

Attentional selection and the processing of task-irrelevant information: insights from fMRI examinations of the Stroop task

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Abstract: In this chapter, we discuss our research that reveals how attentional mechanisms can modulate activity of posterior brain regions responsible for processing the *unattended* attribute of a stimulus. To do so, we utilized fMRI to reveal patterns of regional brain activity for variants of the Stroop task that differ in the nature of the task-irrelevant stimulus attribute. In all variants, individuals had to identify the ink color in which an item was presented. To vary attentional demands, we manipulated whether or not the task-irrelevant information contained conflicting color information. The variants differed in whether the conflicting color information was contained in a word naming a color (e.g. the word 'red' in blue ink), a word naming an object highly associated with a specific color (e.g. the word 'frog' in red ink), or a line drawing of an object highly associated with a specific color (e.g. a drawing of a frog in red ink). When the unattended stimulus attribute contained color information that conflicted with an item's ink color, increased activity was observed in the posterior brain region that processes the aspect of the task-irrelevant attribute related to color. Increased activity was observed in the left precuneus and left superior parietal cortex when the conflicting information arose from a color word; in the middle temporal gyrus and insular cortex when the word named an object highly associated with a specific color, and included extensive regions of early portions of the ventral visual processing stream when a line drawing was highly associated with a specific color. These areas have been implicated in word processing, semantic processing, and visual processing, respectively. Our results suggest that attentional selection can occur by: (1) increasing the gain on all posterior regions responsible for processing information related to the task demands, regardless of whether that information is contained in the task-relevant or task-irrelevant dimension; (2) limiting the processing of task-irrelevant information in order to reduce interference; and (3) modulating the processing of representations varying from those of a low-level perceptual nature up through those of a higher-order semantic nature.

Introduction

Neural mechanisms of visual selective attention for task-relevant information

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This chapter discusses cognitive and neurobiological mechanisms responsible for the attentional selection of task-relevant visual attributes. We have obtained insights into this issue through a series of fMRI studies examining attentional control in different

variants of the Stroop task. One of the most ubiquitous findings from both neurophysiological and neuroimaging work is that attentional selection enhances activity within brain regions most highly specialized for processing the stimulus towards which attention is directed. A classic example comes from the work of Moran and Desimone (1985). They demonstrated that selective attention modulates neuronal firing in the extrastriate cortex of rhesus monkeys. In their paradigm, two stimuli that differed in visual attributes (e.g. color, orientation, and size) were presented on each trial. One stimulus was an effective stimulus, in that it was very capable of making the cell fire, whereas the other stimulus was relatively ineffective in driving the cell's response. Neurons were isolated in area V4 that had a receptive field that included both stimuli. When the monkey's attention was directed to the location of the effective stimulus, the firing rate of the cell was greatly enhanced as compared to when attention was directed to the location of the ineffective stimulus. It is important to note that the perceptual displays are identical in both cases — both contain an effective and ineffective stimulus. The difference in firing rates between the two conditions depends on where the monkey's attention is directed. When attention is directed to the location of the effective stimulus, the firing rate increases. These results indicate that directing attention to a stimulus effective for stimulating a given brain region can cause an increase in the neuronal responsiveness of that brain region.

Neuroimaging work with humans has yielded similar findings, and also shown that these selective mechanisms can work on much more complex visual forms than those composed of simple visual attributes. One example is imaging work that examined visual selection for faces (Wojciulik et al., 1998). In this study, the region of the brain that responds differentially to faces as compared to other objects (i.e. the fusiform face area) was identified in each participant on an individual basis. Having identified this region, the researchers then examined the degree to which activity in this region could be modulated by covert attention. Individuals were shown displays that contained five items: a fixation cross, two faces, and two houses. To keep the location of spatial attention constant, individuals were told to fixate on the cross, and displays were brief

enough to preclude saccadic eye movements. On half the trials, participants decided whether the faces matched, and on the other half decided whether the houses matched. Greater activation was found in the fusiform face area when faces as compared to houses were attended (i.e. the decision was about faces), even though both faces and houses were always within the same display. When covert attention is directed towards the face stimuli, attentional mechanisms increase activation of areas specialized for processing faces. These results indicate that directing attention to location, as in the case of the Moran and Desimone study, is not the only means by which attentional regulation can affect processing in posterior sensory areas. Covert attention to a specific stimulus can also increase activation of the posterior region specialized for processing that visual stimulus.

In all the studies discussed so far, the selection process has been one in which a particular visual item or class of items (e.g. faces) is selected over other items in the display. Yet selection may also require that a particular attribute of a single visual stimulus (e.g. its form) be attended to over another visual attribute (e.g. its color). The neural mechanisms that allow for such selection appear to be similar to those discussed above — an enhancement of the neuronal response in the posterior processing region most specialized for processing that visual attribute. A classic example of this phenomenon is demonstrated by the work of Corbetta et al. (1991). They utilized positron emission tomography (PET) to examine the effect of selective attention for three basic visual attributes: shape, color, and motion. In their task, individuals viewed two consecutively presented displays that contained a set of shapes (e.g. rectangles) displayed in a particular color (e.g. red) moving at a particular rate across the screen (e.g. slowly). For a given set of trials, individuals were instructed to decide whether the displays were the same based on one visual attribute (e.g. color) and not the others (e.g. form and motion). Activity was modulated in different regions of posterior cortex depending on the visual attribute to which participants attended. For example, when individuals were instructed to make decisions based on color as compared to when passively viewing the same display, activation was increased in the collateral sulcus between lingual and fusiform gyri. This area has been

implicated in color perception (Zeki and Marini, 1998) and damage to it produces achromatopsia, a selective deficit in color vision (Damasio et al., 1980). In contrast, when the decision had to be based on form as compared to passively viewing the displays, increased activations were noted in different regions of extrastriate cortex — bilaterally in the fusiform and parahippocampal gyri. These results indicate that not only do attentional mechanisms increase activity in regions of extrastriate cortex, but that attentional selection for a specific attribute of a presented stimulus increases activation in areas responsible for processing that attribute.

These studies are all characterized by situations in which the relationship between the attributes of an item (e.g. shape, form, motion) or items within a display are relatively random (i.e. there is no particular reason why squares would be displayed in red as compared to blue). Hence, in all these tasks, there are no sources of information that conflict with, or are relevant to selection of a particular visual attribute. In contrast, in the paradigms we have used, a relationship exists between the task-relevant visual attribute and task-irrelevant information. Such a situation creates very different demands on attentional selection. In the series of studies described below, we have systematically varied the way in which task-irrelevant information is able to interfere with selection of the task-relevant visual attribute. By doing so we can further explore the mechanisms of attentional selection in visual processing areas.

Selective attention for the task-relevant attribute in the Stroop paradigm

In the Stroop task, individuals view colored words. Their task is to identify a basic visual attribute of the item, its color, while ignoring the identity of the word. Because this task requires the selection of visual information about color, it can inform us with regard to mechanisms of attentional selection for simple visual attributes. Attending to the item's color under such condition is attentionally demanding, as word reading occurs more automatically than does color identification. Hence, attentional control is required to selectively attend to the color of the word as compared to its identity. Moreover, the word's identity can have a very large effect on how

easily attention can be directed to its color. It takes longer to identify the ink color when the word is incongruent and names a different color (e.g. the word 'red' in blue ink) as compared to when the word is neutral and is unrelated to color (e.g. the word 'lot' in blue ink). Attentional demands are greater on the incongruent trials than neutral trials because the word's identity contains a task-irrelevant source of information about color.

Examining patterns of brain activation for different types of Stroop trials can provide insights into mechanisms of selective attention for the basic visual attribute of color. It has been found that a comparison of incongruent as compared to neutral Stroop stimuli generally does not reveal an increase in activation of color perception regions (i.e. V4) (e.g. Pardo et al., 1990; Bench et al., 1993; George et al., 1994; Carter et al., 1995; Taylor et al., 1997). In many ways, this finding might be considered surprising because it takes more attentional resources to direct attention to the ink color when the word contains competing color information (i.e. on incongruent trials) as compared to when it does not (i.e. on neutral trials). Likewise, increased activation in the color area is not observed for the comparison of either incongruent or neutral Stroop stimuli as compared to a lines of XXXXs (Bench et al., 1993). Once again, the greater difficulty of selecting color information from words as compared to a line of XXXXs does not appear to cause increased activation of the color processing region. This lack of increased activation in the color processing area suggests that activation of this region is not influenced by the difficulty of selecting the task-relevant color information *relative* to the task-irrelevant information. Rather, as suggested by the Corbetta et al. (1991) study, activation may increase in color processing areas whenever color is the attended attribute. Because the need to extract color information is similar across incongruent words, neutral words, and a line of XXXXs, no difference in activation in V4 is observed across these conditions.

These findings are important as they suggest that there must exist other means of attentional regulation besides boosting activation of the region responsible for processing the attended attribute. The question then arises as to what other mechanisms aid in attentional control, and are sensitive to the *relative*

demands placed on extracting task-relevant information in comparison to task-irrelevant information.

A neural model of attentional control in the Stroop paradigm

To answer this issue, we have performed a series of fMRI studies with variants of the Stroop task. Although there are a large number of studies that have examined patterns of brain activation during the Stroop task (Pardo et al., 1990; Bench et al., 1993; Carter et al., 1995, 1997; Bush et al., 1998; Brown et al., 1999; Petersen et al., 1999), our use of variants of the Stroop task were specifically designed to delineate the role that each of these brain regions plays in attentional control (Banich et al., 2000a,b). Before discussing the evidence in detail, we provide a brief overview of our findings.

Our results suggest that dorsolateral prefrontal regions are critically important for creating an ‘attentional set’ that modulates activity within posterior processing systems and facilitates selection of task-relevant representations within working memory. Furthermore, the involvement of dorsolateral prefrontal regions in task performance is more prominent when effortful control is required to select the task-relevant over the task-irrelevant dimension. In contrast, when the task-relevant dimension is processed more automatically than the task-irrelevant dimension, no such increase in dorsolateral prefrontal activation is observed (Banich et al., 2000b). The role of dorsolateral prefrontal cortex is distinct from that of medial prefrontal regions, such as the anterior cingulate, which appear to be involved in response selection (Milham et al., submitted for publication). Furthermore, the dorsolateral region identified in these studies seems to co-activate with a region of parietal cortex (precuneus). We posit that this dorsolateral/parietal circuitry is the source of attentional control, responsible for selecting and maintaining an attentional set that specifies the nature of task-relevant information.

Although this system may provide for top-down control of attention by maintaining an attentional set, there must be sites at which processing of information is modulated by this attentional set (see Posner and Petersen, 1990 for a distinction between the *site* of selective effects and the *source* of the signals

producing those effects). As reviewed above, in the Stroop task this modulation *does not* occur in V4. Rather, our studies have suggested that some aspects of attentional control may occur through modulation of processing of the *task-irrelevant* attribute, rather than the task-relevant one (e.g. color). The studies that have led to these conclusions are described in detail below.

Attentional selection and task-irrelevant attributes

Initial findings

To determine how attentional control occurs in the Stroop task, we examined differences in the neural network responsible for attentional control in the face of incongruent information for pairs of variants of the Stroop task (Banich et al., 2000a). In one experiment, we examined activation that accompanied increased attentional demands for a color–word task and a color–object task (Banich et al., 2000a, Expt. 2). Our nomenclature for these tasks is to hyphenate the name, with the first word referring to the task-relevant dimension (e.g. color) and the second word referring to the task-irrelevant dimension (e.g. object). As discussed above, in the color–word task, an individual must identify the color of a word, while ignoring the word’s identity. In the color–object task, an individual must identify the color of an object, while ignoring its identity. To vary attentional demands, we contrasted performance on incongruent trials to neutral trials. For the color–word task, an incongruent trial is one in which the word names a color other than the word’s ink color (e.g. the word ‘red’ in blue ink). A neutral trial is one in which the word is unrelated to color (e.g. the word ‘lot’ in blue ink). For the color–object task, an incongruent trial is one in which an object is depicted in a color distinct from that with which it is highly associated (e.g. a red frog). A neutral trial is one in which the object is not strongly associated with a single color, but is shown in one of many colors with which it can be associated (e.g. a red car).

Notice that the comparison between patterns of brain activation in these two tasks can be particularly informative because in both tasks an individual must attend to the same attribute — color. Hence, those brain regions that are specifically responsible for

attending to the task-relevant attribute should show similar activation across both tasks. In contrast, the source of task-irrelevant information differs across the two tasks. Therefore, the brain regions that exhibit different patterns of activation for the two tasks are those that are sensitive to the to-be-ignored information.

The behavioral results for both tasks did indeed indicate that we were successful in manipulating attentional demands. A significant Stroop effect was observed for both the color–word and color–object task as responses to incongruent trials were elongated compared to neutral trials. With regards to brain activation, we indeed found evidence that the dorsolateral prefrontal region is important for imposing an ‘attentional set’. Dorsolateral prefrontal cortex was significantly more active on incongruent than neutral trials for both the color–word and color–object task. Furthermore, the region that was activated in both tasks significantly overlapped. Such a finding was expected, as in both cases the task-relevant attribute is color.

The role of the dorsolateral prefrontal region in imposing an attentional set was confirmed in another experiment in which we compared activation for a color–word Stroop task with a spatial–word Stroop task (Banich et al., 2000a, Experiment 1). In the spatial–word Stroop, individuals must decide if a word is located above, below, or inside a box. On incongruent trials, the word names a position incongruent with its location (e.g. the word ‘below’ positioned above the box). On neutral trials, the word has no spatial information (e.g. the word ‘house’ positioned above the box). For both tasks, we obtained dorsolateral prefrontal activation. In this case, however, the region of activation was overlapping, but partially distinct — more dorsal regions were only activated by the spatial–word task, and more ventral regions only by the color–word task. We interpreted these findings as indicating that dorsolateral prefrontal regions are important for imposing an attentional set, but with some degree of specialization depending on whether the task-relevant attribute is processed by the dorsal visual processing stream (i.e. space) as compared to the ventral visual processing stream (e.g. color).

These two experiments also shed light on the posterior sites at which dorsolateral prefrontal regions

exert their attentional control. Most informative was the difference in the pattern of activation between the color–word and color–object task because this difference reveals which brain regions are sensitive to the task-irrelevant information (e.g. the word vs. the object). Although both tasks produced activity in the parietal lobes (BA 7 and BA 40), the color–word task produced unique activation in three regions of the parietal lobe. These were: (1) the precuneus; (2) a superior region of the left superior parietal region; and (3) a lateral region of the left inferior region. In contrast, although both tasks produced activation in the left fusiform gyrus (BA 19), there was significantly more activation for the color–object than color–word task extending throughout the ventral visual processing stream, including the inferior occipital, middle occipital, fusiform, lingual, and middle temporal gyri.

This pattern of results suggests that attentional selection in the Stroop task may work by modulating processing of task-irrelevant information. All of the parietal regions specifically activated by the color–word task appear to be involved in word-related processing. The left precuneus region has been reported to become active when processing words compared to letter strings (Jessen et al., 1999). The lateral left inferior region is likely to reflect the translation of orthography to phonology (e.g. Price, 1998), as this area has been reported to be more active when viewing or naming words as compared to pictures. Finally, the left superior region becomes activated when words must be encoded into memory (Kelley et al., 1998). The extensive patterns of activation noted within ventral visual processing stream specific to the color–object task is strikingly similar to those areas activated when objects are encoded into memory (Kelley et al., 1998). The one notable difference is that our activations did not extend as far anteriorly, terminating before the parahippocampal gyrus.

Interpretation

We interpret these findings as suggesting that a series of distinct mechanisms in posterior cortex serve to regulate attentional selection. First, we interpret the parietal lobe activation that is common across the tasks (i.e. regions of BA 7 and BA 40) as re-

flecting activation imposed by an increased need for attentional control in the incongruent as compared to neutral condition. These brain regions have been found to be activated across a variety of attentionally demanding tasks, and have been described as being part of a general attentional activation system that allocates resources regardless of the stimulus dimension (e.g. Coull and Nobre, 1998). Such increased activation appears to be the neural correlate of the elongation of reaction time in on incongruent as compared to neutral trials that is observed in the behavioral data.

In contrast, the areas uniquely activated for each task (as compared to those activated in common) in the incongruent as compared to neutral condition, represents the modulation of activity in regions responsible for processing task-irrelevant information when that information is related to color. The mechanism behind this modulation of activity is not entirely clear. One possibility is that the attentional set imposed by dorsolateral prefrontal regions may result in increased activation of any posterior brain region that is responsible for processing information related to task demands. Therefore, when the task demands require attention to color, upregulation of activity may occur in any region that is processing color-related information, regardless of its source — whether it be contained in the task-relevant or task-irrelevant dimension. This idea is consistent with the results of Moran and Desimone (1985), Wojciulik et al. (1998), Corbetta et al. (1991), and others, indicating an increase in activity of brain regions that process information about the to-be-attended attribute. Our findings, however, suggest a more broad tuning of activity of regions in posterior cortex than has been suggested previously, one that encompasses modulation of activity of all regions involved in processing any information that is color-related. Furthermore, the activation in these posterior regions does not appear to be driven by conflict between the task-relevant and task-irrelevant dimensions, but rather that information contained in the task-irrelevant dimension is *related* to the task-relevant information. Support for such a notion comes from the finding that the same ventral regions show increased activity for objects highly associated with colors, regardless of whether they are presented in congruent or incongruent colors (Banich et al., 1999).

Whenever dorsolateral regions impose an attentional set for color, *all* posterior regions are put on ‘alert’ for color information. The outcome of this ‘alerting’ function differs for neutral and incongruent trials. On neutral trials, the task-irrelevant dimension contains no color information. Even if areas sensitive to task-irrelevant information are on ‘alert’, no color-related information is detected, and hence activation is not increased. In contrast on incongruent trials, the task-irrelevant dimension contains color information, which leads to greater activation of those regions processing task-irrelevant information that is color related. We speculate that the increased activation might reflect a mechanism whereby prefrontal regions ‘re-interrogate’ posterior regions after detecting that these regions are processing information related to that which is task-relevant.

In studies using paradigms in which there is no relationship between the information contained in the attended and unattended attribute such an alerting function would go undetected. For example, in any task in which one is to attend to an item’s color and ignore its form, the form-processing area might become more sensitive to color information. However, if the relationship between form and color is arbitrary (as in the study by Corbetta et al., 1991 and others like it), no increased activation in the form-related area would occur since the information processed by that area is not systematically related to the task-relevant dimension.

Our findings also indicate that the processing of the task-irrelevant information is not completely suppressed, as it must be processed to some degree for its relationship to the task-relevant dimension, color, to be detected. It appears that the imposition of an attentional set by frontal areas is not so precise as to completely limit processing of color information only to that contained in a particular information channel (i.e. color information contained in the ink color but not in word). If suppression were total, we would not expect variations in the pattern of uniquely activated regions depending on the nature of the task-irrelevant attribute.

Other evidence from our data, however, indicates that the pattern of increased activation in these posterior regions may, at the same time, represent the end product of an attentional mechanism that serves to limit the processing of task-irrelevant information.

Supporting this suggestion, the ventral stream activations observed in our study were less extensive than those noted by Kelley et al. (1998). The activation for incongruent as compared to neutral trials in the color–object task did not extend to anterior regions of the ventral visual processing stream where there is a linkage between object form and identity. Likewise, for the color–word task, increased activation on incongruent as compared to neutral trials was observed in parietal regions associated with the mapping of orthography to phonology. This activation did not extend anterior into temporal regions that are associated with the full semantic processing of words.

Additional support for this interpretation comes from the pattern of activation observed for the color–word task in older individuals (60–75 years of age) (Milham et al., 2001). One striking effect was that relative to younger adults, the elderly adults exhibited much more extensive activation of the ventral visual processing pathway, which was accompanied by a marginally significant increase in Stroop interference (i.e. the difference in reaction time between incongruent and neutral trials). For young adults, the color–word task only produced activation in the left fusiform gyrus. In contrast, the activation in the elderly extended further along the ventral processing stream, distributed through areas BA 18, 19 and 37. We conjecture that this more extensive activation indicates that processing of the task-irrelevant word information is not as limited in the elderly as in young adults.

Modulation of processing by task-irrelevant information can occur regardless of whether the information that elicits a competing representation of color is actually present in the stimulus or not. In the case of the color–word task, the competing color information is specified by information contained in the stimulus, as the incongruent word names a specific color that is distinct from the ink color. In contrast, in the color–object task, the incongruent stimulus does not directly specify a competing color. Rather, interference must occur via the linkage in memory of the object’s form (e.g. a frog) with its prototypical color (e.g. green). It is this prototypical color that interferes with correctly identifying the actual color in which the object is depicted.

The increased activation on incongruent trials relative to neutral trials in the word processing regions

in the color–word task and the ventral visual processing region in the object–word task stands in marked contrast to a lack of modulation in activity for areas associated with the processing of color information. For neither task did we observe increased activation in the region previously identified as being the area associated with color perception (e.g. $x = -12$, $y = -74$, $z = 0$) (Zeki and Marini, 1998), nor in areas of the inferior temporal lobe (BA 20) that are associated with retrieving color knowledge (Chao and Martin, 1999). Our results, therefore, are consistent with other Stroop studies that do not indicate increased activation in the color processing area.

Further examination of attentional control by modulation of task-irrelevant information

The results from these studies suggest that attentional selection can influence the processing of the task-irrelevant information, and that the site of this effect will vary depending on the nature of that task-irrelevant attribute (e.g. a word versus an object). Here we wished to further examine this issue. On the basis of our prior results, we have argued that the pattern of regional activation across Stroop tasks that differed with regards to the task-irrelevant attribute (i.e. color–word vs. color–object), could inform us as to the nature of the interfering representation. In the color–object task, we argued that the source of the interfering information about color was one that is retrieved when processing the form of the object, activating ventral object processing regions. In contrast, in the color–word task, we argued that the source of the interfering information about color was one that was intimately linked to the word’s identity, activating word processing areas.

To further explore the idea that attentional selection can be linked to task-irrelevant information, we examined performance on a color–object word task. In this task, incongruent trials consist of words that name objects highly associated with a specific color (e.g. ‘frog’). In the less attentionally demanding neutral trials, the words name objects that are associated with multiple colors (e.g. a car can be green, red, blue, gray, white, tan, black, etc.). In contrast to the color–object task, in which the *visual form of the object* elicits information about color, we propose that interfering color information in the color–

object word task is retrieved without the aid of object recognition areas. We also propose that the interfering color information in the color–object word task differs from that in the standard color–word task. In the case of the standard color–word Stroop task, the linkage of the word with color is direct (‘blue’ has a color meaning). In contrast, in the case of the color–object word task, the linkage of the word with color is indirect (‘frog’ has a meaning of an animal that typically is green). Therefore, we expect to see increased activation on incongruent as compared to neutral trials in different posterior areas in the color object–word task than previously observed in either the standard color–word task or the object–word task. We propose that the modulation of activation in the color–object word task will likely occur in amodal semantic areas, as semantics provides a means to link the object word with associated color information. To test this hypothesis, we conducted an experiment that allowed us to compare patterns of brain activation on the standard color–word Stroop task with that of a color–object word task. We then compared the pattern for both these tasks that we had obtained previously for the color–object task (Banich et al., 2000a, Expt. 2).

Methods

Participants

Participants were 14 right-handed native English speakers with normal or corrected to normal vision (age range: 21–35 years). All participants were screened to ensure that they did not have a history of neurological damage or color-blindness and gave informed consent prior to participation.

Stimuli and design

The stimuli were programmed using Mel V2.0 and presented using an IBM-PC compatible computer. Our task made use of three ink colors: red, orange, and green. Three trial types were included in our experiment: (1) *incongruent standard color–word trials* in which the word named a color incongruent with the ink color in which it was printed (e.g. the word ‘GREEN’ in red ink); (2) *incongruent color–object word trials* in which the ink color of a word was

incongruent with the color highly associated with the object named by that word (e.g. the word ‘FROG’ printed in red ink); and (3) *neutral trials* in which the word was unrelated to color (e.g. the word ‘LOT’ in red ink). Half of the neutral words were matched with the color words for word frequency and length, and the other half matched the object words, in that they also described objects, except in this case the objects are not highly associated with any particular color (e.g. the word ‘CAR’ in red ink).

We made use of a blocked fMRI design, in which neutral blocks were alternated with incongruent standard color word and incongruent color–object word blocks (i.e. neutral; incongruent standard color–words; neutral; incongruent color–object words) such that participants were presented a total of four incongruent standard color–word and four incongruent color–object word blocks. Neutral trials were intermixed in incongruent blocks (50 : 50 mix) to prevent the development of strategies regarding the degree to which the words are read. Each block consisted of 18 trials, presented at a rate of one trial every 2 s. Each trial consisted of a 300-ms fixation cross followed by a 1200-ms presentation of the stimulus (colored word) and 500-ms pause.

Procedure

Participants were placed in a 1.5 Tesla GE Signa scanner equipped for echo-planar imaging (EPI). Head position was stabilized using a bite-bar attached to the head coil to minimize motion during the session. A total of 248 gradient T1 weighted EPI images acquired for each participant (TR = 2400 ms, TE = 40 ms, flip angle = 90°), each consisting of 15 contiguous slices (3.75 × 3.75 × 7.0 mm) parallel to the AC–PC line. A high-resolution 3D anatomical set (T1-weighted 3-dimensional spoiled gradient echo images) was collected for each participant, as well as T1-weighted images of our functional acquisition slices. Stimuli were presented on a goggle system by Magnetic Resonance Technologies, and responses were acquired on a three-button response pad.

Image processing

The first six volumes of each run were discarded to allow the MR signal to reach steady state. Functional

data for each participant was then convolved using a 3D Gaussian kernel (FWHM = $8 \times 8 \times 8$ mm, kernel width = 7×7 mm), temporally denoised using an ID-wavelet transform (visu-shrink, number of levels = 4), intensity normalized, and linearly detrended. MedX3.2 was used for image processing and statistical analysis.

Image analyses

For each participant, we calculated a mean image for each of the three conditions: (1) neutral; (2) incongruent standard color words; and (3) incongruent color-object words. Mean image maps were warped into a common stereotaxic space (Tallarach and Tournoux, 1988). Pair-wise comparisons of the three conditions were then carried out using a paired *t*-test ($n = 14$) (the paired *t*-test was employed due to its ability to remove the impact of between subject variability). Voxels with a *z*-score exceeding 3.1 ($P < 0.001$) were considered active. The peak detection algorithm described by Mintun et al. (1989) was employed for localizing activations.

Results

Behavioral results

RT to incongruent color words (750 ms) were significantly elongated compared to neutral words (625 ms) ($P < 0.001$), whereas RT to incongruent object words (666 ms) were only marginally significantly elongated compared to neutral words ($P < 0.10$).

Imaging results

Standard incongruent color-word vs. neutral word

The standard color-word task activated a set of brain structures that we have observed in our prior studies. These regions include dorsolateral prefrontal cortex ($x = -42, y = 10, z = 34$), inferior prefrontal cortex ($x = -34, y = 22, z = -2$), anterior cingulate cortex ($x = 2, y = 16, z = 42$), precuneus ($x = -6, y = -74, z = 50$), extrastriate cortex ($x = 16, y = -74, z = 14$, BA 19; $x = 2, y = -74, z = -8, x = 12, y = -86, z = -6$; BA 18), superior parietal ($x = -24, y = -74, z = 42$, BA 19/7), and infe-

rior parietal ($x = -42, y = -44, z = 42$, BA 40) cortex.

Incongruent color-object word vs. neutral word

The color-object word task activated regions different from those seen active in the standard color-word task. These regions include the middle temporal gyrus ($x = -56, y = -10, z = -2$), and the insula ($x = -40, y = -14, z = 10$). Although both the color-object word task and standard color-word task activated inferior prefrontal regions bilaterally, the center of these activations in the color-object word task differed from those found in the standard color-word task. Activation in the left inferior frontal cortex during the color-object word task was more anterior, superior, and lateral ($x = -58, y = 26, x = 12$, BA 45) than the activation found in left inferior frontal regions during the standard color-word task ($x = -34, y = 22, z = -2$, BA 47).

Results from the color-word task and color-object word task compared with previous results from the color-object task

We were also interested in comparing activations in the standard color-word and the color-object word task with those obtained previously with the color-object task. In the color-object task participants viewed a line drawing of the objects depicted by the words in the color-object word task (i.e. viewed a red frog as compared to seeing the word 'frog' in red). We generated a mask that assigned a value of zero to brain regions activated by either the standard or color-object word task, and a value of one to the remaining voxels. This mask was then applied to previously reported results obtained during a color-object task (Banich et al., 2000a, Expt. 2). This manipulation revealed regions active in the color-object task that were not active in either the color-word or color-object word tasks. The activations found comprised an extensive band of cortex in visual processing areas extending posterior to $y = -96$, anterior to $y = -54$, superior to $z = 60$, and inferior to $z = -16$. Peaks of activation were located both dorsal ($x = -38, y = -48, z = 48$), ventral ($x = -38, y = -54, z = -10$), and bilateral, with more extensive and greater activation in the

left hemisphere. Hence, this analysis indicated that the areas of the ventral visual processing stream activated by the color–object task were activated neither by the standard color–word task nor the color–object word task.

Discussion

The results of the current study accord well with our prior ones in indicating that attentional effects be linked to the modulation of processing of task-irrelevant information. There were unique patterns of activation under conditions of increased attentional demand for regions in the posterior cortex in the standard color–word task that differed from those of the color–object word task, which in turn differed from the previous results obtained in the color–object task. The increased activation of distinct regions of posterior cortex depending on the task irrelevant-dimension may reflect part of a mechanism by which attention ultimately modulates or gates task-irrelevant information in order to reduce interference and increase task performance. We hypothesize that processing of task-irrelevant information is modulated in these tasks because the task-irrelevant information is related to that which is task-relevant (i.e. is related to color).

The regions uniquely activated across our different Stroop tasks varied, which we believe reveals the level of representation at which information from the unattended attribute influences performance. In the case of the standard color–word task, comparison of brain activity during incongruent and neutral trials yielded unique areas of activation in regions previously reported to be engaged by word processing. The region of the left precuneus that exhibited increased activation in our study has been reported to become active when processing orthography to phonology (Jessen et al., 1999). Furthermore, the left superior parietal region has been shown to become active when words must be encoded into memory (Kelley et al., 1998). Hence, in this task, the representation of color information from the task-irrelevant dimension that is influencing performance appears to be one linked to a orthographic or phonological representation.

For the color–object word task, a different set of posterior regions was uniquely activated. Increased

activation on incongruent as compared to neutral trials was observed in regions of the middle temporal gyrus (BA 20/21) that have been found to become active during retrieval of previously acquired color information and during color naming of objects (Chao and Martin, 1999). Hence, the representation of color information from the task-irrelevant dimension that is influencing performance in this case appears to be one linked to form, that is the association between an object’s form and its prototypical color. Finally, in the case of the color–object word task, increased activation under conditions of higher attentional demand were noted in the middle temporal and insular regions, as well as an inferior frontal region (BA 45) that was not activated by the standard color–word task. These findings suggest that the representation of color information from the task-irrelevant dimension that is influencing performance is one that is amodal and semantic. In this case, a word such as ‘frog’ evokes a representation of a color (i.e. green) through the semantic association of frogs with that color.

The difference in the site of activation in the left inferior frontal between the standard color–word task and the color–object word task also suggests a difference between the two tasks in the nature of the representation of color information from the task-irrelevant dimension that is influencing performance. Left inferior frontal regions have been reported to become active during retrieval, selection, maintenance, or evaluation of semantic knowledge (Wagner, 1999). This region (BA 45 and BA 47) appears to be selective to semantic processing (Thompson-Schill et al., 1997) and its activation is uninfluenced by task difficulty (Demb et al., 1995). BA 47 became active during the color–word task while an area slightly more anterior, superior, and lateral (BA 45) was active during the color–word object task. We speculate that activation in these distinct regions of the inferior frontal cortex may reflect specialization for extracting meaning from color words as compared to color–object words. Alternatively, this differential activation might arise from a more general difference in retrieval mechanisms between the two tasks. Interference in the standard color–word task arises out of a one-step process in which color meaning is directly extracted from the word, whereas the interference in the color–object word task arises

from a two-step process in which the object word must be processed for meaning, from which, in turn, arises the interfering color information.

The results of our research clearly suggest that attentional modulation can vary depending on the nature of the task-irrelevant attribute and the nature of the representation from which interference arises (visual, orthographic, phonological, semantic). Modulation of activation occurs in those brain regions that process the specific representation that allows information in the task-irrelevant dimension to be linked to that which is task-relevant (e.g. color). In summary, our results suggest that attentional selection can occur by: (1) increasing the gain on all posterior regions responsible for processing information related to the task demands, regardless of whether that information is contained in the task-relevant or task-irrelevant dimension; (2) limiting the processing of task-irrelevant information in order to reduce interference; and (3) modulating the processing of representations varying from those that are of low-level perceptual nature up through those of a higher-order semantic nature.

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