The Effects of Feature-Based Attention on the Discrimination of Letters and Numbers

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Abstract

Feature-based attention refers to the phenomenon that attending to a feature value (e.g., a specific shade of red) enhances the detection of similar feature values (e.g., the same shade of red or other shades of red similar to the attended shade) relative to different feature values (e.g., green) that belong to a different object, and that this facilitation effect can be found across the visual field. In previous studies, the participants' task was primarily the detection or discrimination of simple features such as orientation, colour or motion. The experiments reported in this thesis investigated whether feature-based attention could also influence the speed and/or accuracy of discriminating alphanumeric stimuli such as letters and numbers. In three experiments, participants saw displays that consisted of a series of stimulus patterns at a central location followed by the appearance of an alphanumeric stimulus at one of two peripheral locations. Experiment 1 tested whether paying attention to a specific orientation in a central stimulus would affect the speed and/or accuracy of identifying a peripheral letter whose principal axis was either the same as or different from the attended orientation of the central stimulus. Experiment 2 changed the peripheral stimulus from a letter to a number. In Experiment 3, a peripheral stimulus occurred randomly on 50% of the trials instead of on 100% of the trials. The results showed that attending to a specific orientation of a central stimulus could affect the processing efficiency of both letters and numbers at a peripheral location when the alphanumeric stimulus occurred on every trial (Experiments 1 and 2), but not when it appeared on 50% of the trials. These results suggest that feature-based attention could influence the identification of alphanumeric stimuli. However, the effect may be quite short-lived.

The effects of feature-based attention on the discrimination of letters and numbers

Visual attention is the process of selective enhancement and/or suppression of visual information which allows relevant information to be acted upon and irrelevant information to be ignored (Carrasco, 2011; Posner, 1980). Due to the vast amount of information in our natural environment and the limited processing capacity of our visual system, only a small fraction of what we see can be processed fully. Attention can be deployed overtly, by the movement of the eyes to fixate on an item or location, or covertly, which is independent of eye movements. Both overt and covert attention typically results in shorter response latencies and/or more accurate responses to the attended stimuli. Attention can also be directed endogenously or exogenously. Whereas endogenous attention is goal driven and directed towards a target deliberately, exogenous attention is stimuli driven and occurs automatically. Furthermore, attention can be directed towards a particular location, an object, or a specific feature value of a feature dimension (e.g. red or green). These forms of attention are referred to as space-based attention, object-based attention and feature-based attention, respectively. In real world viewing, these different types of attention often interact with each other and compete for the control of behaviour (Desimone, 1998; Desimone & Duncan, 1995; Posner, 1980; Shulman & Wilson, 1987). This thesis focuses on feature-based attention. Before I review the relevant literature on feature-based attention, I will briefly review space- and object-based attention because of their close relation to feature-based attention.

Types of attention

Space-based attention. Space-based attention refers to the deployment of attention to a specific location (see Cave, 2013, for review). Typically when attention is directed to a location, either overtly or covertly, the processing of objects at that location is facilitated.

Posner, Snyder and Davidson (1980) investigated space-based attention by comparing response times to a target presented at either a correctly or an incorrectly cued location. Participants saw displays that consisted of a cue followed by a target. In valid trials, which occurred 80% of the time, the target was presented at the location the cue indicated. In invalid trials, which occurred 20% of the time, the target was presented at one of the three other possible locations not indicated by the cue. Responses to the target were significantly faster in valid trials than in invalid trials. This study, together with many other studies (e.g., Eriksen & St. James, 1986; Posner, 1980; Tsal & Lavie, 1993), showed that attention can be deployed to a specific location and reduce the processing time of the stimuli at that location.

Evidence for space-based attention has also been found in neural studies. For example, Luck, Chelazzi, Hillyard, and Desimone (1997) measured the responses of cells in V1, V2 and V4 of two macaque monkeys whose task was to release a response bar when a target appeared at an attended location. They found that in both V2 and V4, attention modulated the responses of the majority of cells they measured. Specifically, when two stimuli, one preferred (i.e., a stimulus that the cell responds strongly to) and the other non-preferred (i.e., a stimulus that the cell responds weakly to), appeared simultaneously inside a cell's receptive field, the cell's responses became substantially larger when attention was directed to the preferred stimulus compared with when attention was directed to the non-preferred one, even though both stimuli remained within the cell's receptive field in both cases. Importantly, when the monkeys attended to a specific location within a cell's receptive field, the cell's baseline firing rate increased, even when there were no stimuli presented within the cell's receptive field. This demonstrates that there is an increase in the baseline firing of the neurons that corresponds to the attended location in response to spatial attention. Together, these results indicate that spatial attention can modulate the processing of a stimulus at both a neuronal and sensory level. Similar results of space-based attention have been reported in many other studies (e.g., Goldberg & Wurtz, 1972; Morgan, Hansen, & Hillyard, 1996; Woldorff, Fox, Matzke, Lancaster & Veeraswamy, 1997).

Object-based attention. Object-based attention refers to the deployment of attention to a part of an object or all of an object (see Chen, 2012, for review). Object-based attention typically results in faster and/or more accurate responses to features that belong to the same object compared with features that belong to different objects (e.g., Chen, 2000; Duncan, 1984), or if a task requires shifts of attention, attentional shift is faster within a single object rather than between different objects (e.g., Baylis & Driver, 1993; Chen, 1998; Egly, Driver, & Rafal, 1994). For example, Egly et al. (1994) showed their participants two equal sized parallel rectangles that were displayed either both vertically or horizontally. Participants were cued to one end of one rectangle, and shortly after this, a target would appear at one end of the rectangles. There were three types of trials: valid, same-object, and different-object trials. In valid trials, the target appeared at the cued location. In same-object trials, the target appeared at the uncued end of the cued object. In different-object trials, the target appeared on the uncued rectangle, at the end closest to the cued end of the other rectangle. The distance between the cue and the target were the same in both the same-object and different-object conditions. Participants responded fastest in the valid trials. Importantly, they also responded significantly faster in the same-object condition than in the different-object condition. These results demonstrate both space- and object-based effects of attention. They suggest that attention spreads from a cued end to an uncued end of an object more readily than from a cued end of one object to an uncued end of a different object an equal distance away.

Object-based attention can also facilitate the discrimination of features of an attended object. Duncan (1984) compared the cost of attending to one object with the cost of attending to two objects by measuring participants' accuracy in discriminating features that were either part of one object or parts of two objects. Two objects, i.e., a rectangle and a line, were shown superimposed at the same location. The rectangle had a gap on either the left or right side and could be large or small. The line could be dotted or dashed and tilted to the left or right. The display was shown briefly before being replaced by a mask. Participants responded to either one or two features of the objects that were presented. In the latter case, the features were either part of the same object (i.e., both features belonged to the rectangle or to the line) or parts of different objects (i.e., one feature belonged to the rectangle and the other to the line). The results showed that responding to two features had a cost (i.e., lower accuracy) relative to responding to one feature if and only if the two features were parts of two different objects. This cost could not be attributed to space-based attention because both objects were displayed at the same location.

Feature-based attention. Feature-based attention is deployed when attention is paid to either a feature dimension such as colour or orientation, or to a specific feature value of a feature dimension such as red or vertical (see Carrasco, 2011, for review). In this thesis, I will focus on feature value. One of the first studies of feature-based attention was reported by Shulman and Wilson (1987), who found that attending to a feature value facilitated the detection of similar feature values. In that study, participants were shown two sequentially presented stimulus configurations, each consisting of a global letter made of local letters, for example, a large letter T made up of small letter H’s. This means that the same stimulus configuration could be attended at a global/large level (T) or at a local/small level (H). Participants were cued to attend to either the global letter or the local letters and then to respond to whether the attended letter was in the first or second half of the alphabet. Half of the trials also contained a secondary task. In those trials, a near detection threshold sinusoidal grating was sometimes added shortly after the onset of the second stimulus configuration.

Following the response to the letter task, the participants were asked if they detected a grating. It was found that when the participants were cued to attend to the global stimulus in the letter task, they were better at detecting the gratings that had a lower spatial frequency. Conversely, when the participants were cued to attend to the local stimuli, they were better at detecting the gratings with a higher spatial frequency. These results demonstrated that the level of attention (i.e., global/large vs. local/small) influenced the detectability threshold of a peripheral grating. The improved detection of the attended feature value is consistent with the notion that attending to a specific feature value enhances the processing of stimuli with similar feature values, and that the facilitation in performance does not have to be limited to features that belong to the same object.

Evidence for feature-based attention has also been found in single-cell recording studies and in fMRI and EEG studies (e.g. Martínez-Trujillo & Treue, 2004; Liu, Larsson & Carrasco, 2007; Snyder & Foxe, 2010; Treue & Martínez-Trujillo, 1999). Treue and Martínez-Trujillo investigated the neural correlates of feature-based attention. They compared the response rate of middle temporal (MT) cells when attention was directed to a stimulus pattern either within or outside the cells' receptive field (RF) and when the attended direction of motion was in the preferred or non-preferred direction. In one experiment, the monkeys were shown two random dot patterns (RDP), one inside a cell's RF and one outside, and either RDP could be attended to. While the dots in the RDP inside the cell's RF were always in the cell's preferred direction of motion, the dots in the RDP outside the cell's RF were equally likely to be in the cell's preferred or anti-preferred direction of motion. When the RDP inside the RF was attended to, the firing rate of the cell was not influenced by the direction of motion of the dots in the RDP outside the RF. However, when the RDP outside the receptive field was attended to, the direction of motion of the dots modulated the neural response of the cell inside the RF. Attending to the cell's preferred direction to a stimulus outside its RF increased the cell response rate by 13%. This shows that feature-based attention causes an increase in a cell's response only when the task was behaviourally relevant.

More recently, Saenz, Buracas and Boynton (2002) used fMRI to measure the effect of feature-based attention on the neural responses of unattended stimuli. The areas of interest were V1, V2, V3, V3a, V4 and MT+ areas. The stimulus display consisted of two RDPs, an attended one in one hemi-field, and an ignored one in the other hemifield. The unattended RDP contained motion in a single direction and the attended RDP contained overlapping fields of dots moving upwards and downwards. On each trial, the participants were cued to attend to the dots moving in one direction. The results showed that when the target dots moved in the same direction as those in the ignored RDP, there was a stronger neural response to the ignored RDP than when the target dots moved in the opposite direction. Similar results were found in a subsequent experiment when attention was paid to colour. These findings suggest that when a feature value is attended to its processing is increased across the whole visual field, even at ignored locations.

Common paradigms in feature-based attention research

Since Shulman and Wilson's study (1987), there have been many experiments on feature-based attention using a variety of experimental paradigms (e.g., Liu & Mance, 2011; Wegener, Ehn, Aurich, Galashan & Kreiter, 2008; White & Carrasco, 2011). As the experiments reported in this thesis used behavioural measures (i.e., reaction times and accuracy) to investigate feature-based attention, my review of the paradigms will be limited primarily to those used in behavioural studies. It should be noted, however, that feature-based attention has also been studied using a variety of physiological measures as the two studies described above demonstrate. One commonly used paradigm in behavioural studies is what I will refer to as the detection/discrimination paradigm. In this paradigm (e.g. Rossi & Paradiso, 1995; Saenz, Buracas & Boyton, 2003; Shulman & Wilson, 1987; White & Carrasco, 2011), participants typically complete a primary task that requires attention to be paid to a specific feature value of one stimulus, and then on some trials perform a secondary task that requires them to detect, or to make a discrimination about, a second stimulus that has either the same feature value as or a different feature value from that of the previously attended object. The Shulman and Wilson study that I described earlier is an example of this paradigm.

The study conducted by Rossi and Paradiso (1995) also used the detection/discrimination paradigm. In this study, the primary stimuli were Gabor patches (sinusoidal gratings). On each trial, two Gabor patches were shown in the centre of the display sequentially. Depending on the trial type, the participants' task was to make an orientation or spatial frequency judgment about the two patches. One third of the trials also contained a secondary task. In these trials the task was to detect a surround grating presented shortly after the offset of the second Gabor patch. The surround grating, which varied in orientation and spatial frequency, did not overlap in location with the primary stimuli.

The results showed feature-specific attentional effects. In orientation trials the participants detected the presence of the surround grating better when its orientation was similar to that of the central Gabor patch. Whether the spatial frequency of the grating was similar to the central patch did not affect performance. In spatial frequency trials, the participants detected the presence of the surround grating better when it had a similar spatial frequency or a similar orientation as that of the Gabor patches they had recently been attending to. These results show that feature-based attention can improve the detection of similar feature values at an unattended location. Importantly, when the participants in a subsequent experiment were asked to passively view the first two Gabor patches and then respond to whether the critical surround grating was presented, the feature-based facilitation in orientation and/or spatial frequency was no longer found. This indicates that the facilitation was due to the effect of attention rather than the effect of low-level stimulation of a stimulus with a specific feature value. Whereas Shulman and Wilson's (1987) findings show that attending to a feature value enhances the subsequent detection of items which share that feature value, the study by Rossi and Paradiso (1995) indicates that feature-based attentional effects can sometimes extend to task irrelevant feature values of an attended item.

In addition to the detection/discrimination paradigm, another paradigm commonly used in feature-based attention research is the adaptation paradigm, in which the primary measure is the strength of attention-induced adaptation such as motion or tilt aftereffects (e.g. Boynton, Ciaramitaro & Arman, 2006; Liu et al., 2007; Liu & Mance 2011). The experiments using the adaptation paradigm typically consist of two phases. The first is an adaption phase, during which participants attended to a feature value at a specific location. The second is a test phase, during which the effect of adaptation on a stimulus at an unattended location was measured.

Boynton et al. (2006) measured how feature-based attention affected the motion aftereffect induced by an unattended object. The adapting phase consisted of two stimuli, one in an attended hemifield and one in an unattended hemifield. The stimulus in the attended hemifield, which consisted of two overlapping fields of upward and downward moving dots at one side of a central fixation, was displayed twice with a short interval in between. The participants attended to dots moving in one direction. In different experiments, the task was speed discrimination or luminance discrimination. In the opposite hemifield the ignored stimulus contained dots moving only upwards or downwards. The critical manipulation was whether the dots in the unattended stimulus moved in the same direction as the attended direction of motion in the attended stimulus. This adaptation phase was followed by the test phase where a probe stimulus was presented at the location of the unattended stimulus. The probe consisted of dots which were either stationary or moving very slowly upwards or downwards. The participants' task was to decide the dots' direction of motion. The results showed that the motion aftereffect of the unattended stimulus was stronger when it contained dots moving in the same direction rather than moving in the opposite direction to the attended direction of motion during the adaptation stage. Importantly, the magnitude of the motion aftereffect was similar regardless of whether the task was speed or luminance discrimination, indicating that the effect was not task specific. As this attention-induced adaptation effect occurred to an object different from the attended object and the two objects were at different spatial locations, this effect is consistent with the notion that feature-based attention can spread across the visual field.

In the two paradigms described above, participants typically perform two tasks (i.e., a primary task that requires responses on every trial and a secondary task that requires responses on either every trial or a proportion of trials). Accuracy and/or detection thresholds were the dependent variables that measure the effect of feature-based attention to one stimulus on the perception of a second stimulus. A third paradigm uses response latencies to measure feature-based attention (e.g., Ho, Brown, Abuyo, Ku & Serences, 2012; Wegener et al., 2008). In this paradigm, participants typically perform a single task. Response latencies across different conditions or different experiments within the same study were compared to determine the effect of feature-based attention. For example, Wegener et al. compared the difference in the time taken to detect a change to a feature dimension when both that feature and the object with the feature were cued (validly or invalidly) and when only the object was cued. In one experiment, participants saw a display that consisted of two drifting sine-wave gratings at left and right of fixation. Either the colour or the speed of one of the gratings could change. The task was to report changes in speed or colour as fast as possible. The participants were cued (correctly on 75% of the trials and incorrectly on the rest of the trials) either to the object where the change would occur or to the specific feature dimension (i.e., colour or speed) which would undergo the change. The results showed that the participants were faster to detect the change when an object was correctly than incorrectly cued. Furthermore, they were also faster when a feature was correctly than incorrectly cued regardless of whether the object was correctly cued. Interestingly, relative to the condition when only the object was cued (i.e., neither the colour nor the speed of the object was cued), participants were slower to respond to an incorrectly cued feature. These results suggest a functional advantage of feature-based attention over and above object-based attention, and a processing cost for an unattended feature when attention is paid to another feature relative to when attention is not directed to any specific features.

Factors that modulate feature-based attention

The studies described above demonstrate that the deployment of attention to a feature value facilitates the processing of that feature value at both attended and unattended locations. Several studies have investigated the factors that influence the strength and spread of this facilitation. Both behavioural and neural studies have demonstrated that the effects of feature-based attention are both stronger and can be detected earlier when the attended stimuli contain response-competing irrelevant information (distractors) than when irrelevant distractors are not present (Saenz, Buracas & Boyton, 2002; Saenz et al., 2003; Zhang & Luck, 2009).

Zhang and Luck (2009) demonstrated the effects of distractors by comparing attentional modulation of the P1 wave in several experiments. In these experiments red and/or green dots were displayed on one side of fixation and the participants were required to detect a luminance change to the dots of a cued colour. On the other side of fixation (the ignored side), either red or green probe dots were flashed. Feature-based attentional modulation was indicated by the difference between the P1 wave produced by the task irrelevant probe dots of the attended colour and the P1 wave produced by the task irrelevant probe dots of the ignored colour. In two experiments the red and green dots were intermixed on the attended side of fixation and displayed concurrently. In the third experiment they were displayed sequentially. In the experiments with the mixed dots, P1 amplitude measuring the probe dots was larger when the colour of these dots matched the colour of the attended dots compared with when they matched the colour of the unattended dots in the first, indicating feature-based attention. However, evidence for feature-based attention was not found in the third experiment. These results demonstrate that at a neural level feature-based attention is modulated by the presence or absence of distractors in the attended field.

The effect of distractors on feature-based attention has also been found in behavioural studies. In one experiment, Saenz et al. (2003) showed participants displays that consisted of two simultaneously presented RDPs, one on each side of fixation. Each RDP consisted of 100 dots with 50 of the dots moving upwards and 50 of the dots moving downwards. Participants performed a divided attention task, which was to detect a speed change at each RDP to either the dots moving upwards or the dots moving downwards. The experiment had two conditions. In the same condition, the participants attended the same direction in both RDPs (upwards/upwards, or downwards/downwards). In the different condition, the participants attended to a different direction in each RDP (upwards/downwards, or downwards/upwards). The results showed that the participants responded more accurately in the same condition than in the different condition. Importantly, when the experiment was replicated with the exception that each RDP contained only the dots moving in the attended direction, the magnitude of the effect was much smaller. These results were in line with those found by

Zhang and Luck (2009), demonstrating that feature-based attention is stronger when distractors are present.

Another factor which can influence the strength of feature-based attention is whether the feature in question is a task-irrelevant incidental feature or a task-relevant feature that needs to be acted upon. Born, Ansorge and Kerzel (2012), in a study designed to determine the coupling of attention and saccades, compared the strength of feature-based attention in an experiment where colour was a task-relevant feature for a saccade before the participants judged the shape of another target whose colour was either matched (the same condition) or mismatched (the different condition) that of the saccade target, with the strength of feature-based attention in an experiment where colour was an incidental feature for the saccade target that preceded the discrimination task. The magnitude of feature-based attention, i.e., better performance in the same than the different condition, was larger when colour was a task-relevant than irrelevant feature, suggesting that feature-based attention is modulated by task relevancy. It should be noted, however, that in addition to task relevancy, the two experiments also differed in intertrial priming (see Theeuwes, 2013, for a review), for the experiment with the task-relevant colour used a blocked design where the colour of the saccade target was the same throughout the entire experiment. As the authors pointed out, this raised the possibility that feature-based attention in that study was caused, at least to some extent, by intertrial priming.

One factor that does not appear to influence the strength of feature-based attention is the eccentricity from the attended location. Many studies have demonstrated that feature-based attention spreads to unattended locations of the visual field (i.e. Boynton et al. 2006; Liu & Mance 2011; Rossi and Paradiso, 1995; Saenz et al., 2002; Treue & Martínez-Trujillo, 1999; White & Carrasco 2011). Importantly, it has also been demonstrated that the strength of feature-based attention remains constant across the visual field, or across hemifeilds. In one experiment, Liu and Mance (2011) compared the strength of attention deployed to a distractor that was in the same hemifeild as the probe with the strength of attention deployed to a distractor that was in the hemifeild opposite to the probe. They systematically manipulated the spatial separation between an attended RDP and a probe RDP, then compared the strength of the attention induced motion aftereffect (MAE) at different locations of the probe RDP. The experiment contained an adaptation phase and a test phase. The adaptation phase consisted of two displays of a RDP which contained both upwards and downwards moving dots, and the participants completed a speeded discrimination task on the dots moving in a cued direction. The RDP was presented 10^o from the centre of the display in either the upper right or lower right quadrant of the display. Following the adaptation phase the test phase began. In the test phase, the probe RDP was presented 10^o from the centre of the display in one of the three remaining quadrants which the adapting stimuli had not been presented in. It was found that the strength of the MAE was the same across locations. In other words, the effect was not stronger when the probe RDP was presented in the same hemifield as the adapting RDP, if both RDPs were presented in the bottom or top half of the display or if the probe was presented in the most distant quadrant diagonally adjacent to the probe. These results, together with the results of another experiment which compared the strength of the MAE at 5^o, 10^o and 15^o eccentricity from a central adaptor and did not find an effect of eccentricity on the strength of the attention induced MAE, provide strong evidence that the strength of feature-based attention is constant across the visual field.

Aims of the present study

The present study aims to generalize and extend the findings from previous feature-based attentional research (e.g. Boynton et al., 2006; Liu et al., 2007; Liu & Mance 2011; Rossi & Paradiso, 1995; Ho et al., 2012; Wegener et al., 2008). In previous studies, the participants' task was primarily the detection or discrimination of simple features regarding orientation, colour, or motion, and so far, only a couple of studies have used response latencies as a primary dependent measure (i.e., Ho et al., 2012; Wegener et al., 2008). The experiments in this thesis were designed to determine whether feature-based attention could also influence the speed and accuracy of discriminating alphanumeric stimuli such as letters and numbers.

The Present Study

The present study investigates whether attending to a specific feature at one location can influence the speed and/or accuracy of discriminating letters and numbers at a different location. In three experiments, participants saw displays that consisted of a series of stimulus patterns followed by the appearance of a letter (Experiment 1) or a number (Experiments 2 and 3). Each trial consisted of two phases: an attention-inducing phase followed by a probe phase. During the attention-inducing phase, participants saw a centrally presented compound stimulus that consisted of lines of two different orientations and colours. Participants were required to pay attention to the lines at a specific orientation while ignoring the lines at a different orientation and to count the number of times a critical display, in which the lines at the attended orientation changed from being dashed to being dotted, was presented. In the probe phase, either a letter or a number would appear briefly at one of two peripheral locations. The orientation of the test stimulus matched the orientation of either the attended or unattended lines. The participants performed two tasks on each trial. The first task was to make a speeded letter or number discrimination either on every trial (Experiments 1 and 2) or on some of the trials (Experiment 3), and the second task was to report the number of critical displays that were presented. The effects of feature-based attention were measured by comparing the differences in response time and accuracy when orientation of the probe letter or number matched or was different from the orientation of the previously attended or ignored lines in the adaptation phase. Based on previous research, it was hypothesized that attending to a specific orientation of the lines during the adaptation phase would result in faster and/or more accurate responses to letters or numbers when they were shown at an attended rather than unattended orientation.

Experiment 1

In Experiment 1, the attention-inducing phase was followed by the probe phase in every trial. The stimuli in the probe phase were the letters E and F presented in an orientation that matched either the attended or the ignored orientation during the attention-inducing phase. Of special interest was whether responses to the letter discrimination task (E or F on a given trial) differed depending on whether they were presented at either the attended or the ignored orientation.

Methods

Participants. Twenty-two students (mean age 22, nine male) with normal or corrected to normal vision from the University of Canterbury, New Zealand, participated in Experiment 1. They either completed the experiment for course credit or were remunerated with a $10 shopping voucher. All participants were given a verbal description of the task and read a brief information sheet about the nature of the experiment (in general terms without mentioning any specific hypotheses) before giving informed consent. All the experiments presented here were approved by the University of Canterbury Human Ethics Committee prior to participant recruitment.

Apparatus and Stimuli. Stimuli were displayed on a 40.5cm CRT monitor with a refreshing rate of 85 Hz. E-prime version 2.0 was used to display stimuli and collect responses. The participants (whose heads were not restrained) viewed the display from approximately 60 cm in a dimly lit room. All responses were recorded through a Cedrus response box (model RB-830). The relevant keys on the response pad were labelled to indicate to the participants which buttons to respond with.

All trials started with a fixation cross, which consisted of a plus sign that subtended a visual angle of 0.95^{o} both horizontally and vertically. The primary stimulus display during the attention-inducing phase was a compound grating configuration that consisted of two overlapping fields of gratings, each with five equally spaced parallel lines (see Figure 1). One field of grating was orientated at 45^{o} clockwise, and the other at 45^{o} counter clockwise from the vertical axis. The centre of the grating configuration contained a small black dot ($.25^{o}$ visual angle). The dot acted as a fixation point during the attention-inducing phase. On each trial, the lines of one orientation were red (RGB 255, 0, 0) while those of the other orientation were blue (RGB 0, 0, 255). The colour was determined randomly at the start of each trial and remained consistent throughout the duration of a given trial. The grating configuration was presented in the centre of the computer screen and subtended 6.2^{o} of visual angle both horizontally and vertically. It could be displayed in one of two states, either the normal state (Figure 1a) or the critical state (Figure 1b). In the normal state, the lines at both orientations were dashed. In the critical state, the lines at the attended orientation became dotted while those at the unattended orientation remained dashed. The stimulus pattern in the attention–inducing phase had lines at both the attended and the ignored orientation for two reasons. Firstly, previous studies have found that feature-based attention has a stronger effect when distractor stimuli are present (Saenz et al., 2003; Zhang & Luck 2009). Secondly, having lines at both orientations could control for low level visual effects such as adaptation, and this would ensure that any differences in response were likely to be induced by attention rather than by adaptation. The stimuli in the probe phase were presented peripherally to measure feature-based attention at a global level.

(a) (b)

Figure 1. An example of the stimuli used in the attention-inducing phase, assuming that the participants were instructed to attend to the lines that were oriented counter clockwise from the vertical. (a) The standard state, in which the lines at both the attended and unattended orientations were dashed. (b) The critical state, in which the lines at the attended orientation were dotted. The colour of the lines could alternate between trials but remained constant within a trial.

The probe stimulus in the probe phase consisted of the letter E or F. The letters were custom made, and each was 1.9° by 1.9° of visual angle and displayed 7.1° to the left or right of the fixation with equal frequency. It was equally likely to be orientated either 45° clockwise or counter clockwise from the vertical. At these orientations, the main axis of the letter was either congruent (i.e., the same orientation) or incongruent (i.e., orthogonal to the attended orientation) with the attended direction.

Procedure. A within-subjects repeated measures design was used. The experiment consisted of two practice blocks and two experimental blocks. Trials were blocked by the orientation the participants attended to, and each participant completed one practice block and one experimental block for each of the two orientations. Each practice block consisted of two sets of three trials with a break between each set. The experimental blocks consisted of four sets of sixteen trials with a message for break between each set, and to press any key to continue when they were ready. In order to ensure speed and accuracy, the participants were monitored during the practice blocks. Those participants not responding fast or accurately enough were given additional practice.

The procedure of a trial was as outlined in Figure 2. Each trial began with a 1000 ms display of the fixation cross followed by a 500 ms blank interval. This was followed by the primary display. To prevent participants from anticipating the probe stimulus, the primary display consisted of either 25 or 29 frames, with the number of frames in a trial determined randomly. Each display lasted for 250 ms and was followed by a 120 ms blank screen which acted as an interstimulus interval (ISI). The primary stimulus was displayed in either the normal state where the lines at both orientations were dashed, or the critical state, where the lines at the attended orientation were dotted. Participants were instructed to count the number of times the attended lines changed from the normal state to the critical state. However, they were instructed to withhold their response until a prompt appeared at the end of the trial, which occurred after the letter discrimination task.

The critical state was shown between one to three times on each trial. The position of the critical display in the sequence of displays was determined randomly, with the exception that the critical state was not shown on either the first or the last display in a trial. The latter was to prevent the detection of the critical display from interfering with the letter discrimination task, which occurred following the attention-inducing stage. The offset of the grating configuration was followed by a blank screen of 120 ms, and this in turn was followed immediately by the presentation of the letter E or F. The letter was presented equally likely to the left or right of the centre of the screen for 120 ms. The main axis of the letter was oriented 45^{o} clockwise or counter clockwise so that the letter as a whole was equally likely to match either the orientation of the attended lines (the congruent condition) or that of the ignored lines (the incongruent condition) in the counting task. Following the probe stimulus the screen went blank until participants responded to the letter they had just seen. They were instructed to respond as quickly and as accurately as possible. Once a response to the probe stimulus had been registered, a question mark appeared. It cued the participant to indicate the number of dotted displays that were shown. For this counting task, only accuracy was emphasized.

The participants were instructed to use their left hand to respond to the counting task by pressing the ‘1’, ‘2’ or ‘3’ keys using their ring finger, middle finger and index finger, respectively. With their right hand, they responded to the probe task by pressing the ‘4’ and ‘5’ keys using their index and middle finger for E and F, respectively.

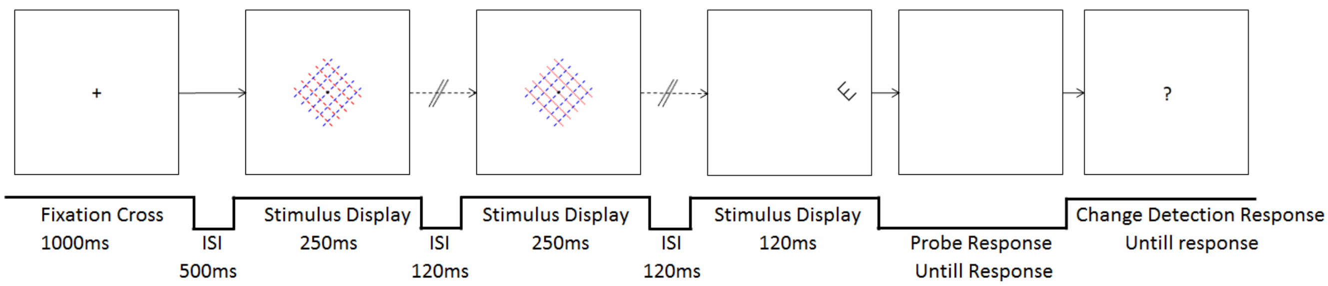


Figure 2. Stimulus sequence for Experiment 1. Participants attended to a specific orientation throughout the trials in a block. In this example, the attended orientation is 45^{o} counter clockwise.

Results and Discussion

Of the 21 participants who completed this experiment (one did not complete the experiment because of computer failure), four were excluded from data analyses due to either high error rates in the counting task or slow responses to the probe stimuli. Only the data from the trials where the participants correctly completed the counting task and responded to the probe within 1620 ms from stimulus onset were included in the data analyses. Less than 2.2% of the data exceeded the reaction time limit and were excluded.

The accuracy for the counting task was 91.7%. Response latency in the letter discrimination task was measured from stimulus onset. Response time was significantly slower in the congruent condition (Mean = 780.3 ms, S.D. = 176.2 ms) than in the incongruent condition (Mean = 759.7 ms, S.D. = 161.4 ms), $t(16) = 2.38$, $p = 0.03$; $d = 0.12$. The difference in the error rate between the congruent condition (Mean = 1.9%, S.D. = 2.3%) and the incongruent condition (Mean = 2.1%, S.D. = 2.6%) was not significant, $t(16) = -0.15$, $p = 0.88$; $d = 0.08$.

Surprisingly, there was a negative congruency effect. The participants responded faster in the incongruent than the congruent condition. A close inspection of the stimulus displays revealed that this effect may be due to the specific stimuli used in the letter discrimination task. The critical difference between the letter E and F was the presence or absence of a single horizontal line which appeared at the bottom of only the letter E. When the letter was oriented 45^{o} to the left or right from the vertical, this critical line was orthogonal to the main axis of the letter. This means that in incongruent trials the critical line, which was the discriminating feature between E and F, was always in the same orientation as the attended lines in the primary stimulus. In other words, if feature-based attention facilitated the detection of the attended feature and if the participants focused their attention on the critical line of the probe because of its role in discriminating E from F in the letter discrimination task, they should be faster to do the letter discrimination task in the incongruent than the congruent condition, a result found in Experiment 1. In the next experiment, I investigated whether the negative congruency effect found in Experiment 1 was indeed caused primarily by the specific stimuli used in Experiment 1.

Experiment 2

In Experiment 2, as in Experiment 1, each trial consisted of both an attention-inducing phase and a probe phase. Unlike Experiment 1, the stimuli in the probe phase were the numbers 6 and 9 oriented either clockwise or counter-clockwise (see Figure 3). These stimuli were chosen for two reasons. First, unlike E and F, the new stimuli could not be discriminated by the presence or absence of a single feature. In fact, they were constructed in such a way that they were identical in features (i.e., each was made of 3 horizontal lines and two vertical lines), but different in how these features were combined spatially. Second, because of the way they were constructed, when they were orientated so that their orientation matched that of the attended orientation of the adapting stimulus, there was no critical feature in either of the number stimuli that would align with the ignored orientation of the adapting stimulus, reducing the possibility that feature-based attention would lead to a reversed congruency effect as found in Experiment 1. Based on the results of Experiment 1, it was hypothesized that the participants would respond faster and/or more accurately to the number presented at a previously attended orientation rather than an unattended orientation.

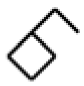
Methods

Participants. Twenty one students (mean aged 23, four male), none of whom had participated in Experiment 1, were recruited for Experiment 2. To facilitate participant recruitment a $15 shopping voucher was offered to the paid participants. All the other aspects of the participants were the same as those described in Experiment 1.

Apparatus and Stimuli. In both practice and experimental trials the stimuli and material were the same as in Experiment 1 except for the probe stimuli, which were Arabic numerals 6 and 9 presented in a custom made font (see Figure 3).

Procedure. The procedure for Experiment 2 was also the same as that for Experiment 1 except that instead of using the index and middle fingers of their right hand to respond to ‘E’ and ‘F’ the participants used their index and middle finger to respond to ‘6’ and ‘9’, respectively.

(a)



(b)

Figure 3. An example of the probe stimuli for Experiment 2. Six (a) orientated clockwise and nine (b) orientated counter clockwise.

Results and Discussion

Four participants were excluded because they exceeded a 25% error rate in the counting task. Again, only the data from those trials where the participants were correct in the counting task and responded to the probe within 1620 ms from stimuli onset were included in data analyses. Less than 2.2% of the data exceeded the reaction time and were excluded.

The accuracy for the counting task was 93%. The mean response latency for the congruent condition (Mean = 706.6 ms, S.D. = 188.8 ms) and for the incongruent condition (Mean = 714.6 ms, S.D. = 181.7 ms) were not significantly different, $t(16) = -0.88$, $p = 0.19$; $d = 0.04$. There was however a significant difference in the error rates between the conditions. The error rate for the congruent condition (Mean = 1.6%, S.D. = 3.2%) was significantly lower than that for the incongruent condition (Mean = 2.5%, S.D. = 3.1%), $t(16) = -1.99$, $p = 0.03$: $d = 0.29$.

Thus the negative congruency effect disappeared with these new stimuli. Instead, a positive congruency effect was found in accuracy. This result is consistent with feature-based attention. It also suggests that the negative congruency effect found in Experiment 1 was indeed most likely the result of the specific stimuli used in that experiment.

Experiments 1 and 2 show that feature-based attention can enhance the discrimination of alphanumeric stimuli. In both experiments, the participants performed the letter/number task on each trial. In previous investigations of feature-based attention, the probe stimuli was displayed on only a proportion of trials in order to discourage participants from attending to the possible location of the probe stimuli (i.e. Rossi & Paradiso, 1995; Shulman & Wilson, 1987). To investigate whether the effect of feature-based attention on alphanumeric stimuli could be found when the probe stimuli appeared on only some of the trials in the present paradigm, I reduced the percentage of the probe trials to 50% of the total trials in Experiment 3.

Experiment 3

Experiment 3 was the same as Experiment 2 except that a number discrimination probe stimulus followed the attention-inducing displays on only half of the trials. Of specific interest was whether evidence for feature-based attention could again be found.

Methods

Participants. Twenty five students (mean age 21, six male), who had not participated in the previous experiments, were recruited for Experiment 3. They were otherwise as described in Experiment 2.

Apparatus and Stimuli. In both the practice and experimental trials the stimuli and material were the same as those in Experiment 2.

Procedure. The procedure for Experiment 3 was the same as that for Experiment 2 with two modifications. Firstly, the probe stimuli followed the attention-inducing displays

displays on 50% of trials. The occurrence of a probe display on a given trial was determined randomly. Secondly, the practice trials were two subsets of six trials rather than two sets of three trials as in Experiments 1 and 2. The practice block was extended due to the reduced frequency at which the probe stimuli were displayed, and doubling the amount of practice trials was required to ensure that the participants had roughly the same amount of practice responding to the probe stimuli as in the previous experiments.

Results and Discussion

One participant was excluded from analyses because he or she exceeded a 20% letter discrimination error rate. Again, only results from the trials where the participants correctly completed the counting task and responded to the probe within 1620 ms were included in the data analyses. Less than 0.59% of the data exceeded the reaction time limit and were excluded.

The accuracy for the counting task was 91.9%. For the probe number discrimination task, the difference in response latencies between the congruent condition (Mean = 697.8 ms, S.D. = 139.0 ms) and the incongruent conditions (Mean = 695.8 ms, S.D. = 131.9 ms) was not significant, $t(23) = 0.21$, $p = .41$; $d = 0.01$. Furthermore, the difference in the error rate for the congruent condition (Mean = 3.1%, S.D. = 3.6%) and the incongruent condition (Mean = 4.1%, S.D. = 5.9%) was not significant, either, $t(23) = -0.71$, $p = .24$; $d = 0.2$.

In Experiment 3 there was no evidence of feature-based attention. How can we explain this result? One possible explanation is the reduced motivation to sustain attention to the end of the primary display. In all the three experiments, the participants were aware that the maximum number of texture change was 3 times per trial. In Experiment 1 and 2, because a probe stimulus always appeared shortly after the offset of the last primary frame and there was no way to determine which frame was the last one until the onset of the probe stimulus due to the varied number of frames in the primary display, the participants had to continue paying attention to the primary display until a probe stimulus appeared. In contrast, in Experiment 3, there was only a 50% chance of a probe stimulus being displayed. This meant there could be a lower incentive for the participants to continue to attend to the primary display if they had already counted three critical displays. This reduced motivation to sustain attention to the end of the primary display could have led to the null result found in Experiment 3. Alternatively, because participants knew that a probe would appear on only 50% of the trials, they might have allocated most of their attentional resources to the primary display at the expense of the number discrimination task. Compared with the error rate in Experiment 2 (an average of 2.1%), the error rate in Experiment 3 was numerically higher (an average of 3.6%), although this difference was not statistically significant, $F(1,39) = 2.18$, $p = 0.3$. This suggests that participants may have paid less attention to the probe stimulus in this experiment. However, it is unclear how reduced attention would contribute to the null result of Experiment 3.

General Discussion

The experiments presented in this thesis investigated the effects of feature-based attention on the discrimination of letters and numbers. The results demonstrated that feature-based attention can facilitate the discrimination of both letters and numbers, to a limited extent. This facilitation is expressed as an inverse congruency effect in reaction time in Experiment 1 and as a congruency effect on accuracy in Experiment 2. These results cannot be attributed to low level visual effects such as adaptation because the stimulus configuration used in the attention-inducing phase consisted of lines of both the attended and ignored orientations.

Experiment 3 did not produce a significant result. As stated previously, this could be caused by reduced incentive to continue attending to the relevant orientation once the attention-inducing stimulus had undergone three critical displays. If the null result in Experiment 3 reflects a lack of incentive to attend to the probe stimuli, it appears the effects of feature-based attention may be transient. Further research is needed to explore this issue.

These experiments provide converging evidence to support and expand the findings of previous search on feature-based attention. Previous research has shown that feature-based attention can spread globally in that attending to a specific feature value at one location facilitates the processing of the same feature value at other locations (Liu & Mance, 2011; Saenz et al., 2003; White & Carrasco, 2011). In both Experiments 1 and 2, attention was directed initially towards a centrally presented stimulus pattern. Yet, the effect of attending to a specific orientation of the central stimulus was found in a peripherally presented probe stimulus, suggesting that feature-based attention is not tied to a specific location or object. The results in the present study are also consistent with the findings of prior research that feature-based attention can affect the speed of visual information processing (e.g. Ho et al., 2012; Wegener et al., 2008). If we assume that the participants in Experiment 1 performed the letter discrimination task on the basis of the presence or absence of a critical, discriminating feature between the two probe letters (i.e., the presence of a horizontal bar at the lower part of the letter E, which is absent in the letter F), they were faster when the orientation of that bar was the same as the attended orientation in the central stimulus, indicating that attending to the orientation of one stimulus could facilitate the discrimination of another stimulus having the same feature. In addition, the results of Experiments 1 and 2 are consistent with previous research in showing that feature-based attention can act on two completely unrelated tasks (e.g., Shulman & Wilson, 1987). In all the three experiments reported in this thesis, the task associated with the attention-inducing stimulus was a counting task while the task associated with the probe stimulus was letter or number discrimination. Yet, feature-based attention was found in both Experiments 1 and 2, suggesting that feature-based attentional effect is not task-specific.

The results of Experiment 1 and 2 also extend previous research by showing that feature-based facilitation can influence the speed and/or accuracy of the discrimination of alphanumeric stimuli. The congruency effect found in Experiments 2 suggests that feature-based attention may not only facilitate the detection or discrimination of simple features but also increase the sensitivity of perceiving and interpreting stimuli shown from a specific viewpoint. As mentioned before, discriminating the number 6 from the number 9 in the custom-made font could not be accomplished by the presence or absence of a critical feature value. Instead, the specific spatial arrangement of the same set of horizontal and vertical lines needs to be perceived and interpreted. If the participants were more sensitive to the attended orientation of the principal axis of the probe stimulus after they had attended to the stimuli of the same orientation, this could facilitate the identification of the probe stimulus with the same orientation, resulting in the observed congruency effect in Experiment 2.

Limitations of this thesis

The experiments presented in this thesis had two limitations. The first concerns the nature of the feature-based attention effects. Upright stimuli are typically faster to be identified than oriented ones (Cooper & Shepard, 1973). For this reason, the present experiments did not contain a neutral condition in which the orientation of the probe stimulus was upright. However, because of this, it is unclear whether the observed congruency effects were caused by the facilitation of the attended orientation, the suppression of the ignored orientation, or both. Neural studies (e.g. Treue & Martínez-Trujillo, 1999) have demonstrated that, relative to their baseline activity, attention increases the activity of the feature detectors whose preferred feature value is similar to the attended one and that attention suppresses the activity of the feature detectors whose preferred feature value is opposite to the attended one. As discussed earlier, Treue and Martínez-Trujillo (1999) compared the response rate of direction sensitive feature detectors to their preferred orientation when attention was deployed towards the preferred or non-preferred direction. They found that relative to the baseline response of the measured feature detectors, when the monkeys attended to the cell's preferred direction in another location, the cell's response was increased to ~5% higher than the baseline rate. Similarly, when the monkeys attended to the cell's anti-preferred direction, the cell's response was decreased to ~6% lower than the baseline rate. This pattern of results, i.e., enhancement of the attended feature values coupled with a suppression of the ignored feature values has also been demonstrated in behavioural paradigms (Ho et al., 2012; White & Carrasco, 2011). The findings of these previous studies suggest that the effects found in this thesis could be the result of either an enhancement of the attended orientation or the suppression of the ignored orientation or a combination of both.

The second limitation of this research is the possibility of reduced motivation to sustain attention in Experiment 3, which might have contributed to the null result found in that experiment. One way to induce participants to sustain attention to the end of the primary display is to increase the possibility that a critical display of the primary stimulus occurred towards the end of the display. This would allow researchers to determine whether the result of Experiment 3 was due to the lack of sustained attention or the proportion of the probe trials per se.

Feature-based versus object-based attention

Feature-based attention and object-based attention are often deployed in similar tasks and with similar results. In some situations, this can result in uncertainty about whether an effect was caused by feature-based or object-based attention (e.g., Liu et al., 2007; Saenz et al., 2003). A good example of this problem can be seen in Saenz et al. (2003). As described earlier, in that study, the participants were shown two overlapping RDPs, one in the left and the other in the right side of fixation. The task was to detect whether the attended dots in each RDP changed its speed of motion. Performance was better when the attended dots in the two RDPs moved in the same direction compared to when they moved in different directions. These results were interpreted as supporting feature-based attention.

However, as the authors pointed out, there was also a second explanation for these results. When the attended dots in the two RDPs all moved in the same direction, they could be perceived as belonging to the same object. As discussed earlier, research on object-based attention has shown that participants are faster and/or more accurate to respond to features that belong to the same object relative to different objects (Duncan, 1984; Egly et al., 1994; see Chen, 2012, for review). The participants in Saenz et al. (2003) might have perceived the upwards or downwards moving dots as a single field of dots viewed through two apertures. If that was the case, when the dots in the two RDPs were moving in the same direction, the participants would be making judgments about features on the same object while they would be making judgments about features on two different objects when the dots in the two RDPs were moving in different directions. According to object-based attention, this would give rise to better performance in the same than different condition. Thus, the results found in Saenz et al.'s study could be caused by feature-based or object-based attention. Similar issues are present in some other studies of feature-based attention (i.e. Liu et al., 2007).

However, no such confound existed in the present experiments. Typically, for object-based attention to occur, the critical stimuli need to be on the same object or can be perceptually grouped through perceptual grouping principles such as colour, motion, good continuation, connectedness, etc. In the experiments presented in this thesis, the attention inducing stimuli and the probe stimuli were presented at separate locations and at different times. They also differed in colour, size, shape, and task. Given these stimulus features, it seems extremely unlikely that the two stimuli could be grouped together. Because of these reasons the effect elicited in the experiments presented in this thesis is unlikely to be object-based attention instead of feature-based attention.

Possible neuronal mechanisms for feature-based attention

Although the exact neural mechanisms for feature-based attention are not entirely clear, feature-based attention has been found to influence neural activities in two major ways. Firstly, it can modulate the activity of feature detectors so that those which prefer the attended feature value increase in firing rate and those which prefer an unattended feature value decrease in firing rate (Martínez-Trujillo & Treue, 2004; Treue & Martínez-Trujillo, 1999). Secondly, it can modulate the neural synchronisation of areas which process the associated feature dimensions (Snyder & Foxe, 2010). With regard to the first mechanism, feature-based attention has been found to modulate neural activities through changes to the firing rate of feature detectors. According to the feature-similarity gain model proposed by Treue and Martínez-Trujillo (1999; Martínez-Trujillo & Tueue; 2004; See also Maunsell & Treue, 2006, for review), the degree to which attention increases or decreases the baseline firing rate of a feature detector is determined by the similarity between an individual feature detector's preferred feature value and the attended feature value. For example, Treue and Martínez-Trujillo (2004) compared the firing rate of the feature detectors of two monkeys when various orientations of a RDP were either attended or not attended (the attended RDP). At the same time, another RDP was presented with motion at varying orientations inside a measured cell's receptive field (the unattended RDP). The principal manipulations were whether the attended RDP was moving in the preferred direction or anti-preferred direction and whether the attended direction was the same as or different from the direction of motion of the RDP inside the recorded cell's receptive field. The results showed that the modulation of neuronal responses depended on the similarity between the attended feature (i.e., the attended direction of motion in the attended RDP) and the cell's preferred feature (i.e., the preferred direction of motion in the unattended RDP). Importantly, neuronal responses did not depend on the similarity between the attended feature and the feature of the stimulus to which the cell was responding to (cf: Motter, 1994). Furthermore, the response of a given neuron was increased if the attended feature was close to the preferred feature, decreased if the attended feature was closed to the cell's anti-preferred feature, and not modulated if attention was allocated to an intermediate feature. These results provide evidence for the feature-similarity gain model, which proposes that the degree of similarity between the attended feature value and the preferred feature value influences the responses of neurons, with more similar feature values eliciting stronger responses (Treue and Martínez-Trujillo 1999; Martínez-Trujillo & Tueue 2004).

The second way that feature-based attention may modulate neural activity is through synchronised firing of feature detectors (Fannon, Saron & Mangun, 2007; Snyder & Foxe, 2010). There is evidence which implicates neural synchronisation as a mechanism for selective spatial attention, which suggests that an analogous mechanism in feature-based attention is plausible (Maunsell & Treue, 2006). Furthermore, alpha-band synchronisation has been implicated in the attentional suppression of ignored feature dimensions (e.g., colour or motion) (Foxe &Snyder , 2011). The strongest evidence that neuronal synchronization plays a role in feature-based attention probably comes from the study by Bichot, Rossi and Desimone (2005). They measured the effects of feature-based attention on individual neurons and local field potential in the monkeys' V4 areas during visual search. They found that when the monkeys were cued to a specific feature value that defined the target (e.g., the colour red), V4 neurons that preferred that feature value synchronized and increased their responses before the target was found. The synchronization and enhancement of responses also occurred, to a lesser degree, in the neurons whose preferred feature value was similar (instead of identical) to the attended feature. These results implicate neural synchronisation as one of the neural basis for feature-based attention.

Conclusion

The experiments reported in this thesis provided further evidence for the effects of feature-based attention on visual information processing. As in previous research, the present experiments showed that feature-based attention does spread across visual field, act on two completely unrelated tasks, and affect the speed and/or accuracy of visual discrimination. In addition, they expanded the results of previous research in demonstrating that feature-based attention may not only improve the detection or discrimination of simple feature values, but also increase the sensitivity of perceiving and interpreting alphanumeric stimuli shown from a specific viewpoint.

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