processing, neurons represent multiple visual features. For example, neurons in V1, the first stage of visual cortical processing, are sensitive to a wide array of stimulus attributes including the location, size, contrast, color and spatial and temporal frequency of stimuli (reviewed in Hubel, 1982). One important question about the way in which neurons represent multiple features is whether these features are represented independently or whether their representation depends on the values of other features. Said another way, do the neurons in a brain region encode a stimulus in a mathematically separable manner? If a neuron's preference for a given feature does not change as a function of other feature values, it can be said that the neuron's preference for that feature is fixed and that this feature is represented separably from

other feature dimensions. Whether or not a set of features is represented separably in a population of neurons will depend on the specific features and brain areas involved, but this simple question has significant implications on two major fronts.

The first issue is practical. When collecting data, experimenters often assume the separability of features that they are measuring. In practice, this means that tuning for different features is measured serially while keeping the values of other features fixed. This strategy has the advantage of greatly reducing the number of trials that are necessary to characterize a neuron's tuning for a certain property. However, this assumption may not always be true and, as we will discuss below, its validity depends on the features and brain area that are being studied.

The second issue is conceptual and involves theoretical models about cortical networks and, more generally, questions about how cortex represents and then reads out information. Depending on the behavioral context, it is often advantageous for the brain to read out particular stimulus dimensions individually. A good example is when an animal is required to make judgments about the direction of a moving stimulus. For direction judgments, other stimulus dimensions, like stimulus speed, color or binocular disparity are irrelevant. The mathematics of separable joint tuning are far simpler than non-separable tuning and are typically relied upon in computational models that attempt to read out one of several stimulus features at a time (Grunewald & Skoumbourdis, 2004; Seung & Sompolinsky, 1993; Zhang et al., 1998).

Many brain areas represent multidimensional stimuli, thus making the read-out of individual stimulus dimensions difficult. If these features are represented separably, averaging across the irrelevant stimulus dimensions will allow for accurate read-out of

the feature of interest (Grunewald & Skoumbourdis, 2004; Heeger, 1987; Qian & Andersen, 1997) whereas a more complicated mechanism would be required to read out this same feature information if it was represented non-separably. It is important to note, however, that separability is only computationally useful in circumstances when the brain wants to read out each of a set of features independently. Many areas encode combinations of features inseparably in order to give rise to more complicated preferences. A key example is direction selectivity, which arises from the inseparable combination of stimulus preferences about both time and space.

Finally, the idea of a neuron having fixed – *i.e.* separable – tuning preferences is conceptually important for issues relating to read-out and also for how the attentional system might be able to highlight the activity of behaviorally relevant sensory neurons. We often think of a neuron's tuning preference for a feature as being fixed – for example, we might say that a neuron "prefers" upward motion, meaning that it responds maximally to upward motion compared with other directions. But this is an empirical question and it needs to be tested whether this assumption is always correct. For example, is the firing rate of an MT neuron a reliable indicator of the direction of motion that is in its RF across other stimulus manipulations? Does this neuron like upward motion at all binocular disparities? At all speeds? Read-out mechanisms could be greatly simplified if the neurons used to compute judgments about stimuli have fixed preferences for the relevant features. Separability, however, is not a requirement for read-out. The behavioral flexibility exhibited by non-human primates is far too flexible to necessitate reliance upon solely separable representations to solve all possible behavioral tasks. But, it would be advantageous for the brain to

rely on neurons that represent stimulus information separably whenever it is possible. If the feature similarity gain (FSG) model (Martinez-Trujillo & Treue, 2004) is true – as will be discussed in detail in Chapter 2 – it would be far easier to implement if neurons that prefer upward motion always prefer upward motion, regardless of the other feature values of the stimulus in its RF.

The question of separability has been studied in several brain areas. For example, neurons in MT have been shown to encode the speed of oriented gratings (Priebe, Cassanello, & Lisberger, 2003). Because stimulus speed depends on the relationship between the temporal and spatial frequency of a grating, these features are not represented separably in MT. This is in contrast to a majority of neurons in V1 where tuning for temporal and spatial frequency tuning, as well as orientation tuning, have been shown to be separable (Mazer et al., 2002; Priebe, Lisberger, & Movshon, 2006). Therefore, it would not be wise for the brain to base judgments about the temporal or spatial frequency of a stimulus on the activity of small groups of MT neurons. However, MT, unlike V1, would be a good place to read out neuronal activity in order to make judgments about stimulus speed.

Recording in the medial superior temporal area (MST), Roy and Wurtz have shown that binocular disparity and direction tuning are not separable. Instead, neurons there exhibit binocular disparity tuning that depends on the direction of a moving stimulus, particularly amongst neurons tuned for horizontal directions. The authors postulated that these neurons might combine information about motion and depth in a way that can reliably signal self-motion in a three dimensional world (Roy & Wurtz, 1990). Because of these tuning properties for binocular disparity, it may not

make sense for the brain to read out the activity of MST neurons when making judgments about the absolute binocular disparity of a stimulus in all situations.

As was discussed above, neurons in primate area MT are tuned to the location, direction, binocular disparity, speed and size of moving stimuli (Born & Bradley, 2005). The tuning of MT neurons for direction of motion is extremely robust and a large percentage of these neurons are also tuned for binocular disparity (DeAngelis & Uka, 2003; Maunsell & Van Essen, 1983b). The two studies presented in this volume will focus on these two tuning preferences in MT. In feature space, these two stimulus dimensions are orthogonal, but it is unknown whether MT encodes them separably. The most exhaustive study of the tuning properties of MT neurons found no correlation between direction and binocular disparity tuning properties (DeAngelis & Uka, 2003) and, like others before them, they tested tuning preferences serially, first determining the preferred direction of a neuron and then the preferred disparity at that direction. Interestingly, neurons in V1, the major source of input to MT, represent direction and disparity separably (Grunewald & Skoumbourdis, 2004). However, as mentioned above, MST, an area further up the visual hierarchy from MT, represents these features inseparably. This raises the question of whether MT represents these features separably, like its inputs, or inseparably, like the area to which it projects. Arguing in favor of their separability, neurons in MT have been shown to be involved in perceptual judgments about both the direction of motion and binocular disparity of stimuli (Bradley, Chang, & Andersen, 1998; Britten et al., 1992, 1996; Sasaki & Uka, 2009) and, further, microstimulation in these areas has been shown to bias judgments related to these features (DeAngelis & Newsome, 2004; Salzman et al., 1992; Uka &

DeAngelis, 2006). These findings suggest that the brain does read out the activity in MT for judgments about direction and binocular disparity, a feat that would be much simpler if the tuning for these features is separable.

In this chapter, we will test whether the tuning for direction of motion and binocular disparity is separable in area MT of the awake, fixating macaque.

Methods

Two adult male macaque monkeys (N and P), *Macaca mulatta*, were seated comfortably in custom chairs (Crist Instruments). The animals were trained to fixate a zero disparity central spot by positive reinforcement via liquid rewards.

Before electrophysiological recordings, each animal was implanted with a custom titanium head-post, two scleral search coils for monitoring eye positions and vergence and a vertically oriented Cilux recording cylinder to protect a craniotomy centered posterior 3 mm and lateral 15 mm relative to ear bar zero. All animal procedures complied with the National Institutes of Health Guide for Care and Use of Laboratory Animals and were approved by the Harvard Medical Area Standing Committee on Animals.

Stimuli consisted of moving dot patches and were presented on a CRT monitor placed 41 cm from the animal with resolution 1024 X 768 pixels (17.8 pixels / degree) and refresh rate 100.1 Hz. The binocular disparity of each stimulus was created by drawing each dot twice, once in red and once in blue, and changing each dot-pair's horizontal offset according to the specified disparity value. Dots at zero binocular disparity were drawn as a combination of the blue and red values, which appeared

magenta. The monkeys viewed the screen through monocular filters colored red or blue (Kodak gelatin filters nos. 29 and 47, respectively), so that only one set of dots was visible to each eye. Crossover between the two eyes, as viewed through the filters, was measured to be less than 3%. Dots were presented at a spatial density of 1.5 dots/degree^2, with 150 ms lifetime and had 100% coherence (*i.e.*, there were no noise dots, but the dots flickered because of their limited lifetime). During all experiments, dots drawn at zero disparity were randomly placed in an annulus around the fixation target to aid the animal in maintaining vergence angle at the plane of fixation. All stimuli were drawn using the Cogent toolbox (www.vislab.ucl.ac.uk) in MATLAB.

For the experiments presented in this chapter, the monkeys fixated a central spot while moving stimuli were presented in the receptive field of the neuron under study (Figure 1.1A). The monkeys were rewarded for maintaining fixation for the presentation of 2 to 4 stimuli, each of which was presented for 1 second total. The stimuli consisted of circular dot patches that were drawn at one of 7 binocular disparities (-1.2°, -0.8°, -0.4°, 0°, 0.4°, 0.8°, 1.2°) and 8 directions of motion (0°, 45°, 90°, 135°, 180°, 225°, 270°, 315°) (Figure 1.1B). When isolating a neuron, we first qualitatively determined the location of its spatial receptive field by hand mapping. Next, we qualitatively determined the neuron's preferred direction and using that direction, qualitatively evaluated the neuron's area summation tuning and speed tuning. The diameter of the stimulus was set to be equal to either the receptive field's eccentricity or the peak of the neuron's area summation curve, whichever was smaller. The stimulus's speed was set to a value, within a range of 4 – 25 °/s, that led to the largest response. We collected data from 69 MT neurons (36 from monkey N and 33

29

from monkey P) where we could obtain at least 15 repetitions per stimulus condition (median = 23 repetitions per conditions).

For display purposes (in Figure 1.2), data were fit with either Von Mises functions (direction tuning) or Gabor functions (disparity tuning). Custom MATLAB code was written for all analyses and several of the built-in MATLAB functions were used, including "svd," which was used to perform the singular value decomposition.
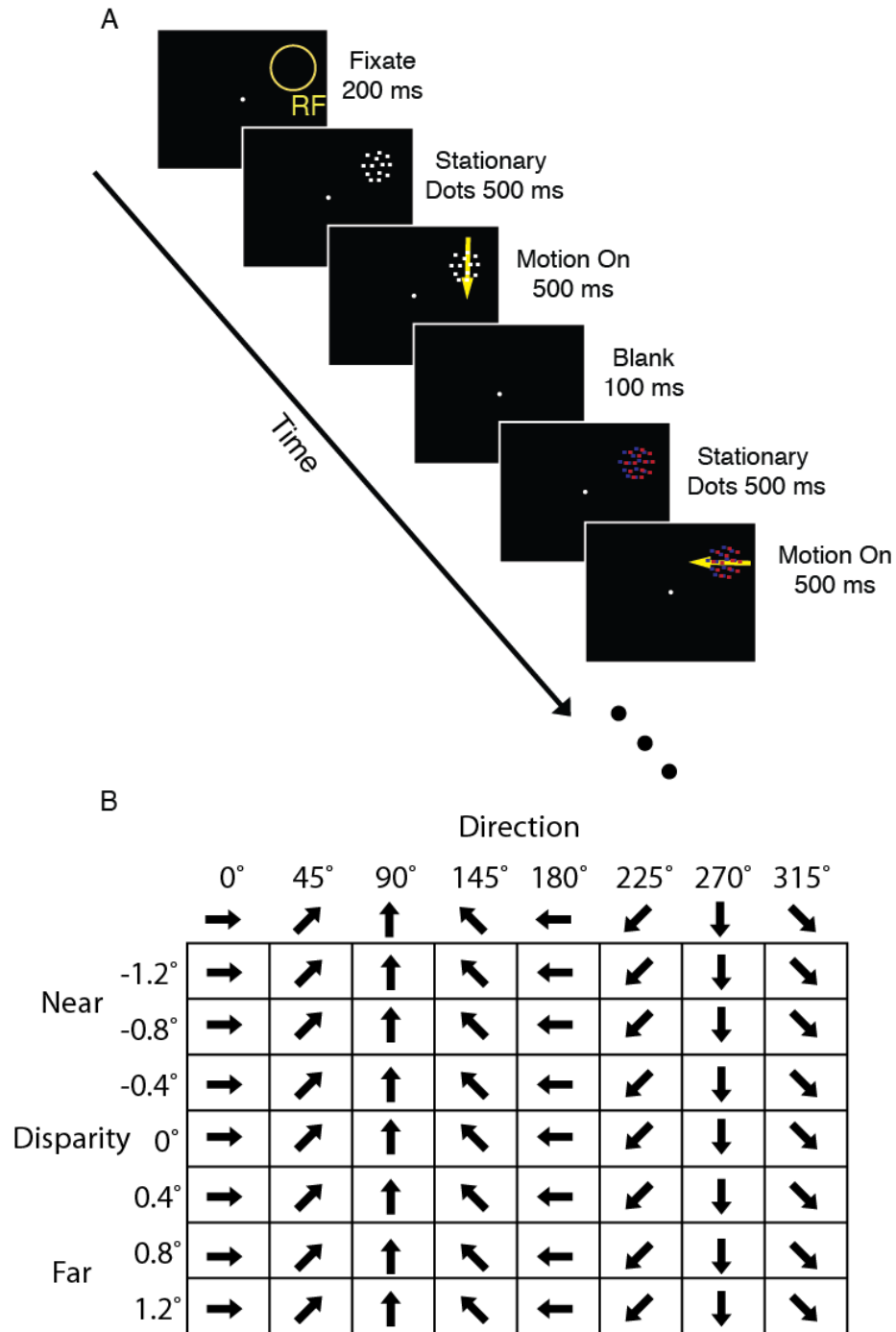
Figure 1.1 – Fixation task and stimuli. (A) Task design. Monkeys fixated a central spot while dot stimuli were presented in the spatial receptive field of the neuron under study. (B) The stimuli were drawn from the matrix populated by 8 directions of motion and 7 binocular disparities.

Single neuron data

The data collected from a representative example neuron during this fixation task is shown in Figure 1.2. Figure 1.2A depicts direction tuning curves from this neuron, collected at each binocular disparity value. These tuning curves show that while the overall firing rate changes at different binocular disparities, the direction preferences of this cell remain largely similar. Figure 1.2B depicts the same data as in Figure 1.2A, but sorted to show the binocular disparity tuning collected at different directions of motion. Figure 1.2C shows these same data in yet another way, as a joint tuning plot. The firing rate in each condition has been plotted as an intensity value in a matrix that is arranged in the same format as the example in Figure 1.1B, which is shown again in Figure 1.2D as a reference. The maximum response of this neuron is highlighted in Figure 1.2C and Figure 1.2D to ensure clarity.
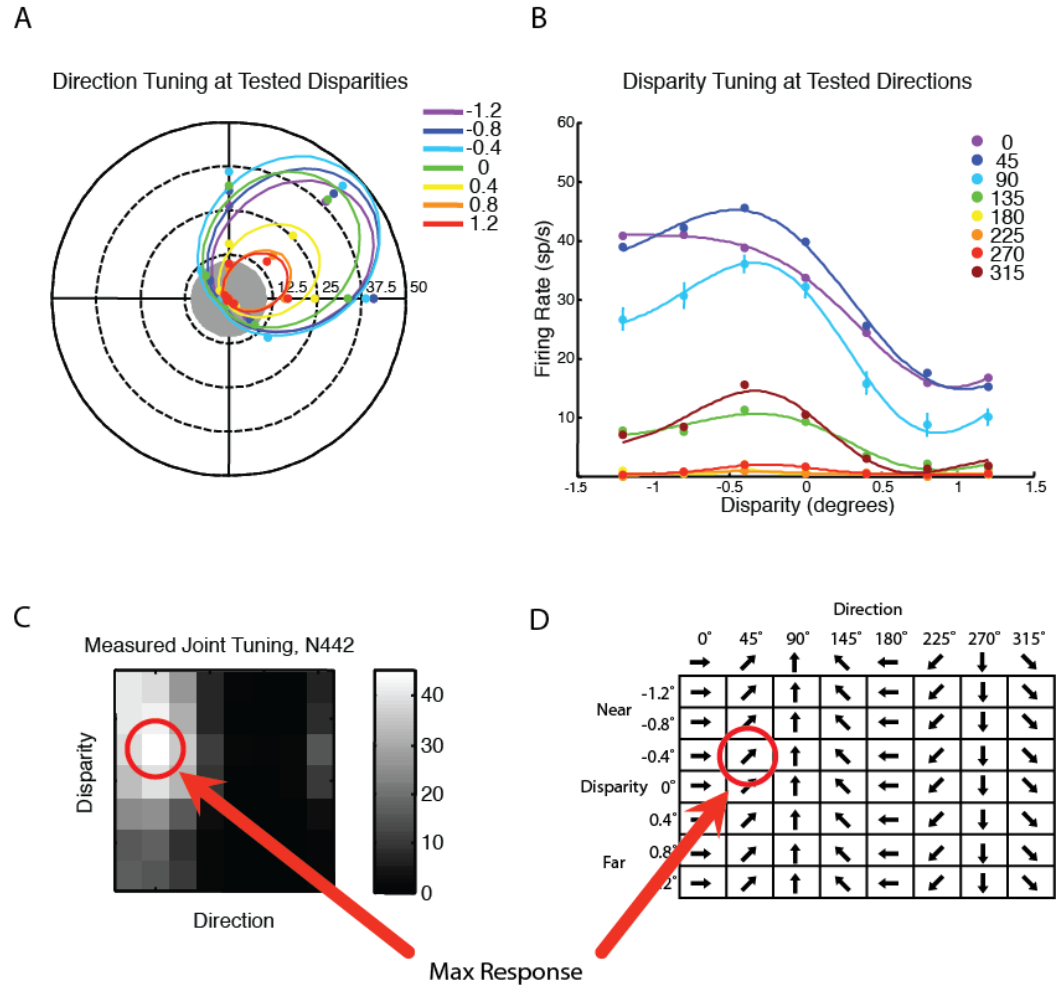
Figure 1.2 – Joint tuning example neuron. (A) Direction tuning curves collected at 7 different binocular disparities, fit with von Mises functions. (B) Same data as in A, but re-plotted to show the binocular disparity tuning at each of the 8 directions, fit with Gabor functions. S.E.M. are shown for one example curve. The colors in A and B are not related. (C) Same data as in A and B, but re-plotted as an intensity map. (D) Stimulus conditions for reference with (C). The max response in (C) is identified for clarity.

Figure 1.3 shows the joint tuning plots of six more example neurons to highlight some of the common features found in the population. The hallmark of a separable distribution in one of these plots is a symmetric response pattern that is either largely circular or oriented horizontally or vertically, instead of being tilted. A tilted response profile would signify tuning preferences for a feature that changed as a function of the other feature. The neurons in Figure 1.3A and 1.3B have similar direction tuning, but the neuron shown in Figure 1.3A has stronger binocular disparity tuning. Both of these neurons exhibit tuning profiles that are vertically oriented, showing that they are more strongly tuned for direction than for binocular disparity, which is typical of MT neurons (DeAngelis & Uka, 2003). The neuron in Figure 1.3C has particularly narrow binocular disparity and direction tuning while the neuron in Figure 1.3D has slightly broader tuning, but both cells exhibit a circular response profile. The neuron shown in Figure 1.3E has a fairly standard tuning profile for the population, while the neuron in Figure 1.3F has a tuning profile that was very uncommon in the population. The neuron in Figure 1.3F has a joint tuning function that is slightly tilted and it seems that the neuron's preferred binocular disparity is slightly different at the 3rd and 4th directions (corresponding to 135° and 180°). This tuning profile suggests slightly imperfect separability, especially when compared to the other examples that all appear to be close to completely separable.
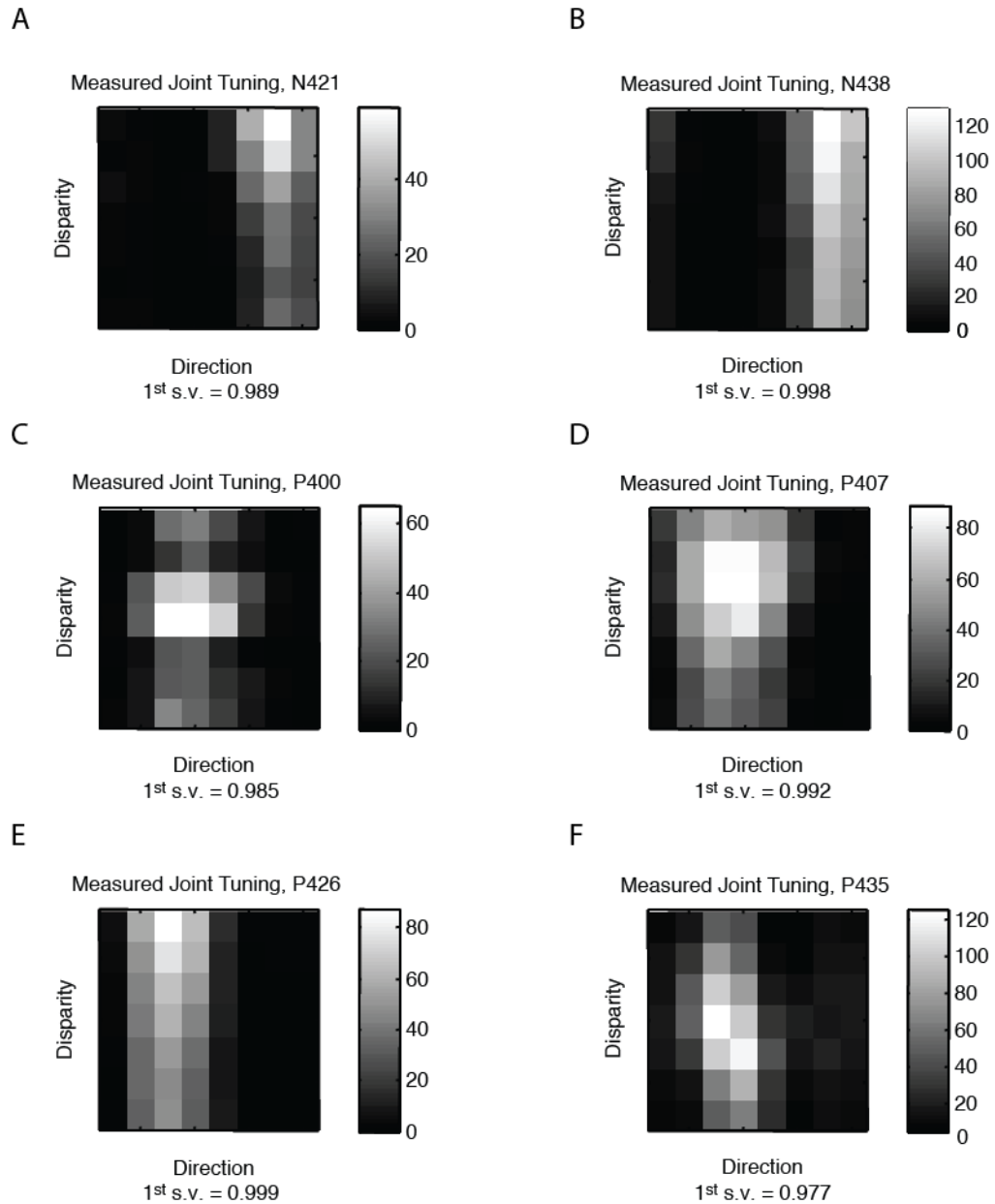
Figure 1.3 – More joint tuning example neurons. (A – F) Responses from 6 different neurons to the 56 stimulus conditions. The first singular value from each neuron is listed below each plot.

The evaluation of separability

A first pass through these data suggests that the tuning for both of these features is largely separable. We have quantitatively confirmed this impression using two methods that have previously been used in the literature (Mazer et al., 2002). The first method was to use singular value decomposition (SVD). SVD decomposes a matrix, *X,* into a linear sum of separable matrices that are each obtained from a weighted combination of two orthogonal vectors. Said another way for these data, SVD breaks up matrix *X* into a series of separable matrices, each of which is formed by the product of two vectors that each can be interpreted as a direction and binocular disparity vector. These vectors are a mathematical description of the neuron's tuning curve for each feature. The first matrix takes the best separable approximation from the original matrix, *X,* and this process continues, using the remainder from each step. The singular values returned by SVD analysis represent the weight given to that matrix. Therefore, if the matrix X is completely separable, only the first singular value would be greater than zero. To determine the proportion of each singular value's contribution, each singular value is squared and divided by the sum of the squares of all other singular values (Depireux et al., 2001; Grunewald & Skoumbourdis, 2004; Mazer et al., 2002). Therefore, the weight of each matrix is defined by its squared power. The sum of all of a matrix's singular value weights equals 1 and the number of non-zero singular value weights is an indication of how separable a neuron is. Most important here is the magnitude of the first singular value weight relative to the magnitude of the second singular value weight. If *X* is completely separable, the first singular value weight will be equal to 1, as *X* becomes less separable, the distance

between the first and second singular value weights will decrease. This method has been used to address the separability of tuning properties in a number of studies (Depireux et al., 2001; Mazer et al., 2002; Peña & Konishi, 2001).

The first singular value from each of the example neurons is reported in Figure 1.3. Figure 1.4 makes it clear that the contribution of the first singular value for the population of neurons is substantially greater than is the second value for all of the neurons in the population. Only a small number of cells have non-zero second or third singular value weights, suggesting that the tuning for direction and binocular disparity is strongly separable in the population. The first singular value from the example neuron depicted in Figure 1.3F has one of the lower weights observed in the population. But note that this neuron's measure of separability, by this metric, is still high.
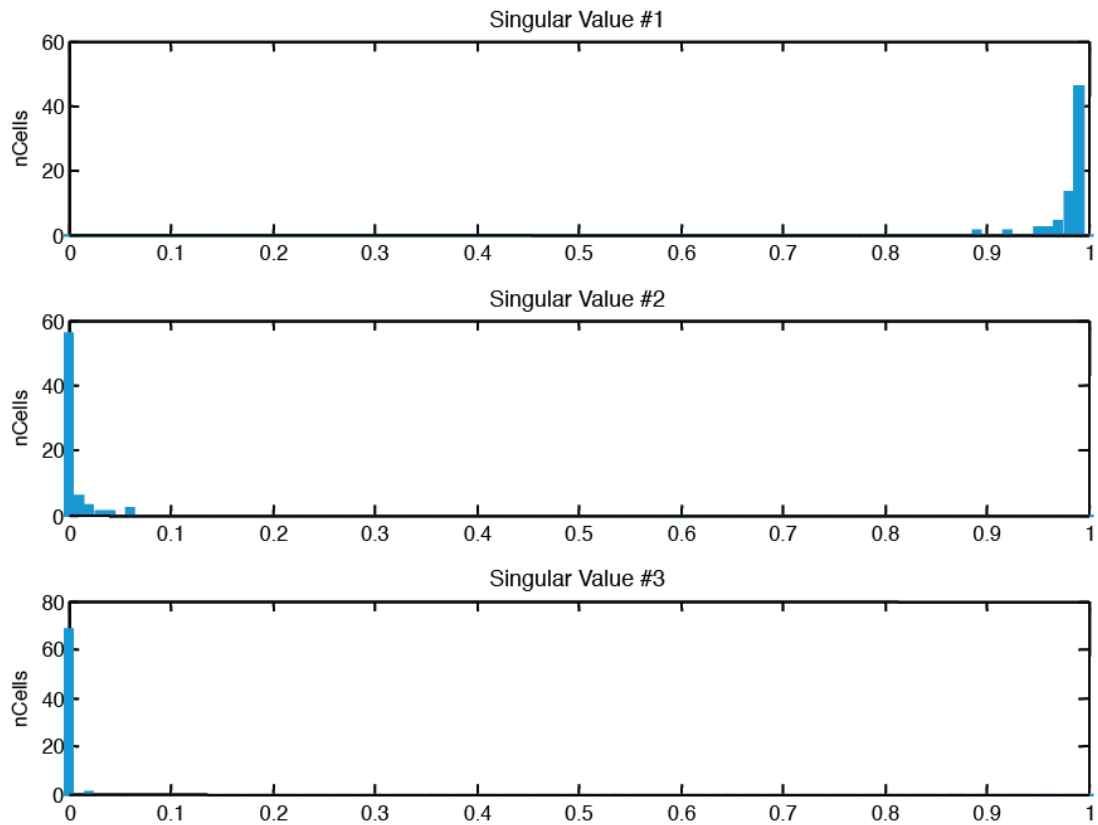
Figure 1.4 – SVD Analysis. The first three singular value weights are shown for the population of 69 neurons.

A related approach for evaluating separability in these data was taken by calculating how well a predicted response matrix correlated with the observed data. First, this prediction was performed using just the first singular prediction from the SVD analysis. This prediction represents the best linear combination (i.e., separable) of the direction and disparity tuning vectors from the SVD analysis. If the data and the linear prediction are very similar, then it can be said that a linear combination of

direction and disparity tuning predicts the joint tuning very well. Figure 1.5A shows

the measured joint tuning (normalized) of the same example neuron shown in Figure

1.2. The prediction from the first singular vectors for this example neuron is shown in

Figure 1.5B. This prediction is generated by multiplicatively combining the calculated

first singular direction and binocular disparity vectors. This separable prediction is

very similar to the measured data as the correlation (R^2) between the two matrices is

0.99. This correlation means that the SVD prediction could account for 99% of the

measured variance in this neuron's joint tuning and demonstrates that the tuning for

these two features is highly separable in this neuron. Figure 1.5D shows that high

correlation (R^2) values were common in the population. The population mean

correlation value was 0.97 and the median was 0.98, which indicates that the separable

model created from the first singular vectors of each neuron accounts for an average of

97% of the observed variance in the population. This is strong evidence that direction

and binocular disparity tuning are almost entirely separable in these neurons.
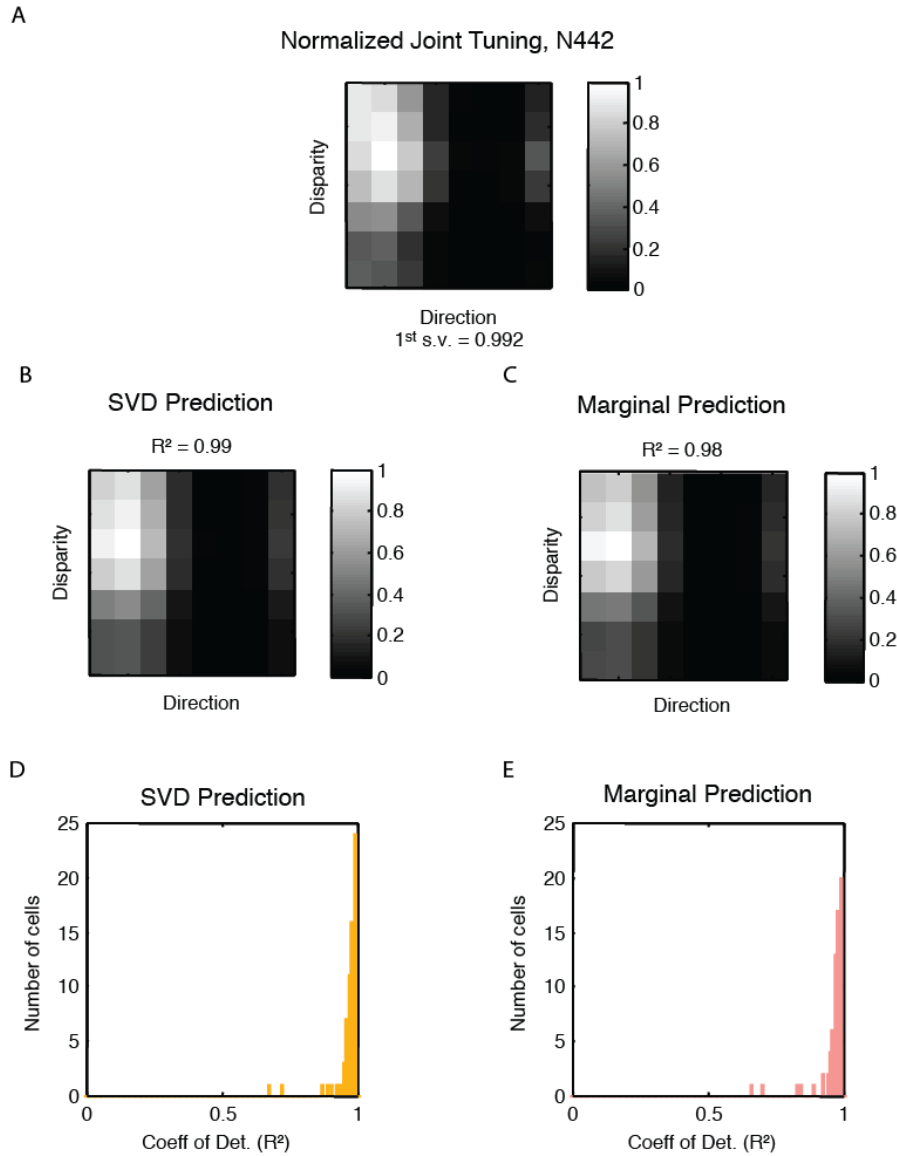
Figure 1.5 – Separability of binocular disparity and direction of motion tuning. (A) The normalized joint tuning from the example neuron in Figure 1.2. (B) The fully separable prediction for this neuron using just the first singular values from the SVD analysis. The correlation between the predicted response and the observed data is shown. (D) Each neuron's correlation between the predicted response using the first singular value and the observed data for the population. (C) The fully separable prediction using the marginal tuning for each feature. The correlation between the predicted response and the observed data is shown. (E) Each neuron's correlation between the predicted response using the marginal tuning and the observed data for the population.

These results were confirmed using the marginal tuning curves for each feature to predict joint tuning. Marginal direction and binocular disparity tuning curves were calculated for each neuron by collapsing across the other dimension (e.g., summing spike counts for a given direction, regardless of the disparity). The matrix product of each tuning curve was calculated and the correlation (R^2) between the measured and predicted combined tuning was computed. Again, it is worth noting that the predicted tuning is, by definition, a perfectly separable combination of the two measured tuning curves. Figure 1.5C shows the marginal prediction for the example neuron. The correlation (R^2) value between this prediction and the observed data is 0.98, demonstrating a strong correlation between the observed data and the perfectly separable, predicted data. Figure 1.5E shows that high correlation values were common in the population. The population's mean correlation value was 0.97 and the median was 0.98, which indicates that the separable marginal prediction model accounts for about 97% of the observed variance and argues that direction and binocular disparity tuning are almost entirely separable. These two prediction measures are slightly different, but both reveal a comparably high degree of separability in the population's tuning for direction and binocular disparity.

Picking a preferred direction

An additional question that can be addressed with these data is whether the value at which one of these features is presented will affect the selection of the preferred value of the other feature. A neuron's direction tuning is often characterized by its mean vector, whose angle corresponds to the neuron's preferred direction and

whose magnitude corresponds to the neuron's tuning width. Therefore, the angle of the mean vector calculated at each binocular disparity will signify how much the estimate of the neuron's preferred direction changed as a function of the binocular disparity of the stimulus. This is a particularly relevant question as direction tuning is usually performed first when recording in MT.

Figure 1.6A shows the mean vectors that were calculated at each of the 7 binocular disparities from the example cell in Figure 1.2. It is clear that the calculation of the preferred direction at each binocular disparity is similar for this neuron. In fact, the maximum angular distance between any pair of these vectors is 6.8° and the average of all pair-wise comparisons is 2.7°. Figures 1.6B and 1.6C show the population distributions for both of these measures. For approximately 80% of neurons, the largest angular distance between the measured mean vectors was less than 20°, and the population median was 10.7°. Larger maximum distances in both plots tended to arise from cells with weaker direction tuning. In these cases, the calculation of the mean vector's angle is affected more strongly by noise. Most cells had an overall pair-wise average difference of less than 10°, with a population median of 4.7°. These results make it clear that, for most neurons, the correct preferred direction can be determined regardless of the binocular disparity of the stimulus that is used.
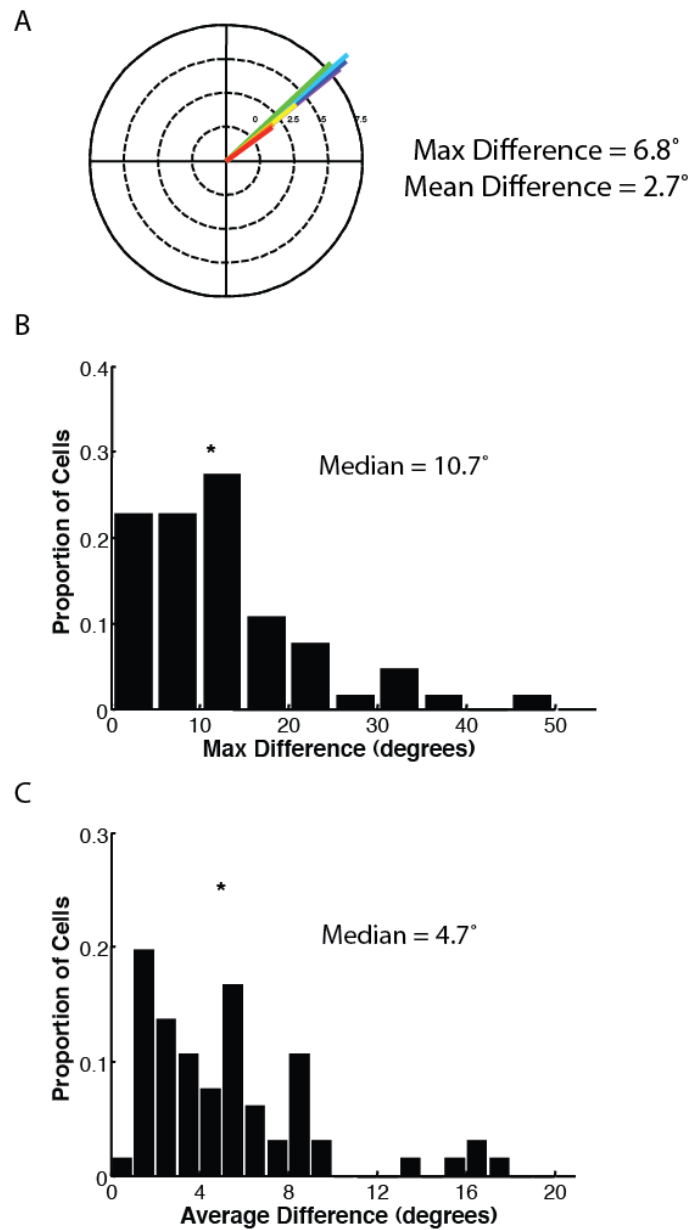
Figure 1.6 – Identifying the preferred direction. (A) The mean vectors from the example cell shown in Figure 1.2 with the maximum difference between any two vector angles calculated at different disparities and the average difference between all pair-wise differences of the mean vectors. (B) The population max differences between any two mean vector angles, the asterisk signifies the median. (C) The population distribution of the average between all pair-wise differences of the mean vector angles. The neurons with the largest values in both B and C tended to be weakly direction tuned.

Summary

Direction and binocular disparity tuning in MT are largely separable. These results suggest that MT neurons have relatively fixed tuning preferences for direction and binocular disparity. This informs the study that will be presented in the following chapter where a neuron's tuning preferences for direction and binocular disparity are assumed to be fixed. Additionally, serially defining a neuron's preferred direction and then its preferred disparity is not likely to lead to major errors in the estimation of a neuron's preferred disparity. This is particularly true for strongly direction tuned neurons, which are the vast majority of the neurons in area MT.

Chapter 2

Attention to Stimulus Features in Visual Area MT Depends on

Tuning Strength

The following chapter is an expanded version of a manuscript that will be submitted.

Abstract

Visual attention directed to a stimulus feature enhances the response of sensory neurons that represent that feature. The feature-similarity gain model proposes that the critical factor determining this enhancement is the match between a particular feature of the attended stimulus and the tuning preferences of a neuron. This model requires the existence of a top-down mechanism that globally modulates neurons with a similar preference for a given feature. We hypothesized that any mechanism that can distinguish the preferred and null values for a feature should also be sensitive to the magnitude of the difference between these two extremes. Using a novel form of feature attention, that for binocular disparity in visual area MT, we found that a neuron's tuning strength is a good predictor of feature attention effects, suggesting that the feature attention system accounts for how well a neuron represents the features contained in an attended stimulus.

Introduction

Attention directed to a specific stimulus feature has been shown to enhance the responses of sensory neurons that represent that feature, irrespective of their spatial receptive fields. Early studies of feature attention (FA) in the middle temporal area (MT) of primate visual cortex have suggested that the critical element for these effects was the match between the value of a particular feature contained in the attended stimulus and a neuron's tuning preferences for that feature —the so-called "feature-similarity gain" (FSG) model (Martinez-Trujillo & Treue, 2004; Maunsell & Treue, 2006). The FSG model requires the existence of a top-down mechanism that can globally modulate neurons with a similar preference for a given feature. Several studies have found evidence for such modulation in both the human (Beauchamp, Cox, & DeYoe, 1997; Jehee, Brady, & Tong, 2011; Kamitani & Tong, 2006; O'Craven, Downing, & Kanwisher, 1999; Saenz et al., 2002; Stoppel et al., 2011; Wojciulik, Kanwisher, & Driver, 1998) and non-human primate brain (Bichot, Rossi, & Desimone, 2005; Chelazzi et al., 1998; Cohen & Maunsell, 2011; Haenny, Maunsell, & Schiller, 1988; Katzner, Busse, & Treue, 2009; Martinez-Trujillo & Treue, 2004; McAdams & Maunsell, 2000; Treue & Martinez-Trujillo, 1999; Zaksas & Pasternak, 2005).

We hypothesized that any mechanism that can distinguish the preferred and null values for a certain feature should also be sensitive to the magnitude of the difference between these two extremes. Thus we tested whether a neuron's "tuning strength," as measured by the index (Pref – Null) / (Pref + Null), for a given stimulus feature could predict modulation by feature attention to that same feature.

To gain better leverage on this question, binocular disparity (BD), a property for which most MT neurons are tuned (DeAngelis & Uka, 2003; Maunsell & Van Essen, 1983a) and for which there is a topographic representation in area MT (DeAngelis & Newsome, 1999) was used. It is important to note that there is a wide range of BD tuning strengths across the MT population (DeAngelis & Uka, 2003), in contrast to tuning for direction of motion, for which nearly all MT neurons exhibit very strong modulation (Albright, 1984; Maunsell & Van Essen, 1983b). First, we identified a novel FA effect for BD in MT, in addition to the previously reported effects for direction of motion (Treue & Martinez-Trujillo, 1999). Feature attention for BD also follows the prediction of the FSG model, its presence does not require a perceptual judgment about BD, and FA effects for either feature cannot be explained by bottom-up, stimulus driven effects. Finally, because of the variability of BD tuning strength in MT, we found the predicted relationship between a neuron's BD tuning strength and the magnitude of modulation by BD feature attention. These results suggest that the feature attention system is wired up in a way that accounts for how well a neuron represents the features contained in an attended stimulus.

Results

Psychophysical Performance

Monkeys performed a reaction time task in which they made a saccade to an attended stimulus when they detected a randomly timed increase in its speed (Figure 2.1A). As previously described (Price & Born, 2010), behavioral performance depended on the Weber fraction, which is the size of the speed change divided by the

reference speed. Smaller speed ratios were associated with more frequent misses and longer reaction times. The amount of the stimulus's speed increase was randomly selected from a small range of values in order to encourage the animal to work hard and enforce behavioral performance to be near 70% correct. Figure 2.1B depicts detection performance as a function of change amount for an example recording session from animal N and P, respectively. Behavioral thresholds were defined as the speed change amount that led to an 80% detection rate. The thresholds from the two example sessions were a 30% speed increase for monkey N (left) and a 19% speed increase for monkey P (right). From the behavior collected during the neuronal recordings included in this study, the median threshold for monkey N was a 30% (± 9.3% standard deviation) speed increase, and a 20% (± 4.4% standard deviation) increase for monkey P. For the two animals, fixation breaks and early responses accounted for an average of 24% of trials across sessions. Of trials where the speed change occurred, it was correctly detected 71% of the time (69% for monkey N, 73% for monkey P) while the remaining 29% of speed changes failed to be detected and were classified as misses.
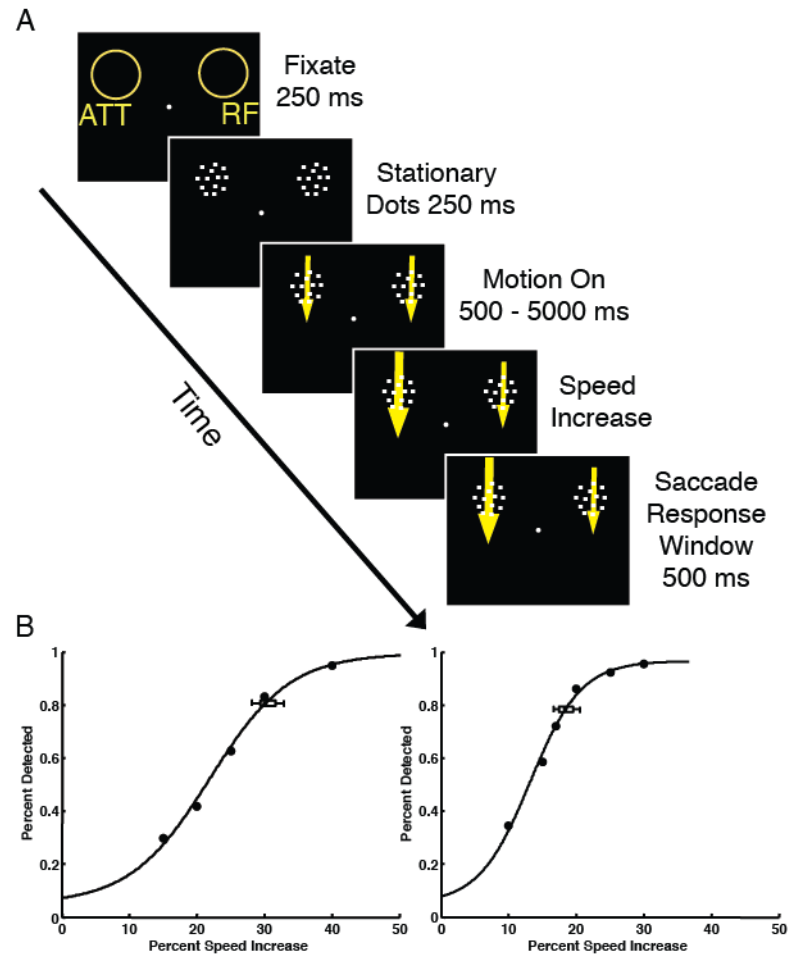
Figure 2.1 - Task design and stimulus configurations. (A) Illustration of behavioral task. (B) Behavioral performance from example recording session from monkey N and P, respectively. Box plot signifies 95% confidence intervals (via bootstrap) of threshold estimation (at 80% detected).

Analysis of Neuronal Activity

Single Neuron feature attention effects for binocular disparity

For the first experiment reported here, the unattended stimulus in the receptive field of the MT neuron being recorded from always moved in the neuron's preferred (PREF) direction at its PREF disparity. The role of this stimulus was to drive the neuron under study but it was not behaviorally relevant. To establish the presence of feature attention for binocular disparity and direction of motion, on any given trial, a second, attended stimulus was presented in one of four configurations in the opposite hemifield; either at the neuron's PREF direction and PREF binocular disparity, its PREF direction and NULL binocular disparity, its NULL direction and PREF binocular disparity, or its NULL direction and NULL binocular disparity.

The responses of a single neuron from correct trials during the main task are shown aligned to the onset of stimulus motion (Figure 2.2A) and to the time of the speed change (Figure 2.2B). The spike density functions depict the neuron's response to the same unattended stimulus in its receptive field, which is a random dot patch moving in the neuron's PREF direction at its PREF binocular disparity. The differences between the traces are due exclusively to the animal attending to the distant stimulus, which was presented in one of four possible combinations of the PREF and NULL directions and binocular disparities (color coded inset in Figure 2.2A). In the example neuron shown in Figure 2.2A and Figure 2.2B, the largest response occurred when the animal attended to the distant stimulus in which both features were presented at the neuron's PREF values (Black) and the weakest response when both were NULL values (Green). Intermediate levels of response occurred for

the two PREF/NULL combinations: Attending to a stimulus moving in the neuron's NULL direction at its PREF binocular disparity (Red) yielded only a slightly lower response than the PREF/PREF combination, and attending to a stimulus moving in the neuron's PREF direction at its NULL disparity (Blue) yielded a much lower response. These same data are shown aligned to the time of the speed change in Figure 2.2B, where the same pattern of attentional effects is apparent. Three additional single neurons are shown aligned to the time of the speed change to demonstrate examples of the heterogeneity observed in the population (Figure 2.2C-E). Figure 2.2C depicts a neuron that exhibits larger attentional modulation for direction of motion than for binocular disparity. This pattern of modulation was most common in the population. Figure 2.2D depicts a neuron with somewhat comparable feature attention modulation to both direction of motion and binocular disparity. Figure 2.2E shows an example neuron with positive attentional modulation for binocular disparity, but negative attentional modulation for attending to the PREF direction of motion. This example cell highlights the observation that the attentional effects for each feature could be of either sign.

Single trial firing rates were calculated from spike counts that occurred in a 250 ms window of time that immediately preceded the speed change on correct trials and, using these data, we performed significance tests and calculated attentional indices (see Methods). Results from the two animals were quantitatively similar and have been combined. A 2 x 2 ANOVA on square-root transformed firing rates revealed a significant main effect of direction in 57 neurons (28%) and a significant main effect of binocular disparity in 44 neurons (21%). Twelve neurons (5.8%)

exhibited significant main effects for both features, which is what would be expected

if the two effects occurred independently within our population of 207 neurons and

only co-occurred by chance (p > .05, χ^2 test). Seventeen cells (8.2%) showed a

significant interaction between attention to direction and binocular disparity. The way

in which the two attentional effects combine will be addressed further, below.
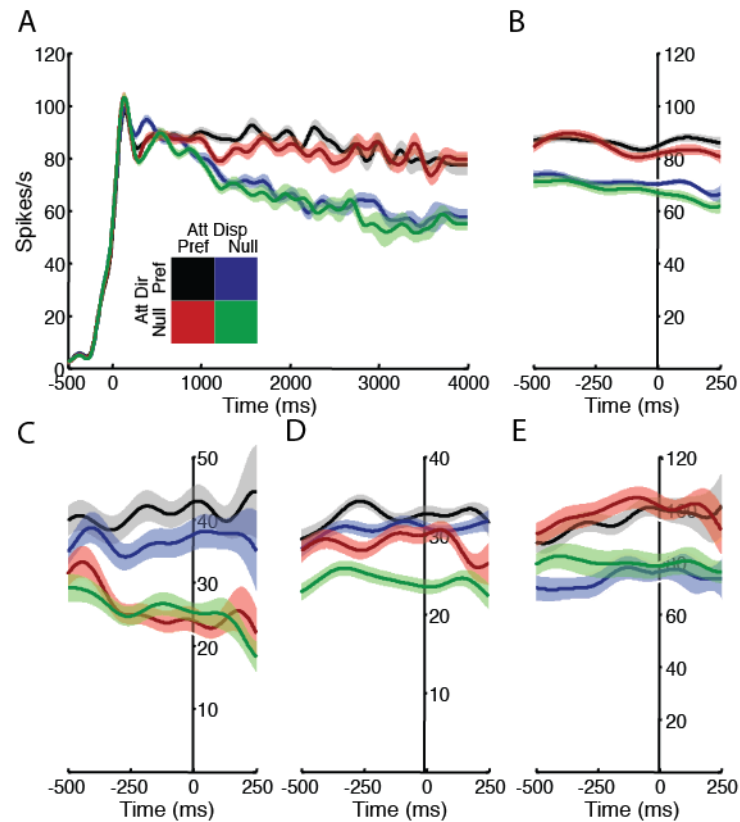
Figure 2.2 - Feature-based attention in area MT to binocular disparity and direction of motion in single neurons. Four example cells are shown. (A) Spike density function aligned to stimulus onset from an example cell, shaded area is SEM. The inset of A is the legend for the four attentional conditions. For each condition, the stimulus in the receptive field is moving in the preferred direction at the preferred binocular disparity. (B) The same cell as in (A) but aligned to the time of correctly detected speed changes. This cell exhibited large feature based attentional modulation for binocular disparity (Disp FA = .086; Dir FA = .017). (C – E) Three additional example cells, aligned to the time of the correctly detected speed change. (C) (Disp FA = .077; Dir FA = .28); (D) (Disp FA = .018; Dir FA = .04); (E) (Disp FA = .12; Dir FA = -.031).

Population Summary of Feature attention effects

Figure 2.3 depicts the population distribution of attentional indices for both binocular disparity (Figure 2.3A) and direction of motion (Figure 2.3B) for 207 neurons recorded from two monkeys. Both distributions are significantly shifted to the right (binocular disparity FA mean = 0.014, Wilcoxon signed rank test $p < 0.005$; direction of motion FA mean = 0.026, Wilcoxon signed rank test $p < 0.001$), demonstrating an increase, on average, in the population's firing rate as a function of attending to the preferred relative to the null value of each feature. The population's feature attention effect for direction is significantly larger than the effect for binocular disparity (Wilcoxon paired signed rank test $P < .05$). The observation of feature attention effects for direction of motion in area MT replicates previous work done by Treue and Martinez-Trujillo (Martinez-Trujillo & Treue, 2004; Treue & Martinez-Trujillo, 1999).

A

Disparity Feature Attention
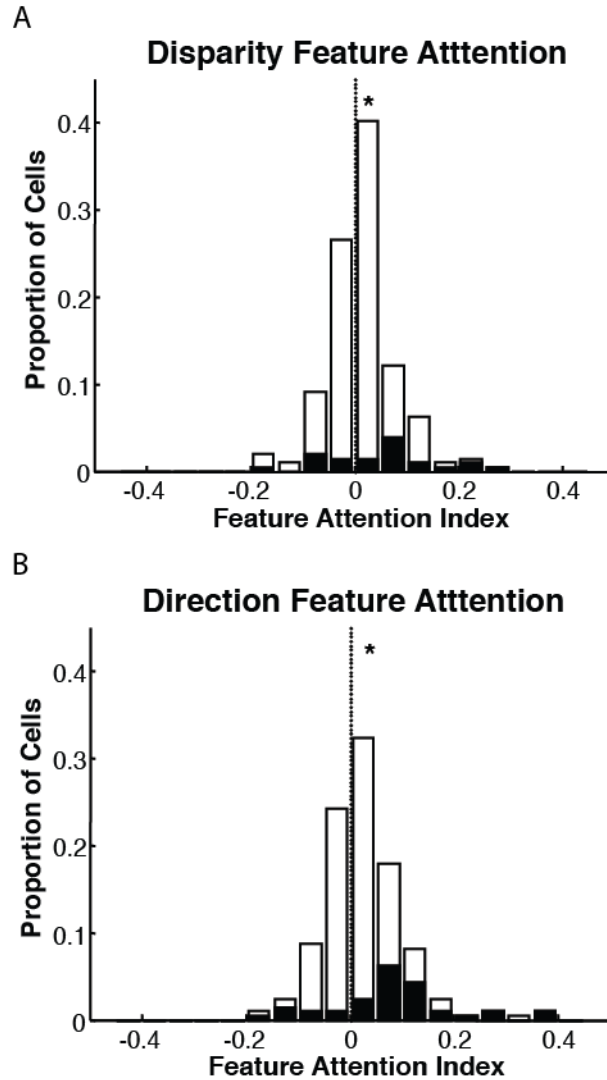
B

Direction Feature Attention

Figure 2.3 - Population feature-based attentional modulation to binocular disparity and direction of motion. Attention indices for each feature, (A) binocular disparity, (B) direction of motion. The asterisk on each plot signifies the population mean, black portions signify significant cells as determined from Wilcoxon test.

In an effort to determine how feature attention effects for these two features combine in single neurons, two models were created that each attempted to predict a neuron's response during the condition when the animal attended to the stimulus that contained the NULL value of each feature using the responses from the other three conditions. In one model, the effects of attention were combined multiplicatively; in the other model, the effects of attention were combined additively. The model that combined attentional effects multiplicatively was significantly better than the additive model at predicting the response during the fourth condition across the population (Wilcoxon paired signed rank test of the prediction error from each model, $p < 0.001$). Despite this statistical significance, the absolute differences between the predictions of the two models were quite small. In fact, the difference between the two model's predictions was, on average, less than 1 spike (median $= .11$, mean $= .36$). This small difference in the predictions of each model is due to the overall small feature attention effect sizes observed in the population and these results should be interpreted cautiously. Similar results were obtained when the models predicted the responses to the stimulus that contained the PREF value of each feature using the three remaining conditions.

Interestingly, both models predicted the response during the NULL/NULL condition to be lower than was actually observed. The median prediction from the multiplicative model was 1.9 spikes lower than was actually observed, while the median prediction from the additive model was 2.1 spikes lower than the observed response. The population distribution of these small differences between the prediction and the observed data were significantly different from zero (Wilcoxon ranked sum, p

< .01) and suggest that there may be some small non-linear component when feature attention effects for different features combine. Again, similar results were obtained if the models were designed to predict the responses to the stimulus that contained the PREF value of each feature using the three remaining conditions.

Does FA for binocular disparity support the FSG model?

After establishing the presence of feature attention for binocular disparity in area MT, these effects were tested to determine whether they support the FSG model. Because the unattended stimulus in the receptive field moved in the neuron's preferred direction at its preferred binocular disparity, there are two potential explanations for the feature attention effects that were observed. The first is that the modulation is the result of attentional enhancement due to feature matching (FM), i.e., a match between the features contained in the attended stimulus and the features of the unattended stimulus in the neuron's receptive field (Motter, 1994). The other potential explanation is that the unattended stimulus in the receptive field is irrelevant for this modulation and instead, the relationship between the value of an attended feature and a neuron's tuning preference for that feature is critical for feature attentional modulation. This latter possibility is formalized in the FSG model (Martinez-Trujillo & Treue, 2004; Maunsell & Treue, 2006). To test which of these hypotheses best explains the results for feature attention to binocular disparity, data from 44 neurons (21 from monkey N) were collected in conditions where the stimulus in the receptive field could be presented at either the PREF or NULL value of a neuron's direction and binocular disparity tuning. Therefore, these two hypotheses could be directly tested as to

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whether the observed attentional modulation is due to the attended stimulus matching the unattended stimulus in the receptive field (FM model) or because the attended stimulus contained the value of a feature that the neuron prefers (FSG model). If the FM model is correct, the response to a NULL stimulus in the RF should be enhanced when the animal attends to the corresponding NULL stimulus relative to when the animal attends to the PREF stimulus, whereas the predicted pattern is opposite under the FSG model (Figure 2.4).
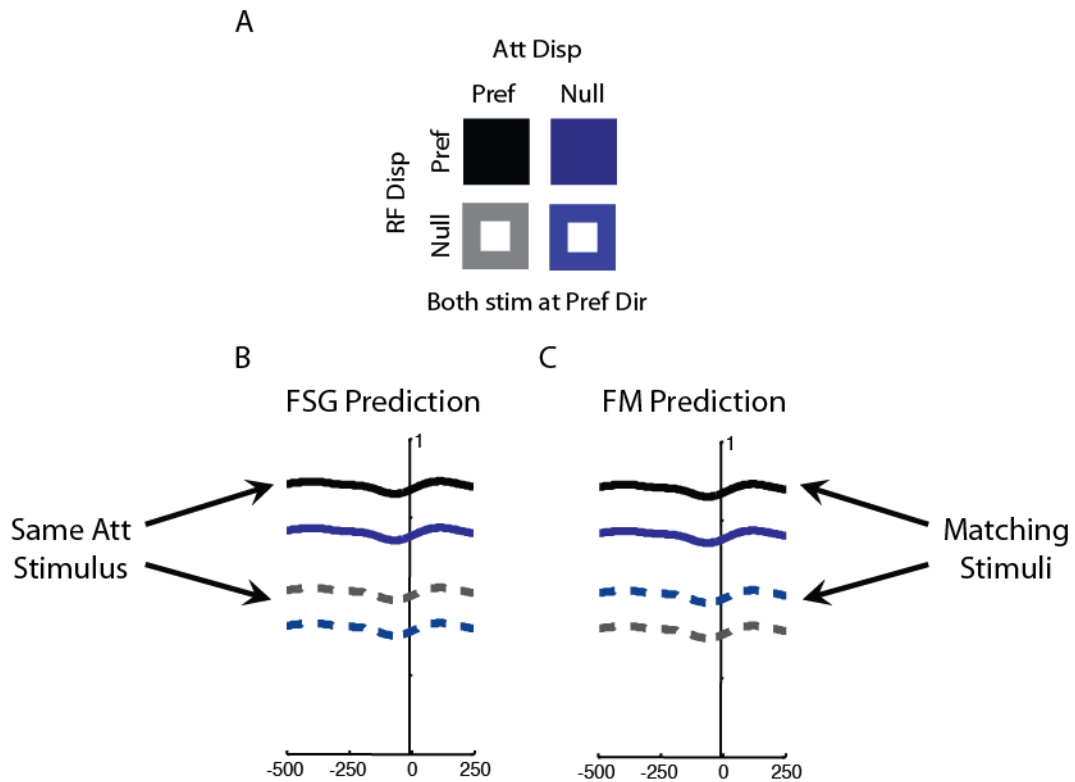
Figure 2.4 - Model predictions. (A) Color code used for displaying stimulus conditions when both stimuli can be presented at either the PREF or NULL binocular disparity. Both stimuli are presented at the neuron's PREF direction (B) Predicted responses if feature similarity gain (FSG) model is true. Attending to the stimulus at the neuron's PREF binocular disparity leads to a larger response regardless of the stimulus in the RF. (C) Predicted responses if feature matching (FM) model is true. Attending to the stimulus that matches the stimulus that is currently in the neuron's RF leads to a larger response.

Figure 2.5A shows the responses of an example neuron, aligned to the time of the speed change on correct trials, for the four conditions used to test these hypotheses for feature attention for binocular disparity. Feature attention for binocular disparity was tested for in the same way as previously described; by changing the binocular disparity of a distant attended stimulus to be at either the neuron's PREF or NULL binocular disparity while the stimulus in the receptive field was at the neuron's PREF binocular disparity (black and blue solid lines). Additionally, conditions were introduced with the identical attended stimuli but where the stimulus in the receptive field was presented at the neuron's NULL binocular disparity (gray and dark blue dashed lines). These responses are in line with those predicted by the FSG model: the neuron's response to an identical stimulus in the receptive field is enhanced when the animal attends to the PREF binocular disparity, regardless of the match between the attended stimulus and the stimulus in the neuron's receptive field. For all responses in this panel, both stimuli were presented moving in the neuron's PREF direction.
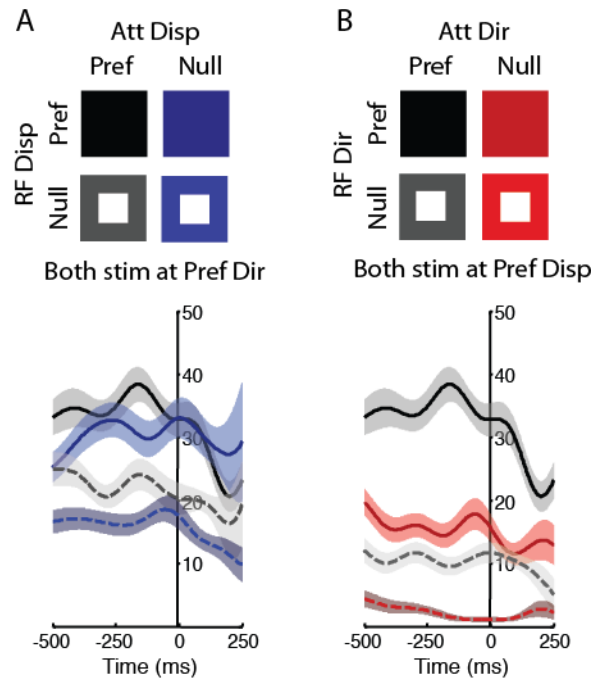
Figure 2.5 - Testing the feature similarity gain model. (A) Four conditions used to test the feature similarity model for attention for binocular disparity and the responses to these conditions from an example neuron. (Disparity, Pref FA = .045; Disparity, Null FA = .14) (B) Four conditions used to test the feature similarity model for attention for direction of motion and the responses to these conditions from the same example neuron as (A) (Direction, Pref FA = .39; Direction, Null FA = .7).

Figure 2.5B shows the responses of the same example neuron as in Figure 2.5A, aligned to the time of the speed change on correct trials, for the four conditions used to test these hypotheses for feature attention to direction of motion. Feature attention for direction of motion was tested for in the same way as previously described: by changing the direction of motion of a distant attended stimulus to be moving in either the neuron's PREF or NULL direction while the stimulus in the receptive field moved in the neuron's PREF direction (black and red solid lines). Additionally, conditions were introduced with the identical attended stimuli but where the stimulus in the receptive field moved in the neuron's NULL direction (gray and dark red dotted lines). Again, the responses are in line with those predicted by the FSG model: the neuron's response to an identical stimulus in the receptive field is enhanced when the animal attends to the PREF direction of motion, regardless of the match between the attended stimulus and the stimulus in the neuron's receptive field. For all responses in this panel, both stimuli were presented at the neuron's PREF binocular disparity.

Figure 2.6 shows the population attention indices when the NULL value of each feature was presented in the receptive field, corresponding to the dashed lines in Figure 2.5A and 2.5B. Positive attentional indices reflect that the important factor in feature attention modulation is the relationship between the attended feature and the neuron's tuning preference for the feature (FSG model), whereas negative indices would indicate that it is the match between the attended stimulus and the stimulus in the receptive field that is most important (FM model). The means of both populations are shifted to the right, supporting the FSG. The population's mean feature attention

index for binocular disparity does not reach significance (mean = 0.019 Wilcoxon signed rank test p < .3), but is close to the value that was observed in the larger population (overall population mean = 0.014, see Figure 2.3). This result will be revisited in the next section. The population's mean feature attention index for direction of motion is significantly shifted to the right (mean = 0.15, Wilcoxon signed rank test p < .01). This mean is larger than the value reported for the larger population (overall population mean = 0.026, see Figure 2.3). This is likely due to the fact that the firing rates on these trials could be quite low because of the presence of a null direction stimulus in the receptive field. Because of the nature of this index, small differences in firing rates at extremely low firing rates can lead to relatively large index values, hence several cells with attentional indices near 1 or -1. These results replicate the effects for direction of motion previously observed by Martinez-Trujillo and Treue (Martinez-Trujillo & Treue, 2004) and demonstrate that feature attention for binocular disparity further supports the FSG model.
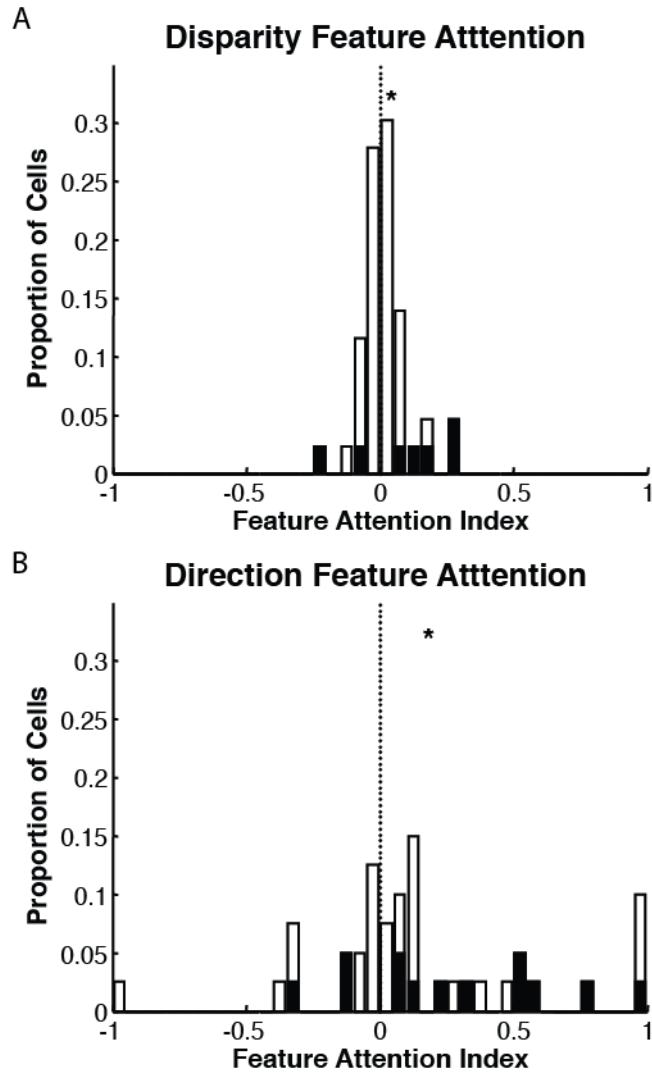
Figure 2.6 - Population attention indices testing the feature similarity gain model for feature-based attention to binocular disparity and direction of motion. Attention indices for each feature, (A) binocular disparity and (B) direction of motion calculated with the null value of each feature in the receptive field. The asterisk on each plot signifies the population mean, black portions signify significant cells as determined from Wilcoxon test. A shift to the left would provide support for the FM model, a shift to the right would suggest that the FSG model is correct.

Feature attention and tuning strength

We hypothesized that because the attentional system can distinguish a neuron's preferred and null tuning preferences for a feature, it should also be sensitive to the magnitude of the difference between these two extremes. Previous studies have shown that neurons in area MT are more strongly tuned for direction than they are for binocular disparity (DeAngelis & Uka, 2003) and this was also true for our population. All of the cells included in the population data had statistically significant differences in firing rate between the preferred and null values of each feature, as determined during quantitative tuning data acquired prior to the main task (see Methods). Neurons that did not meet these criteria were excluded. The tuning strength of each neuron, as measured by a tuning strength index (Pref - Null) / (Pref + Null), for both binocular disparity and direction, are shown in Figure 2.7A and Figure 2.7B (binocular disparity mean index = .38; direction mean index = .81). As a point of reference, using a different modulation index that incorporates spontaneous firing rate, our population binocular disparity mean was .61, which is lower than the .73 measured by DeAngelis and Uka (2003; (Pref - Null) / (Pref - Spontaneous)). In addition to neurons being more strongly tuned for direction than for binocular disparity, there was also larger variance in the population's binocular disparity tuning. This greater range of tuning strengths allowed for testing whether there is a relationship between the strength of tuning for a feature and the amount of feature attention modulation that is observed.
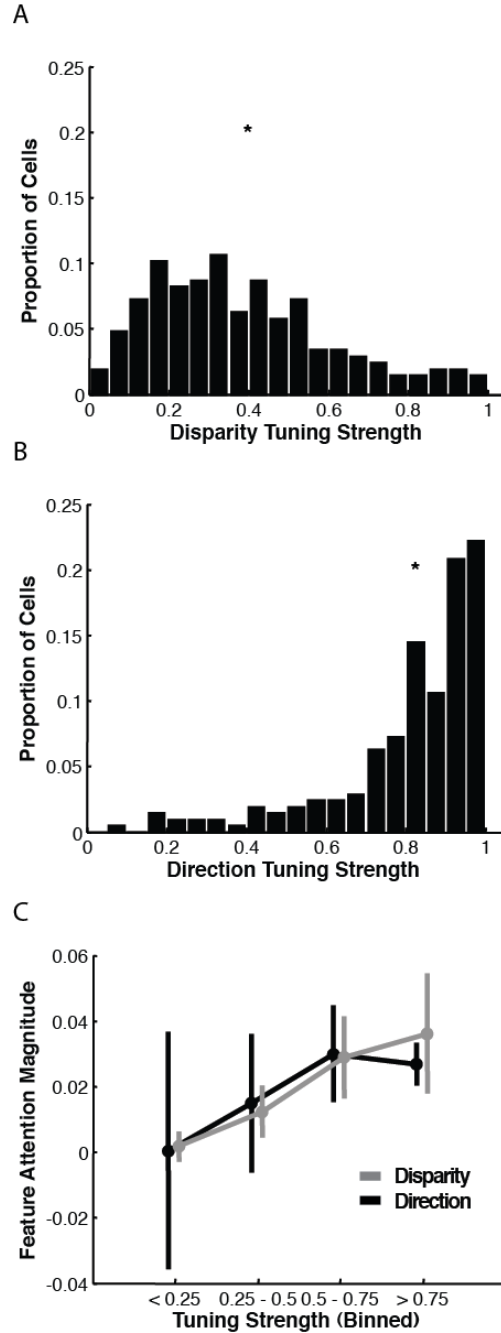
Figure 2.7 - The relationship between tuning strength and feature attention. (A) Population binocular disparity tuning strength. (B) Population direction tuning strength. Asterisks signify population means. (C) Relationship between tuning strength (binned by range) and feature attention for both binocular disparity (gray line) and direction (black line). Number of cells per bin, from weakest tuning to strongest for binocular disparity: 67, 83, 40, 17. For direction: 6, 12, 33, 156.

Figure 2.7C shows the feature attention values for each neuron plotted against an index of tuning strength for both binocular disparity and direction. As tuning strength increases, feature attention effects in the population tend to be larger. The cells from both the largest and second largest bins of binocular disparity tuning strength exhibit significantly larger feature attention modulation for binocular disparity than did neurons in the most weakly tuned bin (Wilcoxon ranked sum test p < .05 for each). There were insufficient numbers of weakly direction tuned cells in the population to perform the same test for direction (number of cells per bin, from low tuning to high: Direction 6, 12, 33, 156; Disparity 67, 83, 40, 17). This relationship is not an artifact of the binning procedure, as a significant correlation was observed for the relationship between tuning strength and binocular disparity (Spearman correlation $\rho = 0.18$, $p < .01$). This effect however, was not observed for feature attention for direction of motion and tuning strength (Spearman correlation $\rho = 0.021$, $p = .76$). Feature attention effect sizes among neurons with similar tuning strength are not distinguishable between the two features (Wilcoxon ranked sum test comparing the means of binocular disparity FA and direction FA amongst cells with similar tuning strength; Bin 0 - .25, $p = .34$; Bin .25 - .5, $p = .59$; Bin .5 - .75, $p = .43$; Bin .75 – 1, $p = .52$). On average, for the entire population of neurons, feature attention effects were larger for direction than they were for binocular disparity. These results suggest that the difference between the population's mean feature attention effects for the two features is likely attributable to the population's differences in tuning strength.

For reference, Figure 2.8 depicts several direction and binocular disparity tuning curves from different neurons, along with their tuning strength index values.

Other tuning metrics failed to reveal significant relationships with feature attention

effect size for direction. These metrics included bandwidth (calculated from fits to the

tuning curves), discrimination indices and modulation indices that included

spontaneous firing rates (see equations 1 and 2 from DeAngelis & Uka, 2003).

Discrimination indices for binocular disparity tuning did exhibit a significant

correlation with disparity FA (Spearman correlation $\rho = 0.16$, $p < .05$) but modulation

indices that included spontaneous firing rates did not (Spearman correlation $\rho = 0.10$,
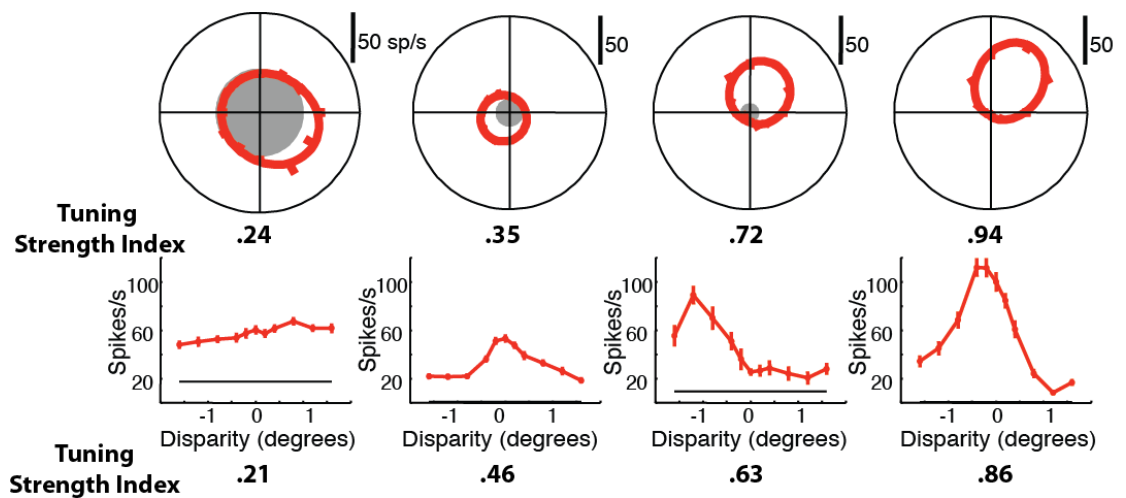
$p = .15$).

Figure 2.8 – Example feature tuning curves. Example direction (top row) and binocular disparity (bottom row) tuning curves from 8 different neurons from each of the four tuning strength bins. Error bars are standard error of the mean. Spontaneous firing rate is specified by a gray circle (top row) or a horizontal black line (bottom row).

With this relationship between tuning strength and feature attention in mind, the binocular disparity data presented in Figure 2.6 was revisited. Using just the neurons with binocular disparity tuning indices larger than .5 (10 neurons in this population) the population mean for binocular disparity was tested to determine whether these more selective neurons alone displayed FA effects consistent with the FSG model. The mean feature attention values for binocular disparity in this population were significantly shifted to the right and thus support the FSG model (disparity mean = .085, Wilcoxon signed rank test p < .05).

In order to determine how a neuron's tuning for both features affected the response during the condition where the animal attended to the stimulus made up of the null value of both features (NULL/NULL stimulus), an index was calculated that combined a neuron's tuning strength for direction and binocular disparity. To do this, the distance from the origin was calculated for each neuron on a plot of its direction versus binocular disparity tuning (Figure 2.9A). The distribution of these distances are plotted in Figure 2.9B (mean = .92, median = .96). These data were then binned into quartiles based on this measure of overall tuning strength and plotted against the feature attention indices calculated by comparing the responses of neurons when the animal attended to the stimulus made up of the pref value of both features (PREF/PREF stimulus) versus the NULL/NULL stimulus (Figure 2.9C) (black versus green lines in Figure 2.2). The neurons from the most strongly tuned quartile exhibited significantly larger feature attention modulation than did the most weakly tuned cells (Wilcoxon ranked sum test p < .05). Again, this relationship was not an artifact of the binning procedure, as a weak, but significant, correlation was observed for the

relationship between overall tuning strength and this measure of feature attention (Spearman correlation $\rho = 0.14$, $p < .05$). Further, no significant correlation was observed between the feature attention indices calculated during the PREF/PREF and NULL/NULL conditions and either feature's tuning strength in isolation (Spearman correlation with direction tuning strength, $\rho = .08$, $p = .24$; Spearman correlation with disparity tuning strength, $\rho = .11$ $p = .127$).
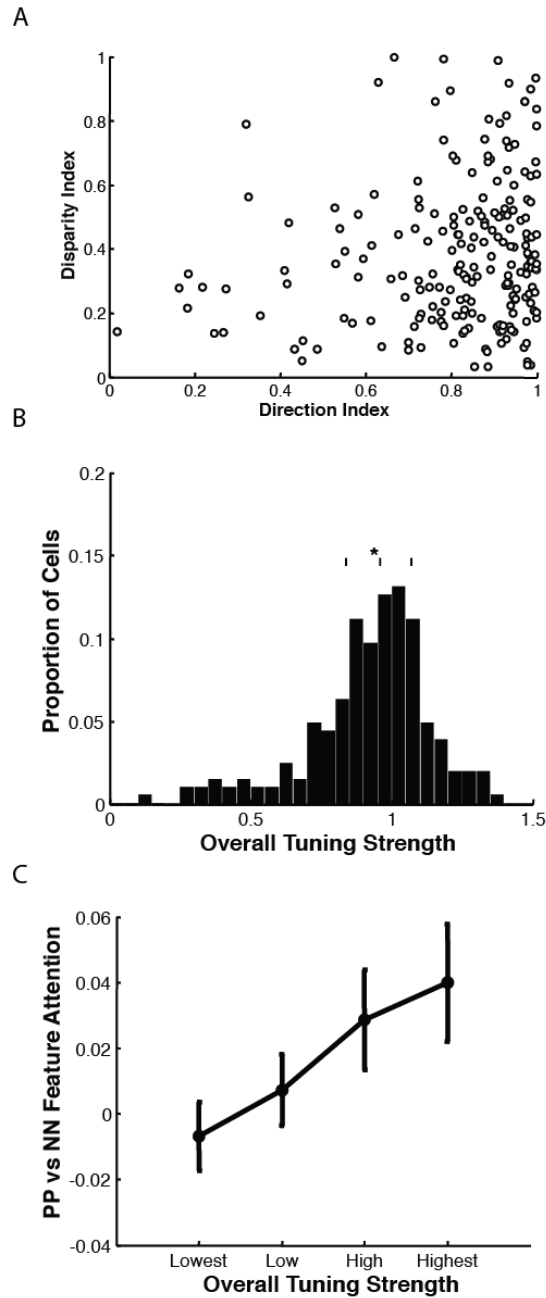
Figure 2.9 - The relationship between overall tuning strength and feature attention for both effects. (A) Scatter plot of direction and binocular disparity tuning indices. Each point is a single neuron. (B) Distribution of indices of the calculation of overall tuning strength for direction of motion and binocular disparity. Asterisk signifies mean and three bars signify quartile boundaries. (C) Relationship between overall tuning strength, binned into quartiles, and feature attention as calculated between the Pref/Pref and Null/Null conditions.

Are these effects the result of bottom-up causes?

Though care was taken to position the attended stimulus far away from the receptive field of the MT neuron under study (see Methods), the modulatory surrounds of MT neurons can extend for some distance and have been shown to include parts of the ipsilateral hemi-field (Albright & Desimone, 1987; Desimone & Ungerleider, 1986; Maunsell & Van Essen, 1987). In such cases, it is conceivable that the attended stimulus engaged the MT neuron's surround and produced the changes that were observed in a bottom-up manner and not via attentional modulation as has been proposed. When isolating neurons for the current study, moving dot stimuli were placed at the attended stimulus location while the animal fixated to ensure that the second stimulus would not directly elicit visually driven spikes. Further, data was collected prior to the start of the main task (in 199 of 207 neurons) where both stimuli were repeatedly flashed on and off for 250ms in all of the possible configurations used during the main experiment, while the animal was rewarded for fixating. Because each stimulus was presented very briefly, it was assumed that there would not be sufficient time for the animal to change its attentional posture and thus these data would isolate any purely visual modulation due to the second stimulus. However, one cannot rule out the possibility that the animal attended to either stimulus during this task.

Using the data collected during the rapid presentation of these stimuli, indices were calculated that were identical in their sensory components to those calculated during the attentional task (250ms window). The indices calculated with these data could not explain the attentional results observed at the population level during the main task (binocular disparity mean = .0051, Wilcoxon signed rank test p = .45;

direction mean = -0.00039, Wilcoxon signed rank test p = .13). In addition, for each

neuron an ANOVA was performed on these data that was identical to the one

performed on the main task data. Fifteen neurons were found with a significant main

effect of having the second stimulus at the preferred versus null binocular disparity, 7

of which had a positive effect, 8 a negative effect. Thirty neurons were found to have a

significant main effect of the second stimulus moving in the preferred versus null

direction, 12 of which had a positive effect, 18 a negative effect. A total of 4 neurons

had a significant main effect for binocular disparity during both the control experiment

and the main attentional task (1 positive, 3 negative) while 11 neurons had a

significant main effect for direction of motion during both the control experiment and

the main attentional task (6 positive, 5 negative). Excluding only those cells with a

significant main effect from both datasets before calculating feature attention indices

on the task data resulted in population mean values similar to those reported for the

entire dataset (binocular disparity FA mean = .0135, Wilcoxon signed rank test p <

.005; direction FA mean = .0231, Wilcoxon signed rank test p < .0001). Excluding all

neurons with a significant main effect during the control experiment from the main

task data resulted in mean population feature attention values that were nearly

identical to those reported above (binocular disparity FA mean = .0131, Wilcoxon

signed rank test p < .005; direction FA mean = .0231, Wilcoxon signed rank test p <

.0001).

These data show that the presence of the distant attended stimulus may have

led to direct stimulus effects in a small number of neurons in the population but that it

cannot fully account for the feature attention effects observed for either binocular

disparity or direction of motion. The other results presented in this paper do not change qualitatively if any of the subsets of cells highlighted by these data are excluded. Thus, these neurons have been left in the population data because of the ultimate ambiguity of whether feature attention effects could have been present during this control experiment.

Relationship of effects with firing rate

Additionally, the dependence of the observed effects on population firing rates was tested. First, the possibility was tested that feature attention effects are related to a neuron's firing rate. Such a relationship could be the result of neurons with firing rates in the tails of the population distribution exhibiting a floor or ceiling effect that could limit attentional modulation. Alternatively, neurons with low firing rates that were not driven well by the stimulus could fail to exhibit feature attention effects. To test for this possibility, the feature attention indices for each feature were plotted against the average firing rate that was observed on all trials, regardless of attentional condition, prior to the correctly detected stimulus change (Figure 2.10). No significant relationships were observed between firing rate and binocular disparity (spearman $\rho =$ -0.1, p = .15) or direction (spearman $\rho = 0.01$, p = .89) feature attention effects. Similar results were obtained using onset responses from the start of trials instead of the time prior to the speed change.
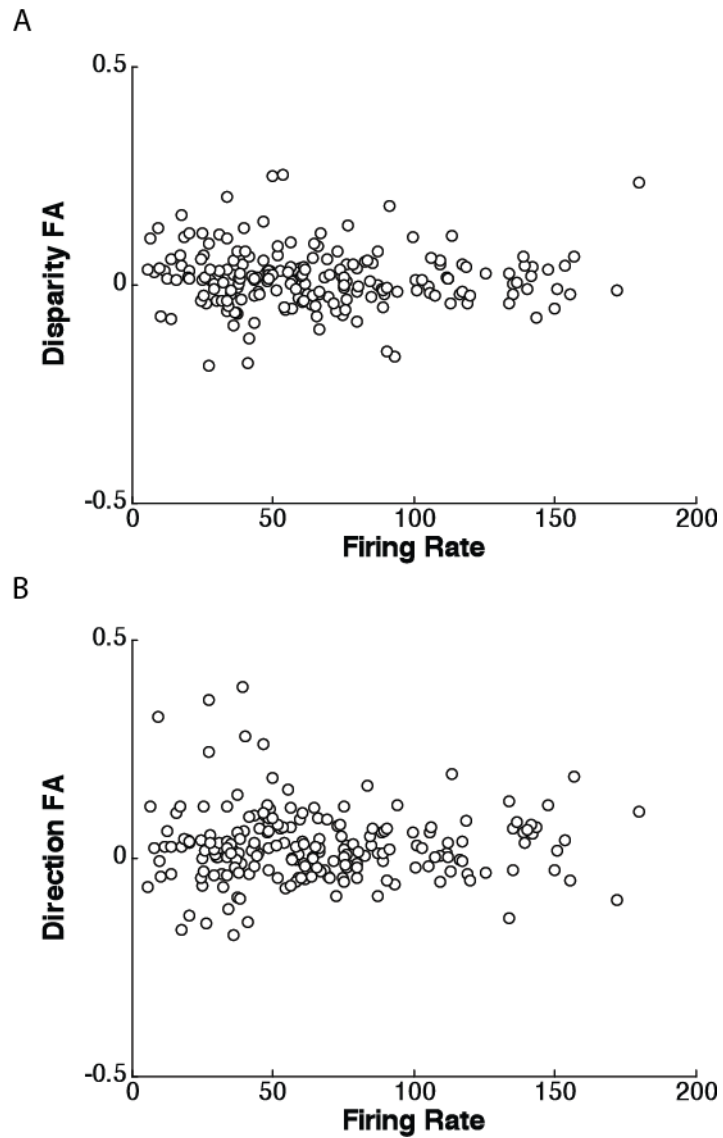
Figure 2.10 – Relationship between feature attention and firing rate. (A) Disparity feature attention effect sizes plotted against the average observed firing rate prior to correctly detected stimulus changes. Each data point represents the responses from one neuron. (B) Same as in (A) but with direction feature attention effect sizes.

A second possibility is that the measure of tuning strength that was employed was related to firing rates during the task. Such a relationship could be the result of weakly tuned cells also having low firing rates, or more generally, the existence of a floor or ceiling effect amongst neurons in the tails of the population distribution that would bias the measure of tuning strength. To address this possibility, each neuron's tuning strength for both features was plotted against the average firing rate that was observed prior to the correctly detected stimulus change, regardless of attentional condition, during the task (Figure 2.11). Again, no significant relationship was observed between either direction (spearman $\rho = 0.029$, $p = .68$) or binocular disparity (spearman $\rho = -0.02$, $p = .77$) tuning strength and the firing rate of the neurons during the task. Similar results were obtained using onset responses from the start of trials instead of the time prior to the speed change.
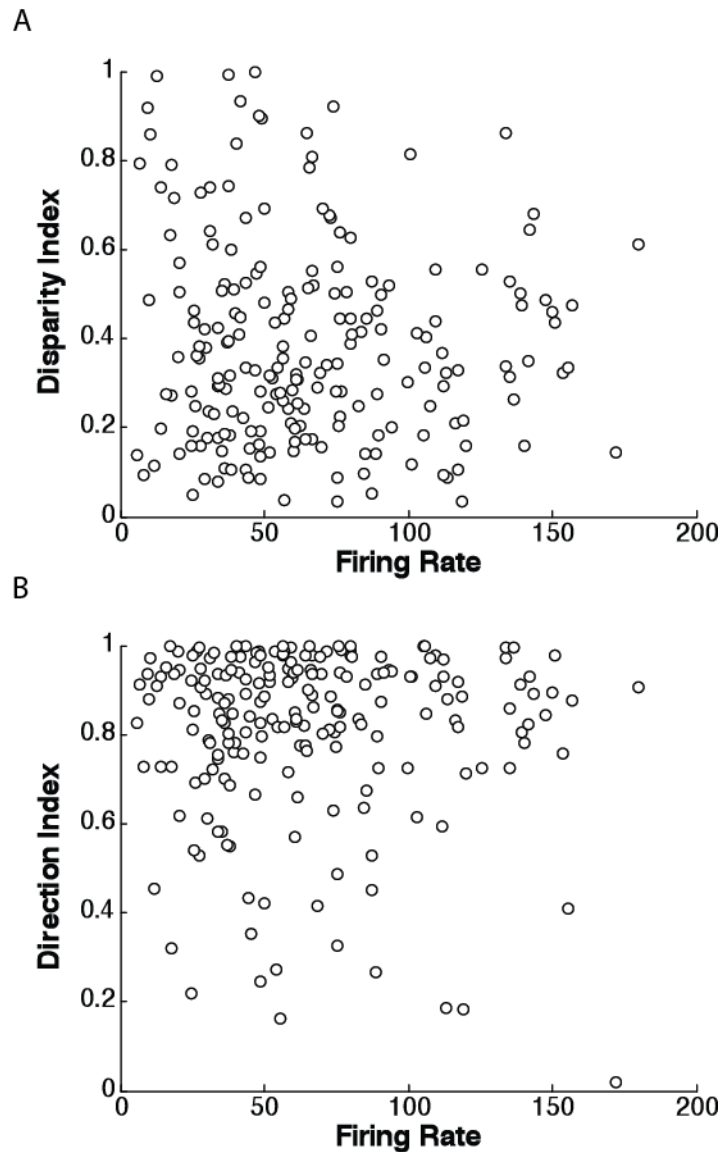
Figure 2.11 – Relationship between tuning strength and firing rate. (A) Disparity tuning strength indices plotted against the average observed firing rate prior to correctly detected stimulus changes. Each data point represents the responses from one neuron. (B) Same as in (A) but with direction feature attention effect sizes.

Discussion

Two monkeys were trained to attend to a moving stimulus while the responses of an MT neuron, whose receptive field was in the opposite hemifield and contained an unattended stimulus, were recorded. The firing rate of MT neurons was modulated by the feature values of the binocular disparity and direction of motion of this distant attended stimulus. These attentional effects could not be explained as being the sole result of bottom-up, stimulus driven effects and did not require the animal to perform a perceptual task that was directly relevant to either of these features. In support of the feature similarity gain (FSG) model (Martinez-Trujillo & Treue, 2004; Maunsell & Treue, 2006) the relationship between the features contained in an attended stimulus and the tuning preferences of a neuron were the critical factors that determine feature attention modulation for binocular disparity. It was hypothesized that feature attention effects would be sensitive to a neuron's tuning strength and a positive relationship between these two variables was observed. These results suggest that the feature attention system is wired in a way that accounts for the tuning preferences of a neuron as well as how strongly a neuron represents the attended features.

Extending the FSG Model

The feature similarity gain (FSG) model was proposed to explain the observation that attending to a stimulus outside of a neuron's receptive field can modulate a neuron's firing rate. This modulation was shown to depend on the relationship between the value of a feature contained in the attended stimulus and a

neuron's tuning preference for that feature. Support for this model has previously been found with feature attention effects for direction of motion in area MT (Martinez-Trujillo & Treue, 2004). The present study confirms this result and additionally observes that feature attention for binocular disparity, another feature to which MT neurons are sensitive, supports this model. Attention to stimuli across depths has been demonstrated (He & Nakayama, 1995) but a single neuron correlate of attending to different binocular disparities has not previously been described. Beyond replicating support of the FSG model using a novel feature, the results of this study extend the FSG model by demonstrating that feature attention effects can be found in neurons for multiple features including those to which they are not most strongly tuned (i.e., not just for direction of motion in area MT). This conclusion is supported by studies demonstrating that neurons in V4 exhibit task related feature attention effects for orientation, spatial frequency, shape and color (Bichot, Rossi, & Desimone, 2005; Cohen & Maunsell, 2011). In sum, these results suggest that feature attention effects may be found in conditions where an attended stimulus contains any of the suite of features to which a sensory neuron is tuned.

The FSG model posits that a stimulus that is placed in the receptive field of a neuron is not important for feature attention modulation. In the current study, changing the relationship between the attended and unattended stimuli did not alter feature attention effects. Strengthening these observations, Zaksas and Pasternak (2005) found feature attention effects in MT for direction of motion during a delayed match to sample task, even when there was no stimulus in a neuron's receptive field.

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While the results of the present study fully support the FSG model, a few notable studies have found results that are at odds with its predictions and instead support the FM model (Motter, 1994). For example, during visual search tasks, evidence to support the FM model has been found in area V4 (David et al., 2008; Zhou & Desimone, 2011). It is unclear, however, whether these effects are present in circumstances that don't require visual search.

Feature attention effects do not result from bottom-up causes

MT neurons have classical receptive fields (CRF) whose diameter tends to be slightly smaller than their eccentricity (Maunsell & Van Essen, 1987) and rarely extend into the ipsilateral hemifield by more than a few degrees (Albright & Desimone, 1987; Desimone & Ungerleider, 1986; Maunsell & Van Essen, 1987). In the current experiment, the attended stimulus was placed in the opposite hemifield from the neuron under study and was usually more than 10 -15° away, making it unlikely to directly excite the neuron's CRF.

Beyond an MT neuron's CRF is a large surround that can be either enhancing or suppressive (Allman, Miezin, & McGuinness, 1985; Born, 2000; Tanaka et al., 1986; Xiao et al., 1995, 1997). These surrounds have been shown to have complex response properties and often broad direction tuning (Hunter & Born, 2011; Pack, Hunter, & Born, 2005). Bradley and Anderson described surround sensitivity for binocular disparity that was most commonly suppressive and was independent of surround preferences for direction of motion (Bradley & Andersen, 1998). Most studies that have investigated surround effects have placed additional stimuli in

locations that are immediately adjacent to the CRF rather than in the opposite hemifield as was done in the current study. This placement argues for a diminished role of these surround effects in the data presented here.

Interestingly, there are prominent connections between MT neurons in opposite hemispheres that have matched RF locations. These connections can occur even at some distance from representations of the vertical meridian (Krubitzer & Kaas, 1990; Maunsell & Van Essen, 1987). While the stimuli in the present study were most often placed in symmetric locations across the vertical meridian, other studies have placed attended stimuli at different locations relative to a neuron's CRF and have still identified feature attention effects (for example, see Zaksas & Pasternak, 2005). These results suggest that bottom-up drive from cross-hemispheric connections is not the cause of feature attention effects.

Martinez-Trujillo and Treue (2004) dealt with concerns about surround effects due to the presence of the second attended stimulus by comparing the responses of MT neurons to identical stimuli in two different attentional conditions. While this did not directly address whether the second stimulus modulated the response of the neurons under study, it isolated the attentional effects that the authors were interested in studying. In the present study, a different approach to address these concerns was taken. Stimuli were rapidly flashed in the configurations that they would appear during the behavioral task while the animals were rewarded for fixating. This was done in an attempt to isolate the bottom-up component of a neuron's response to the two stimuli. While there is some reason to believe that attentional effects will not occur rapidly enough to appear during these experimental conditions, this possibility cannot be

completely ruled out with these data. In fact, several studies have reported evidence of feature attention effects that occur very quickly after stimulus onset in both macaques (Hayden & Gallant, 2005) and in early visual areas in the human brain (Schoenfeld et al., 2007; Zhang & Luck, 2009). Further, while the animals were rewarded for fixating during this task, their attention was not controlled and it is possible that it was directed to one or both of the stimuli. A small percentage of neurons whose responses were either significantly enhanced or suppressed by the second stimulus were identified during this experiment. Excluding these neurons from the population data did not qualitatively or quantitatively change the results, suggesting that the observed feature attention effects did not directly result from bottom-up stimulus driven causes and instead are the result of attentional modulation.

Feature attention effects are not necessarily task related

The present study has demonstrated that the behavioral task need not be explicitly related to the features being manipulated in an attended stimulus in order to observe feature attention effects. When they first described feature attention effects for direction of motion in area MT, Treue and Martinez-Trujillo used both direction and speed change detection tasks (Martinez-Trujillo & Treue, 2004; Treue & Martinez-Trujillo, 1999). Data from these two tasks were pooled, suggesting that these different tasks led to no clear effects on feature attention modulation for direction. Other studies, however, have found explicitly task related feature attention effects on either the firing rates or correlation structure of sensory neurons (Cohen & Maunsell, 2011; Cohen & Newsome, 2008; Mirabella et al., 2007) or effects specifically related to

visual search (Bichot, Rossi, & Desimone, 2005; Motter, 1994; Zhou & Desimone, 2011).

In another study, animals were trained to switch between a direction change detection task and a color change detection task. Interestingly, similar amounts of feature attentional modulation for direction of motion were observed in area MT regardless of the task (Katzner, Busse, & Treue, 2009). The results of this study suggest that attending to a given stimulus will lead to feature attention effects in cortex for all of the features that are contained within the attended stimulus. The results of the present study expand on these findings because the animals were never trained to perform a task directly related to either direction or binocular disparity; instead, they performed a speed change detection task. Despite this task and the animal's training history, feature attention effects for both direction of motion and binocular disparity were observed.

It should be acknowledged that direction and speed are related features and are both used in the computation of velocity. This is particularly relevant to neurons in area MT, which are thought to be involved in the computation of velocity (Born & Bradley, 2005). This raises the possibility that the speed change detection task might be more relevant for MT neuron's direction tuning, or that the animals may have relied on a velocity judgment to solve the task. This relationship could potentially explain why larger feature attention effects were observed in the population for direction of motion compared to binocular disparity. However, accounting for the population's differences in tuning strength, comparable feature attention effect sizes for both direction and binocular disparity were found. This suggests that the choice of task did

not lead to larger feature attention effects for direction of motion and that these differences were the result of different tuning strengths in the population for these two features.

It is possible that designing a task that directly related to direction or binocular disparity could have led to larger overall feature attention effect sizes for these features. Although Katzner et al (Katzner, Busse, & Treue, 2009) found no difference in direction feature attention effect sizes when an animal switched between a color or direction change detection task, these animals had been extensively trained on both tasks. It is possible that because the animals in the present study were never trained to perform either a direction or binocular disparity detection task, larger attention effects could have been observed if they had been trained to attend to these specific features.

Feature attention and tuning strength

An MT neuron's overall strength of tuning for a feature is a significant predictor for the amount of feature attention modulation that a cell will exhibit. This relationship is similar for both direction and binocular disparity (but only significant for binocular disparity; see Figure 2.7) as well as the measure of a neuron's overall tuning strength for the two features (see Figure 2.9) and may suggest a common mechanism for feature attention modulation that increases the gain of sensory neurons in a way that depends on how strongly a feature modulates a neuron's response. While the formulation of the FSG model was based on observations about the relationship between an attended stimulus and a neuron's tuning preference, it is intuitive that the attentional system would be sensitive to how strongly tuned neurons are for certain

features. It may be ideal for the attentional system to highlight the activity of neurons with the clearest preferences, as these neurons are likely to be the most informative for solving the task at hand.

In general, the observation of feature attention effects that are independent of space lead to questions about what these effects might reveal about the connectivity of visual cortex. It is possible that these effects reveal preferential connectivity amongst sensory neurons with similar tuning preferences, irrespective of their spatial receptive fields. There is some evidence that sensory neurons may be preferentially connected to other neurons with similar tuning preferences (Bosking et al., 1997). But the ranges of these connections are thought to be relatively small distances, especially when compared to the scale of feature attention effects, which have been demonstrated across large portions of visual space, including across hemispheres (Cohen & Maunsell, 2011; McAdams & Maunsell, 2000; Treue & Martinez-Trujillo, 1999). Further, previous studies have found specifically task related aspects of feature attention (Bichot, Rossi, & Desimone, 2005; Cohen & Maunsell, 2011) and these observations argue in favor of the presence of a flexible top-down mechanism in mediating these effects. This mechanism, in addition to being able to modulate neurons throughout a single or multiple cortical areas, must also account for sensory neurons' tuning preferences and tuning strength.

It has been suggested that feature attention effects for direction of motion in area MT might result from precise feedback from frontal cortex that depends on a neuron's tuning preferences (Zaksas & Pasternak, 2005). Where exactly this feedback might arrive from is unclear. Zhou and Desimone (2011) have demonstrated that

feature attention latencies in FEF are earlier than those in V4. These results suggest that, in addition to a role in spatial attention (Moore & Armstrong, 2003; Moore & Fallah, 2001), FEF may help integrate feature information with attentional mechanisms to create a saliency map.

But, it remains unknown how the attention system accounts for the tuning preferences and tuning strength of sensory neurons that the data from the present study suggests occurs. The sensitivity of sensory neurons has been shown to be correlated with the relationship between their activity and behavior on a trial by trial basis (Britten et al., 1996; Celebrini & Newsome, 1994; Cook & Maunsell, 2002; Law & Gold, 2008; Price & Born, 2010; Purushothaman & Bradley, 2005; Shadlen et al., 1996; Uka & DeAngelis, 2004). This means that the neurons that most reliably represent a behaviorally relevant stimulus are the same neurons that tend to best predict behavioral performance on judgments about that stimulus. Here, it has been shown that neurons with the largest tuning strength tend to be the neurons that exhibit the strongest modulation by feature attention. These results suggest a link between these properties, but further work will be needed to determine if and how they are related.

Methods

Two adult male monkeys (N and P) were trained to perform a speed change detection task that required them to detect a randomly timed, stepped increase in the speed of a moving visual stimulus by responding with a saccadic eye movement. Both monkeys had previously been trained to perform a speed change discrimination task

where they signified the sign of a speed change by making a saccade to one of two targets (Price & Born, 2010). The targets were removed and both monkeys were trained, within one session, to saccade to the attended stimulus when its speed changed. Additional training was performed to ensure the animals had stable performance across different stimulus locations, directions, binocular disparities (-1.2° to +1.2°), reference speeds (6 to 15 °/s), sizes (4° to 12° diameter), trial durations (up to 5500ms) and that they did not change their vergence when attending to stimuli at different binocular disparities.

Before electrophysiological recordings, each animal was implanted with a custom titanium head-post, two scleral search coils for monitoring eye positions and a vertically oriented Cilux recording cylinder to protect a craniotomy centered posterior 3 mm and lateral 15 mm relative to ear bar zero. All animal procedures complied with the National Institutes of Health Guide for Care and Use of Laboratory Animals and were approved by the Harvard Medical Area Standing Committee on Animals.

Stimuli and Task

Stimuli consisted of moving dot patches and were presented on a black screen placed 410 mm from the animal with resolution 1024 X 768 pixels (17.8 pixels / degree) and refresh rate 100.1 Hz. The binocular disparity of each stimulus was created by drawing each dot twice, once in red and once in blue, and changing each pair of dot's horizontal offset according to the specified disparity value. Dots at zero binocular disparity were drawn as a combination of the blue and red values, which appeared purple. The monkeys viewed the screen through monocular filters colored

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red or blue (Kodak gelatin filters nos. 29 and 47), so that only one set of dots was visible to each eye. Crossover between the two eyes, as viewed through the filters, was measured to be less than 3%. Dots were presented at a spatial density of 1.5 dots/degree^2, with 150 ms lifetime and had 100% coherence (i.e., there were no noise dots, but the dots flickered because of their limited lifetime). Dots were drawn in a stationary circular aperture that either matched the full extent of the excitatory receptive field center of the neuron being studied or had a diameter equal to the eccentricity of the stimulus center, whichever was smaller. The two stimuli were always the same size.

The speed change detection task's trial sequence is shown in Figure 2.1A. A trial began when the animal acquired fixation within an invisible square window that ranged from 1.2 – 2.0° per side and was centered on a small fixation spot. After 250 ms of stable fixation, two stationary random dot patches appeared on either side of fixation. One patch was placed in the receptive field of the neuron under study, the other in an equivalent position on the horopter in the opposite hemifield. The two stimuli were usually centered 15° - 25° away from each other. Both stimuli were always presented at the same elevation, but when the receptive field of an MT neuron was relatively close to the vertical meridian, the attended stimulus was often placed 2 - 5° more laterally in the opposite hemifield. After an additional 250 ms, both dot patches began to move for a duration of time that ranged between 500 and 5500 ms until a stepped increase of speed occurred. In order to keep the speed change's hazard function constant (Luce, 1986), the length of the reference speed was randomly chosen from a truncated exponential distribution with a time constant of 2000 ms. The amount

of the speed changes varied from 105 – 150 % of the reference speed and were
selected to ensure that the animals could correctly detect the change in roughly 70% of
trials. Behavioral responses were assigned to one of four categories: (1) correct, if a
saccade was made to the attended stimulus 150 – 650 ms after the speed change; (2)
miss, if fixation was maintained for greater than 650 ms after the speed change; (3)
false detection, if a saccade was made during the reference period or in the first 150
ms after the speed change; (4) fixation break, if the eye position left a square fixation
window with sides of length 1.2 – 2.0°, but no saccade was made to the attended
stimulus within 100 ms. Only correct trials were rewarded and no speed changes
occurred in the unattended stimulus. Psychometric functions were fitted using the
"psignifit" toolbox version 2.5.6 for Matlab (see http://bootstrap-
software.org/psignifit/) which implements the maximum-likelihood method described
by Wichmann and Hill (2001). Thresholds were defined as the speed change amount
that led to an 80% successful detection rate.

For each neuron, quantitative tuning data was collected for direction of motion,
dot patch size and binocular disparity while the animals were rewarded for fixating a
central target. The preferred and null values for direction and binocular disparity
derived from these data sets were used during the main experiment. The preferred
direction was determined by the result of the mean vector calculation and the null
direction was set as the value 180 degrees opposite of the preferred value. The
preferred and null binocular disparity values were determined to be the maximum and
minimum values from the tuning data, respectively. The two dot patches moved at
slightly different speeds to discourage the animals from using the unattended stimulus

as a reference for the detection task. The attended stimulus was presented between a range of 6 and 15 °/s while the unattended stimulus ranged between 4 and 20 °/ s and was usually 2 – 4 ° /s different from the attended stimulus and could be either faster or slower than the attended stimulus. The speed of each stimulus was constant within a session and the speed of the unattended stimulus was set at a value that drove the MT neuron optimally.

During the main experiment, the stimulus in the receptive field moved in the neuron's PREF direction and was presented at its PREF binocular disparity. The attended stimulus was randomly presented at one of the four configurations made up by choosing from the neuron's PREF and NULL values for both direction of motion and binocular disparity. No systematic differences in behavioral performance were observed across different attended stimulus configurations. In the second experiment, additional conditions were used where the stimulus in the receptive field could also be presented at either the PREF or NULL value of each of the two features (see Figure 2.5A and Figure 2.5B). Additionally, during both quantitative tuning data collection and the main experiment, dots drawn at zero disparity called grounding dots (DeAngelis & Newsome, 1999) were randomly placed in an annulus around the fixation target to aid the animal in maintaining vergence at the plane of fixation.

Neuronal dataset

Single-unit data was recorded from 207 MT neurons using methods described previously (Born, 2000; Price & Born, 2010). Area MT was selected because its tuning properties are relatively well understood (DeAngelis & Uka, 2003) and feature

attention effects have been previously described for direction of motion (Treue & Martinez-Trujillo, 1999). Neurons were identified as being part of MT by a range of criteria including: position of the electrode in the chamber judged relative to postsurgical magnetic resonance imaging; electrode depth relative to the dura; size of the spatial receptive field relative to the eccentricity; amount of overlap of the receptive field into the ipsilateral hemifield; and transitions between gray and white matter as the electrode was advanced. Typically, MT was encountered after MST, which was purposefully avoided due to larger receptive fields that may have been directly stimulated by the second, attended stimulus. Any neurons where spiking activity could be directly driven by placing a moving stimulus in the ipsilateral hemifield were ignored. Task data was only collected from neurons where a statistically identifiable preferred and null value for both direction and binocular disparity were found (paired t-test between maximum and minimum response, $p < .05$). Neurons with at least 80 completed trials from the main experiment were included in the population data. For the main experiment, 97 neurons from monkey N and 110 neurons from monkey P met these criteria. Included in those numbers are 21 neurons from monkey N and 23 neurons from monkey P that contained the additional conditions described in Figure 2.5. Across the population, the median number of completed detection trials was 312 and the mean was 341.

To quantify feature attention effects, the firing rates were calculated on correct trials during a 250 ms window that immediately preceded a correctly detected stimulus change. Using other windows, including ones aligned to the stimulus onset, gave qualitatively similar results but did not allow for direct comparison with the control

data described below. Using these data, statistical tests and attentional indices for both direction and disparity feature attention were calculated. This index took the form $(Resp_{AttPref} - Resp_{AttNull}) / (Resp_{AttPref} + Resp_{AttNull})$, while the other feature was at the neuron's preferred value. This index is bound between -1 and 1, where zero signifies that there was no modulation as a result of feature attention and positive values signify a larger response when the animal attended to the preferred value of a feature compared to when it attended to the null value. There were no significant differences between the effects observed in the two animals, so the data from both animals were combined.

A 2 X 2 ANOVA was performed for each neuron to test for main effects of attending either to its preferred or null direction and binocular disparity as well as the interactions between these main effects. Wilcoxon signed rank tests were performed to determine whether population distributions were significantly different from zero, Wilcoxon ranked sum tests were performed to determine significance for individual neurons on population plots (Figure 2.3 and Figure 2.6).

Using the quantitative tuning data, the preferred and null values for each feature were determined and a tuning index given the form $(Resp_{Pref} - Resp_{Null}) / (Resp_{Pref} + Resp_{Null})$ was calculated. This index was effectively bound between zero and 1 because the preferred value was always larger than the null value. Larger values signified stronger tuning modulation for that feature.

Prior to the main experiment, an additional dataset was collected from 199 of 207 neurons, to test whether the presence of the second, attended stimulus led to direct, bottom-up neuronal responses that could be misattributed to feature attention.

The two stimuli were flashed for 250 ms each in the exact positions and configurations that they would occur during the main task, while the animal was rewarded for fixating. Indices were calculated and an ANOVA was performed with these data, which had the same sensory input as during the task but were collected during a condition where the animal had no incentive to attend to either stimulus and, because of the brief presentation, could not switch its attention between the stimuli during their presentation.

Discussion

We have shown that MT neurons encode direction of motion and binocular disparity in a separable manner and can also be modulated by feature attention for both of these features. Further, the strength of feature attention effects exhibited by these neurons are positively correlated with the strength of a neuron's tuning for these features. These findings lead to larger questions about the intricacies of the attentional system's connectivity in cortex and how the brain flexibly determines which sensory neurons should be modulated by attention.

One such question is whether neurons have fixed functional identities based on their tuning properties and location within a cortical map. By fixed identity, we mean that a neuron represents one or more features reliably and independently of other features. Such a representation would allow for the brain to monitor the activity of a population of these neurons in order to obtain a reliable estimate of a certain feature in a stimulus, regardless of other stimulus properties. If sensory neurons do have fixed functional identities for certain features, one can ask whether these are the neurons whose activity the attentional system will highlight during difficult tasks, or whether these are the neurons whose activity the brain will monitor in order to solve perceptual tasks related to those features. If this is the case, how does the brain recognize a neuron's functional identity and, as we have shown in this study, account for factors like a neurons tuning preferences and tuning strength? What about when these

functional identities are disrupted via an experimental manipulation such as the
cooling experiments that are performed in the Born lab (Ponce, Lomber, & Born,
2008)? During such an experiment, will attentional and read-out mechanisms rely on
the activity of neurons that no longer adequately represent relevant stimulus features
or will they flexibly adapt and account for the altered functional properties that these
neurons exhibit?

Another interesting question involves what remains to be understood about
where feature attention effects occur in cortex and what their presence might signify.
While we currently cannot answer these questions, we can begin to postulate about
what signatures may be important for the presence of feature attention effects for
specific features. As we highlighted earlier in this text, direction of motion and
binocular disparity share many similar functional and anatomical properties in area
MT. The observation of feature attention effects for both of these features in MT could
be interpreted as evidence that one or more of these properties may be important for
feature attention effects, but is this a reasonable interpretation?

In chapter 2, we described a relationship between tuning strength and feature
attention, suggesting that tuning strength plays a role in these effects. But, it should be
noted that moderately tuned neurons still exhibited some degree of feature attentional
modulation. Further, neurons in V4 are rarely as strongly tuned for spatial frequency
or orientation (Desimone & Schein, 1987), as are MT neurons for direction and
binocular disparity (DeAngelis & Uka, 2003), but these neurons have been shown to
exhibit feature attention effects for those features (Cohen & Maunsell, 2011). At the
limit, sensory neurons most likely need to have some degree of tuning for a feature in

order to exhibit feature attention effects for that feature. This may be in contrast to prefrontal cortex where neurons have been shown to exhibit strong changes in their tuning properties depending on behavioral context (Hussar & Pasternak, 2009). But it remains unclear how strongly tuned a population of sensory neurons must be in order to exhibit feature attention effects.

Furthermore, it remains unclear whether aspects of cortical organization contribute to feature attention effects. Given the relationship between feature attention and tuning strength, one wonders if there is a more general relationship between tuning strength and location within a column. A neuron in the center of a column will be surrounded by other neurons with similar tuning preferences and might even receive inputs that are more homogenously tuned than would a neuron at the edge of a column. If this were the case, the relationship we observed between tuning strength and feature attention could be the result of the attentional system targeting neurons in the center of columns. Both direction of motion and disparity tuning exhibit columnar organization in MT, such that adjacent neurons have similar tuning (Albright, Desimone, & Gross, 1984; DeAngelis & Newsome, 1999). These properties could make wiring feature attentional modulation much simpler.

Even more intriguing is the possibility that there are other functional properties that determine feature attention effects. For example, as discussed in chapter 1, tuning for direction of motion and binocular disparity are separable, which could simplify read-out mechanisms by allowing the brain to average out the response to an irrelevant feature. Accordingly, separability may make the attentional system's job easier by allowing it to target neurons with fixed tuning preferences for the attended feature.

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Finally, MT neurons exhibit choice related activity during both direction and depth related tasks (Bosking & Maunsell, 2011; Bradley, Chang, & Andersen, 1998; Britten et al., 1992, 1996; Cook & Maunsell, 2002; Sasaki & Uka, 2009; Uka & DeAngelis, 2004) and one wonders whether these two important functional properties are related.

Although potentially beneficial, it is unlikely that separability, columnar organization and strong tuning are prerequisites for there to be either neuronal or perceptual feature attention effects. While there is currently an incomplete understanding of these factors in the brain, behavior is far too flexible to require a dependence on them for attentionally mediated gains in perception. So, while not a requirement, it remains unknown whether these factors do in fact lead to larger, or more prevalent, feature attention effects. Further, if there are features whose representation in the brain does not possess these properties, it remains unknown if attentionally mediated perceptual benefits are as large as they are for features that do. It is also unknown whether there are features or objects for which feature attention will not facilitate behavior or alter neuronal responses and whether these effects could develop with perceptual learning or sufficient training with such objects.

But what about choice related activity? In addition to the feature attention effects described in chapter 2, the activity of MT neurons has been demonstrated to weakly co-vary with decisions made by monkeys about the direction and binocular disparity of stimuli. Activity that correlates with an animal's decisions and feature attention effects for both orientation and spatial frequency have also been shown in V4 (Cohen & Maunsell, 2010, 2011). Will neurons that exhibit choice related activity also exhibit feature attention effects for the same features? If the role of feature attention is

to highlight task-relevant neurons, we might expect the two to be closely related.

There is currently no strong evidence to support this tantalizing possibility, but one

can reasonably ask what role neuronal attention effects serve if they aren't functioning

to identify the neurons that the brain should monitor in order to solve a certain

perceptual task. In fact, it tends to be assumed that attention selectively increases the

gain and alters the correlation structure of neurons that will in turn be read out by

downstream areas in order to solve perceptual tasks. Further, there is some evidence

that a non-negligible portion of the choice related activity that is observed in sensory

neurons results directly from top-down sources (Nienborg & Cumming, 2009). But

more work is needed to establish the degree to which these two distinct functional

properties are linked and whether they originate from the same top-down sources.

One could presumably test for both feature attention and choice probability in

single neurons, using a feature like direction of motion, in order to ask whether these

measures are correlated. A relationship between the two measures for a given feature

might emerge at one of two levels. These two variables could be highly correlated

within single neurons, suggesting that they may rely on a common mechanism.

Alternatively, they could only be related at the population level, where feature

attention effects and choice related activity would appear only in conjunction in a

population and not in isolation. This would suggest that the brain is relying on the

same population of neurons to solve a task that are being highlighted by the attentional

system, but that the two systems may not be precisely aligned with each other. To

probe this issue further, one would also want to understand the ways in which feature

attention alters the correlation structure between neurons tuned to similar and opposite

values of a given feature. It has been shown that feature attention can have a push-pull effect on neurons with different tuning preferences (Martinez-Trujillo & Treue, 2004), therefore, characterizing the changes in correlation structure between neurons with different tuning preferences would help identify the role that feature attentional modulation serves in disambiguating different neuronal pools. That is, if correlations decrease between oppositely tuned pools, the difference between their activities will become easier to detect. These data would provide a foundation for understanding how feature attention effects might relate to choice probabilities which have been shown to critically depend on the correlation structure of pools of sensory neurons (Cohen & Newsome, 2009; Nienborg & Cumming, 2010; Shadlen et al., 1996).

Additional questions arise when considering how the feature attention network is established. In particular, there may be a very interesting role for perceptual learning in these effects, especially for complex object properties. It would be interesting to know whether the behavioral effects of learning precede or follow feature attention effects or whether they change on the same time scale, suggesting that they may be linked. For direction of motion judgments, Law and Gold have shown, during learning, that there are minimal changes in the representation of stimulus information in MT but that choice probability increases among the most sensitive neurons (Law & Gold, 2008). What would be observed for feature attention effects during a similar experiment? Would these effects change along a similar time line as behavioral performance during learning?

Ultimately, how the brain's read-out and attentional mechanisms account for the functional properties of sensory neurons and flexibly listen to the correct neurons

depending on the current behavioral context is a tremendously interesting question. Establishing that sensory neurons in area MT can be modulated for multiple stimulus features to which they are tuned and that this modulation is related to a neuron's strength of tuning is only a small step towards understanding this fascinating problem.

Bibliography

Albright, T. D. (1984). Direction and orientation selectivity of neurons in visual area MT of the macaque. *Journal of neurophysiology*, *52*(6), 1106-30.

Albright, T. D., & Desimone, R. (1987). Local precision of visuotopic organization in the middle temporal area (MT) of the macaque. *Experimental brain research*, *65*(3), 582–592.

Albright, T. D., Desimone, R., & Gross, C. G. (1984). Columnar organization of directionally selective cells in visual area MT of the macaque. *Journal of neurophysiology*, *51*(1), 16-31.

Allman, J., Miezin, F., & McGuinness, E. (1985). Direction- and velocity-specific responses from beyond the classical receptive field in the middle temporal visual area (MT). *Perception*, *14*(2), 105-126.

Beauchamp, M. S., Cox, R. W., & DeYoe, E. a. (1997). Graded effects of spatial and featural attention on human area MT and associated motion processing areas. *Journal of neurophysiology*, *78*(1), 516-20.

Berman, R. A., & Wurtz, R. H. (2010). Functional identification of a pulvinar path from superior colliculus to cortical area MT. *The Journal of neuroscience*, *30*(18), 6342-54.

Berman, R. A., & Wurtz, R. H. (2011). Signals conveyed in the pulvinar pathway from superior colliculus to cortical area MT. *The Journal of neuroscience*, *31*(2), 373-84.

Bichot, N. P., Rossi, A. F., & Desimone, R. (2005). Parallel and serial neural mechanisms for visual search in macaque area V4. *Science*, *308*(5721), 529-34.

Born, R. T. (2000). Center-surround interactions in the middle temporal visual area of the owl monkey. *Journal of neurophysiology*, *84*(5), 2658-69.

Born, R. T., & Bradley, D. C. (2005). Structure and function of visual area MT. *Annual review of neuroscience*, *28*, 157-89.

Bosking, W. H., & Maunsell, J. H. R. (2011). Effects of stimulus direction on the correlation between behavior and single units in area MT during a motion detection task. *The Journal of neuroscience*, *31*(22), 8230-8.

Bosking, W. H., Zhang, Y., Schofield, B., & Fitzpatrick, D. (1997). Orientation selectivity and the arrangement of horizontal connections in tree shrew striate cortex. *The Journal of neuroscience*, *17*(6), 2112-27.

Bradley, D. C., & Andersen, R. A. (1998). Center-surround antagonism based on disparity in primate area MT. *The Journal of neuroscience*, *18*(18), 7552-65.

Bradley, D. C., Chang, G. C., & Andersen, R. A. (1998). Encoding of three-dimensional structure-from-motion by primate area MT neurons. *Nature*, *392*(6677), 714–717.

Britten, K. H., Newsome, W. T., Shadlen, M. N., Celebrini, S., & Movshon, J. A. (1996). A relationship between behavioral choice and the visual responses of neurons in macaque MT. *Visual neuroscience*, *13*(1), 87-100.

Britten, K. H., Shadlen, M. N., Newsome, W. T., & Movshon, J. A. (1992). The Analysis of Visual Motion: A Comparison of Neuronal and Psychophysical Performance. *The Journal of neuroscience*, *12*(12), 4745.

Busse, L., Katzner, S., & Treue, S. (2006). Spatial and feature-based effects of exogenous cueing on visual motion processing. *Vision research*, *46*(13), 2019–2027.

Cavanaugh, J., & Wurtz, R. H. (2004). Subcortical modulation of attention counters change blindness. *The Journal of neuroscience*, 24(50), 11236-43.

Celebrini, S., & Newsome, W. T. (1994). Neuronal and psychophysical sensitivity to motion signals in extrastriate area MST of the macaque monkey. *The Journal of neuroscience,* 14(7), 4109-24.

Chelazzi, L., Duncan, J., Miller, E. K., & Desimone, R. (1998). Responses of neurons in inferior temporal cortex during memory-guided visual search. *Journal of neurophysiology*, *80*(6), 2918-40.

Chelazzi, L., Miller, E. K., Duncan, J., & Desimone, R. (1993). A neural basis for visual search in inferior temporal cortex. *Nature*, *363*(6427), 345–347.

Chelazzi, L., Miller, E. K., Duncan, J., & Desimone, R. (2001). Responses of neurons in macaque area V4 during memory-guided visual search. *Cerebral cortex*, *11*(8), 761-772.

Chen, G., Lu, H. D., & Roe, A. W. (2008). A map for horizontal disparity in monkey V2. *Neuron*, *58*(3), 442-50.

Cohen, A., & Magen, H. (1999). Intra-and cross-dimensional visual search for single-feature targets. *Attention, perception, & psychophysics*, *61*(2), 291–307.

Cohen, M. R., & Kohn, A. (2011). Measuring and interpreting neuronal correlations. *Nature neuroscience*, *14*(7), 811-819.

Cohen, M. R., & Maunsell, J. H. R. (2009). Attention improves performance primarily by reducing interneuronal correlations. *Nature neuroscience*, *12*(12), 1594-600.

Cohen, M. R., & Maunsell, J. H. R. (2010). A neuronal population measure of attention predicts behavioral performance on individual trials. *The Journal of neuroscience*, *30*(45), 15241-53.

Cohen, M. R., & Maunsell, J. H. R. (2011). Using neuronal populations to study the mechanisms underlying spatial and feature attention. *Neuron*, *70*(6), 1192-204.

Cohen, M. R., & Newsome, W. T. (2008). Context-dependent changes in functional circuitry in visual area MT. *Neuron*, *60*(1), 162-73.

Cohen, M. R., & Newsome, W. T. (2009). Estimates of the contribution of single neurons to perception depend on timescale and noise correlation. *The Journal of neuroscience*, *29*(20), 6635-48.

Cook, E. P., & Maunsell, J. H. R. (2002). Dynamics of neuronal responses in macaque MT and VIP during motion detection. *Nature neuroscience*, *5*(10), 985-94.

Cook, E. P., & Maunsell, J. H. R. (2004). Attentional modulation of motion integration of individual neurons in the middle temporal visual area. *The Journal of neuroscience*, *24*(36), 7964-77.

Cutrell, E. B., & Marrocco, R. T. (2002). Electrical microstimulation of primate posterior parietal cortex initiates orienting and alerting components of covert attention. *Experimental brain research*, *144*(1), 103-13.

Cumming, B. G., & DeAngelis, G. C. (2001). The Physiology of Stereopsis. *Annual review of neuroscience*, *24*(1), 203-238.

David, S. V., Hayden, B. Y., Mazer, J. a, & Gallant, J. L. (2008). Attention to stimulus features shifts spectral tuning of V4 neurons during natural vision. *Neuron*, *59*(3), 509-21.

DeAngelis, G. C., & Newsome, W. T. (1999). Organization of disparity-selective neurons in macaque area MT. *The Journal of neuroscience*, *19*(4), 1398-415.

DeAngelis, G. C., & Newsome, W. T. (2004). Perceptual "read-out" of conjoined direction and disparity maps in extrastriate area MT. *PLoS biology*, *2*(3), E77.

DeAngelis, G. C., & Uka, T. (2003). Coding of horizontal disparity and velocity by MT neurons in the alert macaque. *Journal of neurophysiology*, *89*(2), 1094-111.

Depireux, D. A., Simon, J. Z., Klein, D. J., & Shamma, S. A. (2001). Spectro-Temporal Response Field Characterization With Dynamic Ripples in Ferret Primary Auditory Cortex. *Journal of neurophysiology*, *85*, 1220-1234.

Desimone, R., & Schein, S. J. (1987). Visual properties of neurons in area V4 of the macaque: sensitivity to stimulus form. *Journal of neurophysiology*, *57*(3), 835-68.

Desimone, R., & Ungerleider, L. G. (1986). Multiple visual areas in the caudal superior temporal sulcus of the macaque. *The Journal of comparative neurology*, *248*(2), 164-89.

Dodd, J. V., Krug, K., Cumming, B. G., & Parker, A. J. (2001). Perceptually bistable three-dimensional figures evoke high choice probabilities in cortical area MT. *The Journal of neuroscience*, *21*(13), 4809-21.

Dubner, R., & Zeki, S. M. (1971). Response properties and receptive fields of cells in an anatomically defined region of the superior temporal sulcus in the monkey. *Brain research*, *35*(2), 528-32.

Duncan, J. (1980). The locus of interference in the perception of simultaneous stimuli. *Psychological review*, *87*(3), 272-300.

Ferrera, V. P., & Lisberger, S. G. (1997). Neuronal Responses in Visual Areas MT and MST During Smooth Pursuit Target Selection Neuronal Responses in Visual Areas MT and MST During Smooth Pursuit Target Selection. *Journal of neurophysiology*, 1433-1446.

Girard, P., Salin, P. A., & Bullier, J. (1992). Response selectivity of neurons in area MT of the macaque monkey during reversible inactivation of area V1. *Journal of neurophysiology*, *67*(6), 1437-46.

Glickstein, M., Cohen, J. L., Dixon, B., Gibson, A., Hollins, M., Labossiere, E., & Robinson, F. (1980). Corticopontine visual projections in macaque monkeys. *The Journal of comparative neurology*, *190*(2), 209-29.

Goldberg, M. E., & Wurtz, R. H. (1972). Activity of Superior Colliculus in Behaving Monkey. II. Effect of Attention on Neuronal Responses. *Journal of neurophysiology*, *35*(4), 560-574.

Grunewald, A., & Skoumbourdis, E. K. (2004). The integration of multiple stimulus features by V1 neurons. *The Journal of neuroscience*, *24*(41), 9185-94.

Haenny, P. E., Maunsell, J. H. R., & Schiller, P. H. (1988). State dependent activity in monkey visual cortex II Retinal and extraretinal factors in V4. *Experimental brain research*, *69*(2), 245–259.

Hayden, B. Y., & Gallant, J. L. (2005). Time course of attention reveals different mechanisms for spatial and feature-based attention in area V4. *Neuron*, *47*(5), 637-43.

Hayden, B. Y., & Gallant, J. L. (2009). Combined effects of spatial and feature-based attention on responses of V4 neurons. *Vision research*, *49*(10), 1182-7.

He, Z. J., & Nakayama, K. (1992). Surfaces versus features in visual search. *Nature*, *359*(9), 11-13.

He, Z. J., & Nakayama, K. (1995). Visual attention to surfaces in three-dimensional space. *Proceedings of the National Academy of Sciences of the United States of America*, *92*(24), 11155-9.

Heeger, D. J. (1987). Model for the extraction of image flow. *Journal of the Optical Society of America*, *4*(8), 1455-71.

Hernández-Peón, R., Scherrer, H., & Jouvet, M. (1956). Modification of electric activity in cochlear nucleus during attention in unanesthetized cats. *Science*, (123), 331-332.

Herrero, J. L., Roberts, M. J., Delicato, L. S., Gieselmann, M. A., Dayan, P., & Thiele, A. (2008). Acetylcholine contributes through muscarinic receptors to attentional modulation in V1. *Nature*, *454*(7208), 1110-4.

Horn, G. (1960). Electrical activity of the cerebral cortex of the unanaesthetized cat during attentive behaviour. *Brain: A journal of neurology*, *83*(1954), 57-76.

Hubel, D. H. (1982). Exploration of the primary visual cortex, 1955-78. *Nature*, *299*(5883), 515–524.

Hubel, D. H., & Livingstone, M. S. (1987). Segregation of Form, Color, and Stereopsis in Primate Area 18. *The Journal of neuroscience*, *7*(11), 3378-3415.

Hubel, D. H., Henson, C. O., Rupert, A., & Galambos, R. (1959). "Attention" Units in the Auditory Cortex. *Science*, *129*(3358), 1279.

Hunter, J. N., & Born, R. T. (2011). Stimulus-dependent modulation of suppressive influences in MT. *The Journal of neuroscience*, *31*(2), 678-86.

Hussar, C. R., & Pasternak, T. (2009). Flexibility of sensory representations in prefrontal cortex depends on cell type. *Neuron*, *64*(5), 730-43.

James, W. T. 1890. *Principles of psychology*. New York: Holt, Rinehart & Winston.

Jehee, J. F. M., Brady, D. K., & Tong, F. (2011). Attention improves encoding of task-relevant features in the human visual cortex. *The Journal of neuroscience*, *31*(22), 8210-9.

Kamitani, Y., & Tong, F. (2006). Decoding seen and attended motion directions from activity in the human visual cortex. *Current biology: CB*, *16*(11), 1096-102.

Kasai, T., Morotomi, T., Katayama, J., & Kumada, T. (2003). Attending to a location in three-dimensional space modulates early ERPs. *Brain research*, *17*(2), 273-285.

Katzner, S., Busse, L., & Treue, S. (2006). Feature-based attentional integration of color and visual motion. *Journal of vision*, *6*(3), 269-84.

Katzner, S., Busse, L., & Treue, S. (2009). Attention to the Color of a Moving Stimulus Modulates Motion-Signal Processing in Macaque Area MT: Evidence for a Unified Attentional System. *Frontiers in systems neuroscience*, *3*(October), 12.

Klein, D. J., Simon, J. Z., Depireux, D. a, & Shamma, S. a. (2006). Stimulus-invariant processing and spectrotemporal reverse correlation in primary auditory cortex. *Journal of computational neuroscience*, *20*(2), 111-36.

Krubitzer, L. A., & Kaas, J. H. (1990). Cortical connections of MT in four species of primates: areal, modular, and retinotopic patterns. *Visual neuroscience*, *5*(2), 165-204.

Law, C.-T., & Gold, J. I. (2008). Neural correlates of perceptual learning in a sensory-motor, but not a sensory, cortical area. *Nature neuroscience*, *11*(4), 505-13.

Lee, J., & Maunsell, J. H. R. (2009). A normalization model of attentional modulation of single unit responses. *PloS one*, *4*(2), e4651.

Lee, J., & Maunsell, J. H. R. (2010). The effect of attention on neuronal responses to high and low contrast stimuli. *Journal of neurophysiology*, *104*(2), 960-71.

Li, X., & Basso, M. a. (2008). Preparing to move increases the sensitivity of superior colliculus neurons. *The Journal of neuroscience*, *28*(17), 4561-77.

Liu, J., & Newsome, W. T. (2003). Functional organization of speed tuned neurons in visual area MT. *Journal of neurophysiology*, *89*(1), 246-56.

Luce, R. D. (1986). *Response Times: Their Role in Inferring Elementary Mental Organization* (p. 562). Oxford University Press.

Maljkovic, V., & Nakayama, K. (1994). Priming of pop-out: I. Role of features. *Memory & cognition*, *22*(6), 657–672.

Maljkovic, V., & Nakayama, K. (1996). Priming of pop-out: II. The role of position. *Attention, perception, & psychophysics*, *58*(7), 977–991.

Martinez-Trujillo, J. C., & Treue, S. (2002). Attentional modulation strength in cortical area MT depends on stimulus contrast. *Neuron*, *35*(2), 365-70.

Martinez-Trujillo, J. C., & Treue, S. (2004). Feature-based attention increases the selectivity of population responses in primate visual cortex. *Current biology*, *14*, 744-751.

Maunsell, J. H. R., & Cook, E. P. (2002). The role of attention in visual processing. *Philosophical transactions of the Royal Society of London. Series B, Biological sciences*, *357*(1424), 1063-72.

Maunsell, J. H. R., & Treue, S. (2006). Feature-based attention in visual cortex. *Trends in neurosciences*, *29*(6), 317-22.

Maunsell, J. H. R., & Van Essen, D. C. (1983a). Functional properties of neurons in middle temporal visual area of the macaque monkey. II. Binocular interactions and sensitivity to binocular disparity. *Journal of neurophysiology*, *49*(5), 1148-67.

Maunsell, J. H. R., & Van Essen, D. C. (1983b). Functional properties of neurons in middle temporal visual area of the macaque monkey. I. Selectivity for stimulus direction, speed, and orientation. *Journal of neurophysiology*, *49*(5), 1127-47.

Maunsell, J. H. R., & Van Essen, D. C. (1987). Topographic organization of the middle temporal visual area in the macaque monkey: representational biases and the relationship to callosal connections and myeloarchitectonic boundaries. *The Journal of comparative neurology*, *266*(4), 535-55.

Maunsell, J. H. R., & Van Essen, D. C. (1983). The connections of the middle temporal visual area (MT) and their relationship to a cortical hierarchy in the macaque monkey. *The Journal of neuroscience*, *3*(12), 2563-86.

Maunsell, J. H. R., Sclar, G., Nealey, T. A., & DePriest, D. D. (1991). Extraretinal representations in area V4 in the macaque monkey. *Visual neuroscience*, *7*(06), 561–573.

Mazer, J. A., Vinje, W. E., McDermott, J., Schiller, P. H., & Gallant, J. L. (2002). Spatial frequency and orientation tuning dynamics in area V1. *Proceedings of the National Academy of Sciences of the United States of America*, *99*(3), 1645-50.

McAdams, C. J., & Maunsell, J. H. R. (2000). Attention to both space and feature modulates neuronal responses in macaque area V4. *Journal of neurophysiology*, *83*(3), 1751-5.

Mirabella, G., Bertini, G., Samengo, I., Kilavik, B. E., Frilli, D., Della Libera, C., & Chelazzi, L. (2007). Neurons in area V4 of the macaque translate attended visual features into behaviorally relevant categories. *Neuron*, *54*(2), 303-318.

Mitchell, J. F., Stoner, G. R., & Reynolds, J. H. (2004). Object-based attention determines dominance in binocular rivalry. *Nature*, *429*(6990), 410–413.

Mitchell, J. F., Sundberg, K. a, & Reynolds, J. H. (2009). Spatial attention decorrelates intrinsic activity fluctuations in macaque area V4. *Neuron*, *63*(6), 879-88.

Moore, T., & Armstrong, K. M. (2003). Selective gating of visual signals by microstimulation of frontal cortex. *Nature*, *421*(January), 370-373.

Moore, T., & Fallah, M. (2001). Control of eye movements and spatial attention. *Proceedings of the National Academy of Sciences of the United States of America*, *98*(3), 1273-6.

Motter, B. C. (1994). Neural correlates of attentive selection for color or luminance in extrastriate area V4. *Journal of neuroscience*, *14*(4), 2178-2189.

Movshon, J. A., & Newsome, W. T. (1996). Visual response properties of striate cortical neurons projecting to area MT in macaque monkeys. *The Journal of neuroscience*, *16*(23), 7733-41.

Müller, J. R., Philiastides, M. G., & Newsome, W. T. (2005). Microstimulation of the superior colliculus focuses attention without moving the eyes. *Proceedings of the National Academy of Sciences of the United States of America*, *102*(3), 524-9.

Newsome, W. T., Britten, K. H., & Movshon, J. A. (1989). Neuronal correlates of a perceptual decision. *Nature*, *341*(6237), 52–54.

Nienborg, H., & Cumming, B. G. (2009). Decision-related activity in sensory neurons reflects more than a neuron's causal effect. *Nature*, *459*(7243), 89-92.

Nienborg, H., & Cumming, B. G. (2010). Correlations between the activity of sensory neurons and behavior: how much do they tell us about a neuron's causality? *Current opinion in neurobiology*, *20*(3), 376-381.

Nissen, M. (1985). Accessing features and objects: Is location special. In M. I. Posner & O. S. M. Marin (Eds.), *Attention and Performance XI* (pp. 205-219). Hillsdale, NJ: Erlbaum.

O'Craven, K. M., Downing, P. E., & Kanwisher, N. (1999). fMRI evidence for objects as the units of attentional selection. *Nature*, *401*(6753), 584-7.

Pack, C. C., Hunter, J. N., & Born, R. T. (2005). Contrast dependence of suppressive influences in cortical area MT of alert macaque. *Journal of neurophysiology*, *93*(3), 1809-1815.

Peterhans, E., & von der Heydt, R. (1993). Functional organization of area V2 in the alert macaque. *The European journal of neuroscience*, *5*(5), 509-24.

Peña, J. L., & Konishi, M. (2001). Auditory spatial receptive fields created by multiplication. *Science*, *292*(5515), 249-52.

Ponce, C. R., & Born, R. T. (2008). Stereopsis. *Current biology*, *18*(18), R845-50.

Ponce, C. R., Lomber, S. G., & Born, R. T. (2008). Integrating motion and depth via parallel pathways. *Nature neuroscience*, *11*(2), 216-23.

Price, N. S. C., & Born, R. T. (2010). Timescales of sensory- and decision-related activity in the middle temporal and medial superior temporal areas. *The Journal of neuroscience*, *30*(42), 14036-45.

Price, N. S. C., Ibbotson, M. R., Ono, S., & Mustari, M. J. (2005). Rapid processing of retinal slip during saccades in macaque area MT. *Journal of neurophysiology*, *94*(1), 235-46.

Priebe, N. J., Cassanello, C. R., & Lisberger, S. G. (2003). The neural representation of speed in macaque area MT/V5. *The Journal of neuroscience*, *23*(13), 5650-61.

Priebe, N. J., Lisberger, S. G., & Movshon, J. A. (2006). Tuning for spatiotemporal frequency and speed in directionally selective neurons of macaque striate cortex. *The Journal of neuroscience*, *26*(11), 2941-50.

Purushothaman, G., & Bradley, D. C. (2005). Neural population code for fine perceptual decisions in area MT. *Nature neuroscience*, *8*(1), 99-106.

Qian, N., & Andersen, R. A. (1997). A physiological model for motion-stereo integration and a unified explanation of Pulfrich-like phenomena. *Vision research*, *37*(12), 1683-98.

Qiu, F. T., Sugihara, T., & von der Heydt, R. (2007). Figure-ground mechanisms provide structure for selective attention. *Nature neuroscience*, *10*(11), 1492-9.

Recanzone, G. H., & Wurtz, R. H. (2000). Effects of attention on MT and MST neuronal activity during pursuit initiation. *Journal of neurophysiology*, *83*(2), 777-790.

Reynolds, J. H., & Heeger, D. J. (2009). The normalization model of attention. *Neuron*, *61*(2), 168-85.

Reynolds, J. H., Pasternak, T., & Desimone, R. (2000). Attention increases sensitivity of V4 neurons. *Neuron*, *26*(3), 703-14.

Rodman, H. R., Gross, C. G., & Albright, T. D. (1989). Afferent basis of visual response properties in area MT of the macaque. I. Effects of striate cortex removal. *The Journal of neuroscience*, *9*(6), 2033-50.

Rodman, H. R., Gross, C. G., & Albright, T. D. (1990). Afferent basis of visual response properties in area MT of the macaque. II. Effects of superior colliculus removal. *The Journal of neuroscience*, *10*(4), 1154-64.

Roe, A. W., & Ts'o, D. Y. (1995). Visual topography in primate V2: multiple representation across functional stripes. *The Journal of neuroscience*, *15*(5), 3689-3715.

Roe, A. W., Parker, A. J., Born, R. T., & DeAngelis, G. C. (2007). Disparity channels in early vision. *The Journal of neuroscience*, *27*(44), 11820-31.

Rossi, A. F., & Paradiso, M. A. (1995). Feature-specific effects of selective visual attention. *Vision research*, *35*(5), 621–634.

Rossi, A. F., Bichot, N. P., Desimone, R., & Ungerleider, L. G. (2007). Top down attentional deficits in macaques with lesions of lateral prefrontal cortex. *The Journal of neuroscience*, *27*(42), 11306-14.

Roy, J. P., & Wurtz, R. H. (1990). The role of disparity-sensitive cortical neurons in signalling the direction of self-motion. *Nature*, *348*(6297), 160-162.

Saenz, M., Buraĉas, G. T., & Boynton, G. M. (2002). Global effects of feature-based attention in human visual cortex. *Nature neuroscience*, *5*(7), 631-2.

Salzman, C. D., Murasugi, C. M., Britten, K. H., & Newsome, W. T. (1992). Microstimulation in visual area MT: effects on direction discrimination performance. *The Journal of neuroscience*, *12*(6), 2331.

Sasaki, R., & Uka, T. (2009). Dynamic readout of behaviorally relevant signals from area MT during task switching. *Neuron*, *62*(1), 147-57. Elsevier Ltd.

Schoenfeld, M A, Hopf, J.-M., Martinez, A., Mai, H. M., Sattler, C., Gasde, A., Heinze, H.-J., et al. (2007). Spatio-temporal analysis of feature-based attention. *Cerebral cortex*, *17*(10), 2468-2477.

Seidemann, E., & Newsome, W. T. (1999). Effect of spatial attention on the responses of area MT neurons. *Journal of neurophysiology*, *81*(4), 1783-94.

Seung, H. S., & Sompolinsky, H. (1993). Simple models for reading neuronal population codes. *Proceedings of the National Academy of Sciences of the United States of America*, *90*(22), 10749-53.

Shadlen, M. N., Britten, K. H., Newsome, W. T., & Movshon, J. A. (1996). a computational analysis of the relationship between neuronal and behavioral responses to visual motion. *The Journal of neuroscience*, *16*(4), 1486–1510.

Sincich, L. C., Park, K. F., Wohlgemuth, M. J., & Horton, J. C. (2004). Bypassing V1: a direct geniculate input to area MT. *Nature neuroscience*, *7*(10), 1123-8.

Smolyanskaya, A., Lomber, S. G., & Born, R. T. (2011). Individual neurons in MT have significant detect probabilities for motion and depth detection tasks. COSYNE Meeting Abstract (p. 259).

Spitzer, H., Desimone, R., & Moran, J. (1988). Increased attention enhances both behavioral and neuronal performance. *Science*, *240*(4850), 338.

Stepniewska, I., Qi, H. X., & Kaas, J. H. (1999). Do superior colliculus projection zones in the inferior pulvinar project to MT in primates? *The European journal of neuroscience*, *11*(2), 469-80.

Stoppel, C. M., Boehler, C. N., Strumpf, H., Heinze, H.-J., Noesselt, T., Hopf, J.-M., & Schoenfeld, M. A. (2011). Feature-based attention modulates direction-

selective hemodynamic activity within human MT. *Human brain mapping*, *32*(12), 2183-92.

Sàenz, M., Buraĉas, G. T., & Boynton, G. M. (2003). Global feature-based attention for motion and color. *Vision research*, *43*(6), 629-37.

Tanaka, K., Hikosaka, K., Saito, H., Yukie, M., Fukada, Y., & Iwai, E. (1986). Analysis of local and wide-field movements in the superior temporal visual areas of the macaque monkey. *Journal of neuroscience*, *6*(1), 134-144.

Thomas, O. M., Cumming, B. G., & Parker, A. J. (2002). A specialization for relative disparity in V2. *Nature neuroscience*, *5*(5), 472-8.

Treue, S. (2001). Neural correlates of attention in primate visual cortex. *Trends in neurosciences*, *24*(5), 295-300.

Treue, S., & Katzner, S. (2007). Visual attention: of features and transparent surfaces. *Trends in cognitive sciences*, *11*(11), 451-3.

Treue, S., & Martinez-Trujillo, J. C. (1999). Feature-based attention influences motion processing gain in macaque visual cortex. *Nature*, *399*(6736), 575-9.

Treue, S., & Maunsell, J. H. R. (1996). Attentional modulation of visual motion processing in cortical areas MT and MST. *Nature*, *382*(6591), 539-41.

Treue, S., & Maunsell, J. H. R. (1999). Effects of attention on the processing of motion in macaque middle temporal and medial superior temporal visual cortical areas. *The Journal of neuroscience*, *19*(17), 7591-602.

Uka, T., & DeAngelis, G. C. (2004). Contribution of area MT to stereoscopic depth perception: choice-related response modulations reflect task strategy. *Neuron*, *42*(2), 297-310.

Uka, T., & DeAngelis, G. C. (2006). Linking neural representation to function in stereoscopic depth perception: roles of the middle temporal area in coarse versus fine disparity discrimination. *The Journal of neuroscience*, *26*(25), 6791-802.

Ungerleider, L. G., & Desimone, R. (1986). Cortical connections of visual area MT in the macaque. *The Journal of comparative neurology*, *248*(2), 190-222.

Ungerleider, L. G., & Mishkin, M. (1982). Two cortical visual systems. *Analysis of Visual Behavior* (Vol. 549, pp. 549-586). MIT Press.

Wannig, A., Rodríguez, V., & Freiwald, W. A. (2007). Attention to surfaces modulates motion processing in extrastriate area MT. *Neuron*, *54*(4), 639-51.

Wichmann, F. A. & Hill, N. J. (2001): The psychometric function: I. Fitting, sampling and goodness-of-fit. *Perception and psychophysics, 63*(8), 1293-1313.

Wojciulik, E., Kanwisher, N. G., & Driver, J. (1998). Covert visual attention modulates face-specific activity in the human fusiform gyrus: an fMRI study. *Journal of neurophysiology*, *79*(3), 1574-8.

Xiao, D. K., Raiguel, S., Marcar, V., & Orban, G. a. (1997). The spatial distribution of the antagonistic surround of MT/V5 neurons. *Cerebral cortex*, *7*(7), 662-77.

Xiao, D. K., Raiguel, S., Marcar, V., Koenderink, J., & Orban, G. a. (1995). Spatial heterogeneity of inhibitory surrounds in the middle temporal visual area. *Proceedings of the National Academy of Sciences of the United States of America*, *92*(24), 11303-6.

Zaksas, D., & Pasternak, T. (2005). Area MT neurons respond to visual motion distant from their receptive fields. *Journal of neurophysiology*, *94*(6), 4156-67.

Zeki, S. M. (1974a). Cells responding to changing image size and disparity in the cortex of the rhesus monkey. *The Journal of physiology*, *242*(3), 827.

Zeki, S. M. (1974b). Functional organization of a visual area in the posterior bank of the superior temporal sulcus of the rhesus monkey. *The Journal of physiology*, 549-573.

Zhang, K., Ginzburg, I., McNaughton, B. L., & Sejnowski, T. J. (1998). Interpreting neuronal population activity by reconstruction: unified framework with application to hippocampal place cells. *Journal of neurophysiology*, *79*(2), 1017-44.

Zhang, W., & Luck, S. J. (2009). Feature-based attention modulates feedforward visual processing. *Nature neuroscience*, *12*(1), 24-5.

Zhou, H., & Desimone, R. (2011). Feature-Based Attention in the Frontal Eye Field and Area V4 during Visual Search. *Neuron*, *70*(6), 1205-17.