An Investigation into Local/Global Processing in Grapheme-Color Synesthetes

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Abstract

Grapheme-color synesthesia is a condition in which people strongly associate letters and numbers with colors. Previous research has demonstrated differences in perception, cognition, and even personality, in grapheme-color synesthetes. However, little research has been geared towards investigating local/global processing in synesthetes. Local/global processing is a well-studied aspect of visual processing that is known to differ in individuals with certain sensory abnormalities. In this study, I used a hierarchical figures task, a visual search task, and the ROCF task (which can all be used to assess local/global processing) to determine whether grapheme-color synesthetes differ in local/global processing compared to controls. Based on previous research and theory, it was predicted that synesthetes would show superior local processing abilities compared to controls. However, in the current study no local/global processing differences were found between synesthetes and controls in any of the tasks. These results may suggest that grapheme-color synesthetes do not actually differ from controls in this aspect of visual processing. However, post-experiment research suggests that the tasks used in the current study may not have been tapped into the right construct (local processing). Furthermore, the small sample size may not have been adequate to detect differences between the two groups, as it seems that any differences, if in fact present, are quite small. More research is necessary to determine if grapheme-color synesthetes do in fact display differences in local/global processing compared to non-synesthetes.

Introduction

Synesthesia

Synesthesia is often defined as occurring when a stimulus along one sensory dimension automatically triggers a percept along another sensory dimension, in the absence of any direct stimulation to this second dimension. The authenticity of this condition is well-established, and the condition is estimated to be present in as much as 1 to 4% of the population (Simner et al., 2006).

Types of synesthesia

There are many types of synesthesia, connecting various pairs of sensory attributes or modalities (dimensions). Some types include sound-color synesthesia and lexical-gustatory synesthesia (Meier & Rothen, 2013). In the former, one perceives colors whenever one hears sounds. In the latter, one experiences tastes whenever one hears or reads words.

One very common form of synesthesia is grapheme-color synesthesia, where individual graphemes (e.g. numbers and letters), printed in black ink on a white background, are perceived to have distinct colors. These colors are unique to each individual, although some research suggests that many of these grapheme-color pairings overlap among individuals; specifically, many of these shared pairings are identical to those found in Fisher-Price toys (Witthoft & Winawer, 2013). There is evidence to suggest the perceptual reality of these colors (Palmeri et al., 2002); the main evidence consists of a visual search task in which targets, which were 2s were embedded among a field of distractors, which were 5s. The grapheme-color synesthete, for whom 2s and 5s elicited different synesthetic colors, responded significantly faster than controls. Furthermore, as the number of items in the display increased, the synesthete's resulting increase in response time was much smaller than that in controls. This effect could not have been achieved if the synesthetic colors were mere mental associations, because

mental associations would not cause the target to increase in saliency (e.g. the degree to which it stands out) relative to the distractors as physical perception of color does. In other words, grapheme-color synesthesia is not simply a matter of mentally associating colors with graphemes, but rather, is a matter of perceiving these colors in the mind's eye, or even, sometimes, as if they were in the physical world.

Proposed mechanisms of synesthesia

Cross-wiring hypothesis

Ramachandran & Hubbard (2001) proposed that number-color synesthesia arises from cross-wiring between the color centers (V4 or V8) and the visual numeral area (VNA), due to their observations that both lie in close proximity to one another within the fusiform gyrus. The equivalent mechanism for word-color synesthesia, based on this hypothesis, would be cross-wiring between V4 or V8 and the visual word form area (VWFA), which is also located within the fusiform gyrus. This cross-wiring may be due to excessive proliferation (or defective neural pruning) of neural connections between adjacent brain regions. Maurer (1997) also supports this idea: he claims that infants are born with dense interconnections between cortical sensory systems and that synesthesia occurs when there is a failure of the normal pruning process. Hubbard et al. (2005) propose similar mechanisms underlying grapheme-color synesthesia, using behavioral and fMRI data.
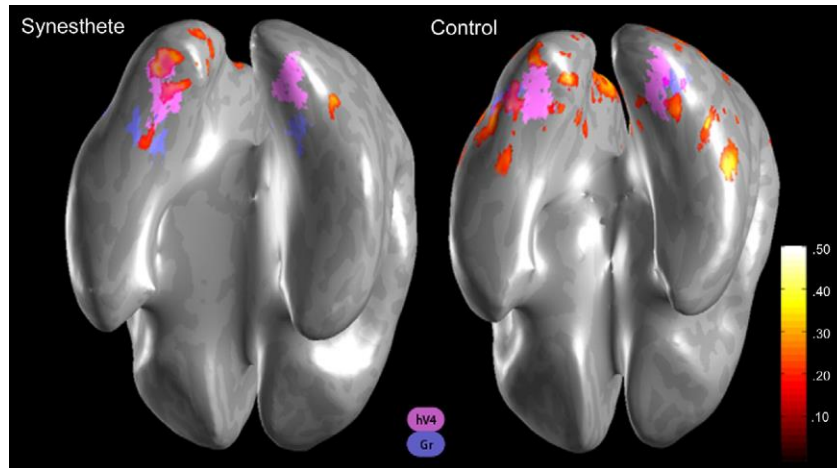
Figure 1. Color and grapheme areas on the ventral surface of the brain.
An fMRI representation (Hubbard et al., 2005) of the ventral surface of the brain in grapheme-color synesthetes (left) and controls (right) in response to graphemic versus non-graphemic stimuli. The purple region corresponds to the color area, hV4, and the blue region corresponds to the grapheme-sensitive area of interest. The yellow and red colors represent degree of activation, with brighter colors corresponding to higher activity.

One of the pieces of evidence cited in these studies is that in some synesthetes, the colors are evoked only in central vision. Since V4 mainly represents central vision, it is possible that the cross-wiring occurs disproportionately for visual areas retinotopically mapped to central vision, causing the synesthetic colors to appear only in central vision. Another line of evidence suggests that people who experience one type of synesthesia are more likely to experience another type of synesthesia, which could be due to a failure of pruning at multiple sites. Furthermore, it was found that the degree of hV4 activation (as measured by fMRI) directly influences the strength of synesthetic colors, which provides indirect evidence for the cross-wiring hypothesis. However, although these physiological explanations for the phenomenology of synesthesia are perfectly plausible, they do not establish conclusively that cross-wiring is the basis of synesthesia, as there are alternate ways to explain these same findings. A few of the dominant alternative explanations are considered below.

Disinhibition hypothesis

Grossenbacher & Lovelace (2001) propose an alternate account. They suggest that synesthesia does not result from altered anatomical connections, but rather from disinhibition of normal anatomical connections. Disinhibition refers to the reduction in or loss of feedback signals from one system to another. Specifically, this hypothesis predicts a failure of feedback connections from a multisensory nexus (such as the temporo-parietal-occipital junction). One piece of evidence that they discuss in support of this account, which seemingly contradicts the cross-wiring hypothesis, is that hallucinogenic drugs can induce synesthetic experiences in non-synesthetes, who presumably have normal connectivity. If these drugs induce disinhibition from a multisensory nexus, then it is entirely plausible that synesthetic experiences arise from this loss of feedback signals.

Re-entrant theory

If the cross-wiring hypothesis is an accurate explanation of what goes in synesthesia, then a given graphemic form should always induce the same color, with the synesthete's specific grapheme-color pairings dictated by his or her specific pattern of cross-connectivity between the grapheme-processing areas and color-processing areas of the brain. However, Myles et al. (2003) found that this was not the case. For example, an ambiguous grapheme could be interpreted as either the letter Z or the number 2, depending on the context (the ambiguous grapheme could be intermixed with letters, causing the synesthete to perceive a Z; alternatively, the ambiguous grapheme could be intermixed with digits, causing the synesthete to perceive a 2) in which it was presented. The authors also used an ambiguous grapheme that could be interpreted as the letter B or the number 3, as well as one which could be interpreted as the letter T or the number 7 (see Figure 2). The synesthete would experience different synesthetic colors depending on which grapheme she perceived, which in turn depended on the context. The local cross-activation theory thus does not seem to be adequate to explain all aspects of synesthesia. This inadequacy prompted the emergence of the re-entrant theory, which can explain how meaning affects synesthetic color.

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Figure 2. Ambiguous graphemes.

The left grapheme can be interpreted as either a 7 or a T, depending on the context. The middle grapheme can be interpreted as either a 3 or a B, and the right grapheme can be interpreted as either a 2 or a Z (Myles et al., 2003).

In the reentrant processing model proposed by Smilek et al. (2001), areas of the posterior fusiform gyrus that process graphemic form relay information to more anterior areas of the gyrus that process graphemic meaning. These areas then communicate via feedback to color areas along reentrant pathways (e.g. pathways that transmit information from higher cognitive centers to perceptual centers of the brain).

Hyperbinding theory

The hyperbinding theory (Hubbard, 2007) posits that synesthesia arises from overactive parietal lobe binding mechanisms (binding refers to the process by which information about color, form, motion, etc. is integrated into a coherent representation of the world). This theory is supported by a transcranial magnetic stimulation (TMS) study conducted by Esterman et al. (2006), which found that repetitive TMS of the right posterior parietal lobe disrupted the binding of color and graphemic form in synesthetes. Specifically, they used a task where two synesthetes were presented with colored letters and asked to name the colors. In the baseline (no rTMS) condition, the synesthetes were slower to respond to the letters when the physical colors were inconsistent with their synesthetic colors than when they were consistent. This interference effect of synesthetic colors was attenuated by rTMS of the right posterior parietal lobe.

It is worth noting that Hubbard (2007) proposes a two-stage model of synesthesia, which is essentially a combination of the cross-wiring hypothesis and the hyperbinding theory.

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Functional brain differences in synesthetes

Paulesu et al. (1995) presented 6 spoken word-color synesthetes with blocks consisting of either pure tones or single, auditorily presented words. They found that areas of the posterior-inferior temporal cortex and the parieto-occipital junction were more activated in response to words than in response to tones in synesthetes, but not in controls. However, this finding did not extend to the visual areas V1, V2, and V4. This would seem to contradict the cross-wiring hypothesis as one of the findings supporting said hypothesis was that V4 was more activated in response to graphemes than non-graphemes. However, this finding is perfectly consistent with the disinhibition hypothesis, which postulates disinhibited feedback connections from regions such as the temporo-parietal-occipital junction.
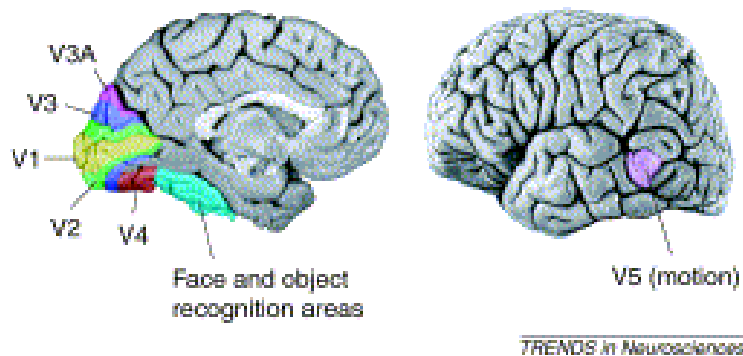
Figure 3. The locations of various visual areas within the brain.
This diagram (Zeki, 2003) shows the locations of the visual areas V1, V2, V3, V3a, V4, and V5 within the brain.

In a follow-up group study, however, Nunn et al. (2002) found a different pattern of results. Although they did not find a difference in activation of the earlier visual areas V1 and V2 to spoken words as compared to tones in synesthetes or controls, they did find that the color-processing areas V4 and V8 were more activated in response to spoken words than in response to tones in synesthetes but not in controls. Unlike the results of Paulesu et al.'s study (1995), the results of this study support the cross-wiring hypothesis.

The results from both of these studies conflict with those obtained by Aleman et al. (2001). The authors administered one spoken word-color synesthete several tasks: a task in which the synesthete passively listened to auditorily presented words, a task in

which the synesthete was given a letter of the alphabet and was asked to generate as many words as possible beginning with that letter, and a control task in which the synesthete listened to tones and pressed a button each time the frequency of the tone changed. During the two verbal, non-control tasks, increased activation of the primary visual cortex, V1, was found. The results of this study suggest differences in synesthetes in early perceptual processing (in line with other research to be discussed later), but the results of the previous two studies did not find this pattern. Further investigation is needed to determine why the results of these three studies differ so drastically (especially as all the synesthetes across the three studies were exclusively spoken word-color synesthetes and were all female, so any visual area activation differences in response to these stimuli were not caused by the confounds of synesthesia type or gender). However, it is important to note that Aleman et al.'s study (2001) only had one synesthete, so it is very possible that the activation found in V1 was unique to that subject and is not generalizable to other spoken-word color synesthetes.

Weiss et al. (2005) failed to find any increased activation in the visual areas of the fusiform gyrus during synesthetic experiences, but they did find enhanced activity of the intraparietal sulcus during synesthetic experiences, a logical finding given that the intraparietal sulcus is a brain region thought to contribute to the binding of color and form (Robertson, 2003). These results would seem to support the hyperbinding theory.

Rich et al. (2006) conducted an experiment in which four of either letters colored congruently to synesthetes' photisms (perceived colors), grayscale letters, or grayscale "placeholders" (squares with no fill) were presented to subjects. One of the items briefly disappeared, and the participants were asked to indicate which of the four had done do. Both the colored letter and grayscale letter conditions, relative to the baseline condition (grayscale "placeholders") resulted in activity in the left medial lingual gyrus in synesthetes. However, neither the colored letter nor grayscale letter conditions resulted in this activity relative to baseline in non-synesthetes. This makes sense because the left medial lingual gyrus has been implicated in tasks involving color knowledge.

Certainly, these results differ from one another, and in some cases the results are outright inconsistent with each other. Nevertheless, there are some common themes that emerge from these studies. First, synesthetes definitely show different activation patterns

from controls in response to their synesthetic-percept inducing stimuli, although these patterns differ from study to study. Second, these results suggest (but do not conclusively prove) that different mechanisms may be at play not only between different types of synesthesia, but within the same type as well. Further research is needed to resolve these inconsistencies. In doing so, we may be able to provide evidence for or against the various neural theories of synesthesia. Understanding these theories, and the results (though conflicting) for and against them, will help us place existing as well as future results into the broader context of what exactly causes synesthesia.

In addition to neuroimaging studies, electrophysiological studies have been conducted. In one study, Schiltz et al. (1999) administered the oddball task to 17 grapheme-color synesthetes. In this task, participants were presented with a sequence of either letters or numbers, and had to press a button when a target letter or number appeared. Synesthetes, as compared to non-synesthetes, were found to have a significantly more positive ERP (event-related potential) waveform over frontal and prefrontal scalp regions for both target and distractor stimuli. One of the interpretations proposed by the authors is that the frontal lobe (which has a large number of multisensory neurons) could be the area where synesthesia occurs, with the frontal positivity reflecting frontal inhibition to keep the synesthetic perceptions to a minimum. However, it seems difficult to reconcile this interpretation with any of the most common theories of the neural basis of synesthesia, so other explanations for this frontal positivity must be examined as well. Perhaps these results in the frontal cortex are related to attentional demands caused by synesthetic stimuli, which may double the perceptual load (for example, number-color synesthetes attend to both the number form and the induced synesthetic color).

Structural brain differences in synesthetes

Rouw & Scholte (2007) found increased fractional anisotropy (FA) in four brain regions in synesthetes: the left superior frontal lobe, right superior frontal lobe, left parietal lobe, and right temporal lobe. Increased FA may reflect factors such as greater density of axons, increased myelination, or increased coherence of white matter tracts, all of which improve functional connectivity within a brain region. However, Jäncke et al.

(2009) were not able to replicate all of the above results. For example, Rouw & Scholte (2007) found higher FA in the fusiform gyrus, while Jäncke et al. (2009) did not.

More research is needed to uncover the explanation for this discrepancy. One possibility is that there is inter-individual variability in the mechanisms underlying grapheme-color synesthesia, which would explain the divergence in the functional neuroimaging study results as well.

Jäncke et al. (2009) found increased cortical thickness, volume, and surface area in the left and right fusiform gyrus, as well as in the lingual gyrus (which plays a role in letter and word processing, see Mechelli et al., 2000) and the calcarine cortex, in grapheme-color synesthetes.

The results of Jäncke et al. (2009) are consistent in part with those of Weiss & Fink (2009), who found that grapheme-color synesthetes had increased gray matter volumes in the fusiform gyrus and in the intraparietal cortex. These results are consistent with the two-stage model of synesthesia, described above.

Cognitive advantages in synesthetes

While some studies have looked at the neural bases of synesthesia, many others have focused on cognitive and behavioral differences in people with grapheme-color synesthesia. Understanding these differences may allow us to draw connections between brain and behavior and help narrow down the brain regions that are affected in synesthesia.

Some studies have shown that grapheme-color synesthesia produces advantages in a wide variety of cognitive domains. Other studies, however, did not find these advantages. Constructs under investigation include several types of memory, such as digit memory (Smilek et al., 2002, Yaro & Ward, 2007, Gross et al., 2011), word memory (Radvansky et al., 2011; Yaro & Ward, 2007; Gross et al., 2011), and name memory (Mills et al., 2006), as well as creativity (Ward et al., 2008; Chun & Hupé, 2016), mental imagery (Chun & Hupé, 2016; Spiller et al., 2015), and verbal comprehension (Chun & Hupé, 2016). These enhancements, if in fact present, may be related to differences in the manner in which the synesthetes process information, and this in turn may be related to,

or perhaps even due to, differences in local and global visual processing. Each of these constructs is discussed in turn.

Memory of synesthetes

There is evidence to suggest that visual memory and visual perception may be related. Specifically, Kang et al. (2011) found that the contents of visual working memory could directly influence perception. They found that subjects misperceived the physical direction of motion of a stimulus if they held a different motion direction in visual working memory. These results also suggest that the neural mechanisms underlying visual working memory interact with the mechanisms underlying visual perception, or perhaps even share some of these mechanisms. Thus, it is entirely plausible that if synesthetes exhibit differences in memory, then they may also exhibit differences in local/global processing.

Word Memory

Radvansky et al., 2011, tested ten grapheme-color synesthetes in a word list recall task. Some of the word lists were presented in black, some were presented in colors congruent to (matching) the synesthetes' experiences, and some were presented in colors incongruent to (not matching) the synesthetes' experiences. Synesthetes were found to have superior performance overall for word list recall compared to controls, although they performed worse on incongruent word lists than on black and congruent word lists, while such differences were absent for controls. These findings suggest that the synesthetes' photisms (visual experiences elicited by their synesthetic stimuli) enhance their overall recall of words, but that this enhancement is disrupted for incongruent word lists due to these same photisms.

Yaro & Ward, 2007, were able to replicate these results using a somewhat different paradigm. 46 synesthetes were administered the Rey Auditory-Verbal Learning Test (RAVLT), which involves recalling lists of nouns several times. The synesthetes had an advantage over controls in most of the recall conditions. Mills et al., 2006, obtained similar results using the same task (the RAVLT).

Gross et al., 2011, replicated these results. Nine grapheme-color synesthetes were tested on three verbal memory tasks. The first task was the Warrington Recognition Memory Test-Words (WRMT). In this task, the participants rated words as pleasant or unpleasant. Later, new words as well as words from the original list were presented, and participants indicated whether they had seen the words before. The second task was the Paired Verbal Associates subtest of the Wechsler Memory Scale- Third Edition (WMS-III). This task assesses both cued immediate and delayed (30 minutes) recall. During recall, participants reported which word was paired with a verbal cue. The third task was the California Verbal Learning Test (CVLT-II). Participants heard and repeated a list of words several times. After hearing and reporting a list of distractors, the participant immediately recalled words from the first list. After 30 min, the participant again recalled words from the first list, without hearing it repeated again. Synesthetes performed significantly better on all three tests.

Name Memory

Mills et al., 2006, tested a letter-color synesthete in a name recall task. Stimuli consisted of first-last name pairs, which participants were given three minutes to recall, following a short delay. There was also a cued recall condition, in which participants were given the first names and needed to write in the corresponding last names. Overall, the synesthete outperformed controls on both the free recall and the cued recall conditions.

Digit Memory

In a case study, Smilek et al., 2002, tested a digit-color synesthete (code-named C) in a digit recall task. C was presented with three matrices of digits. In one matrix, the digits were black, in another, the digits were congruent with C's synesthetic colors, and in the other, the digits were incongruent with C's synesthetic colors. C's immediate recall of the black digits was superior to that of controls. However, her immediate recall of the incongruent digits was significantly poorer than her recall of either the black or the congruent digits. Furthermore, while controls showed a significant decrease in

performance between immediate and delayed recall, C did not show such a difference. These findings suggest that C's synesthetic photisms contribute to her enhanced digit memory overall, but that these same photisms can hamper her digit memory for incongruent digits.

In a large group study, Yaro & Ward, 2007, presented synesthetes with two matrices of digits. One matrix was congruently colored, and the other was incongruently colored. The results of this study contradict those of Smilek et al., 2002: no difference between synesthetes and controls was found in performance, and the authors also failed to find an effect of congruency on performance.

In a small group study, Gross et al., 2011, administered grapheme-color synesthetes the Digit Span subscale of the WMS-III. In this task participants repeated a sequence of numbers in the same order as they were presented. Participants were also asked to repeat a sequence of numbers backwards. Performance on this task did not differ between synesthetes and controls.

The results of Gross et al. (2011) suggest that grapheme-color synesthetes are not fundamentally different from controls in their recall of auditorily presented digits, perhaps because the synesthetic percepts occur primarily in response to visual graphemes. As for the inconsistency between the results of Smilek et al. (2002) and those of Yaro & Ward (2007), this could potentially be explained by the different sampling parameters of the studies. Smilek et al. (2002) conducted a case study, while Yaro & Ward (2007) conducted a large group study. Further attempts to replicate these results are necessary to determine the differences between synesthetes and controls in digit recall, as well as the effect of color congruency on digit recall in synesthetes.

Color Memory

Yaro & Ward, 2007, also administered a colored matrix recall task to their synesthetes and non-synesthete controls. One matrix consisting of 27 colored squares (using 9 different colors) was presented to the synesthetes and controls. The subjects then studied the matrix for 2 minutes, after which they were given a 2-minute recall period in which they needed to write as many color names as they could in the squares of a blank matrix. This cycle was repeated one more time. After an hour filled with other activities,

they again had 2 minutes to fill out a blank matrix. The authors found that synesthetes were significantly superior to controls in their delayed recall of the colored matrix., with the synesthetes able to recall on average 12 of the 27 colors, and controls only able to recall 7.

Yaro & Ward, 2007, also administered the Farnsworth-Munsell Colour Recognition Memory Test. For this task, 20 colored caps with specific hues were the targets, and 40 distractors (2 per target) were selected that differed by either 4 or 8 hues from the target. The 20 targets were divided into five groups of four. Within each group of four, the caps were presented, one at a time, for 5 seconds each. After this, they were presented with the caps again, in the same order, but this time each of the targets was paired with its two distractors. The participant was asked to identify which of the three caps was the target originally presented. The authors found that synesthetes outperformed controls on this task as well.

Creativity

Zmigrod et al. (2015) found a connection between creativity and local/global processing style in non-synesthetes. Interestingly, they found that a stronger bias towards paying attention to the "bigger picture" (global processing) lends itself to increased divergent (but not convergent) thinking; in other words, this translated into an increased ability to think of multiple solutions to a given problem. Given that research (discussed below) suggests that synesthetes are more creative than non-synesthetes, these results would seem to contradict some of the hypotheses of this thesis, namely that synesthetes might exhibit a more locally-oriented processing bias than controls. Nevertheless, Zmigrod et al.'s results definitely suggest that there is some relationship between creativity and global (vs. local) processing style, and that such processing styles should be investigated in synesthetes.

Ward et al. (2008) asked synesthetes and non-synesthetes about the amount of time they spent engaged in the creative arts. They also administered two psychometric tests of creativity (the Remote Associates Test, "RAT" and the Alternate Uses Test, "AUT"). In the former task, subjects are given three words and must find a fourth word that is related to each of the first three. In the latter task, subjects are given a list of

common objects and are asked to find up to six alternate uses for each object. Synesthetes reported spending more time engaged in the creative arts than controls, and also performed better than controls on the RAT, but not the AUT. Furthermore, there was no relationship between the participants' tendency to be engaged in the creative arts and their performance on the psychometric tests. These results suggest that the mechanism underlying synesthetes' increased propensity to engage in creative arts, and the mechanism underlying their performance on psychometric tests of creativity, are distinct from one another. These results also suggest that synesthetes are superior to controls in verbal convergent, but not verbal divergent, thinking.

In a fairly large group study, Chun & Hupé (2016) administered the RAT and the Alternative Uses Test (ALT, in this version, subjects named as many uses as possible within one minute) to their subjects. They also completed the Visual Associates Test (VAT), in which the participant is asked to find the conceptual link among three images, as well as the Figural Test of the Torrance Tests for Creative Thinking (FTTTC). In the FTTTC, participants are asked to draw interesting stories using abstract stimuli. This test included three tasks: one using a dark, rounded form, one using 10 incomplete, irregular figures, and one using 30 pairs of straight lines. Participants have 10 minutes per task, and must come up with a title for each drawing. They also used two verbal fluency tasks, one of which required participants to come up with as many animals as possible (measuring category fluency), and the other one of which required them to come up with as many words as possible that begin with the letter C (measuring letter fluency).Results indicated that synesthetes performed better than controls on the VAT and ALT, but not on the RAT, FTTTC, or verbal fluency task (results for the category fluency and letter fluency tasks were combined and analyzed as a single task). These results specifically suggest that grapheme-color synesthetes are superior to controls in visual convergent, but not visual divergent, thinking. Conversely, these same synesthetes are superior to controls in verbal divergent, but not verbal convergent, thinking.

In terms of the differences between synesthetes and controls on verbal convergent and divergent thinking, the results of Ward et al. (2008) are the polar opposite of the results of Chun & Hupé (2016). Why is this the case? One possible explanation is the different sample sizes used by the two studies, with that of Ward et al. (2008) being far

greater. Furthermore, each study included a wide variety of types of synesthesia, and the types that are included, and the proportions of each of these types within the samples, vary between the two groups. Thus, further research is needed to determine whether synesthetes actually differ from controls in visual and verbal convergent and divergent thinking.

Mental Imagery

Although there is little research on how mental imagery relates to local/global processing abilities, there is research to indicate that mental imagery relates to creativity, which itself is related to local/global processing. For example, González et al. (1997) found a significant effect of imagery ability on multiple aspects of creativity. Therefore, because synesthetes seem to show differences in mental imagery ability, it is not unreasonable to think that they might also show differences in local/global processing.

Chun & Hupé (2016) administered the French Questionnaire on Mental Imagery to their participants in order to measure the usage and intensity of mental imagery. Synesthetes scored higher along the usage (the extent to which mental imagery is used in daily life) dimension, but not along the intensity (the vividness of the mental imagery) dimension.

In a very large group study, Spiller et al. (2015) obtained different results. They administered the Spontaneous Use of Imagery Scale to synesthetes and controls. This scale contains a series of statements describing the use of visual imagery in everyday situations, with the participants being asked to indicate the appropriateness of each statement to their own experiences. Participants also completed the Vividness of Visual Imagery Questionnaire (VVIQ), in which they are asked to create a series of visual mental images, and then to rate the vividness of certain aspects of these images. Synesthetes with vision as one of their cross-linked sensory modalities were found to score higher on both usage and vividness of visual imagery.

The reason for the discrepancy between the results of Chun & Hupé (2016) and those of Spiller et al. (2015) may be that they used very different sample sizes. Another possible explanation is that they used different measures to assess mental imagery, which may use different strategies to assess the construct of imagery intensity/vividness.

Verbal Comprehension

Weaver & Rosner (1975) found a highly significant relationship (in terms of correlation coefficients) between visual perceptual skills (as measured on Raven's Colored Progressive Matrices, a task in which participants are given a sequence of matrices containing various patterns and must identify the next matrix in the sequence) and listening and reading comprehension. Thus, any differences in verbal comprehension in synesthetes may be associated with differences in visual perceptual skills and visual perceptual processing style (e.g. local or global). It is important to note that there is a distinction between visuo-perceptual reasoning, as measured by Weaver & Rosner (1975) and visuo-perceptual processing style, although they might be related.

Chun & Hupé (2016) administered the Wechsler Adult Intelligence Scale-Third Edition to their participants. They found that synesthetes scored higher on verbal comprehension than controls.

Personality of synesthetes

One study (Partos et al., 2016) found that individuals high in positive schizotypy have an increased bias to construe meaning out of random visual noise (e.g. to see something that is not actually there), while also being less sensitive at detecting actually present scenes, cartoons, and faces embedded in noise. The implications of this study are huge; personality and perception may actually be related! If grapheme-color synesthetes have different personalities than controls, then their local/global processing abilities may differ accordingly.

Synesthesia has been associated with an atypical personality profile. Banissy et al. (2012), administered the Oxford-Liverpool Inventory of Feelings and Experiences (O-Life) to 30 synesthetes who had color as their evoked sensation. This measure has 4 scales: Unusual Experiences (UnEx), Introvertive Anhedonia (IntAn), Cognitive Disorganization (CogDis), and Impulsive Non-Conformity (ImpNon). These scales measure the positive, negative, disorganized, and impulsive aspects of schizotypy, respectively. These synesthetes were found to exhibit higher levels of positive and disorganized schizotypy. Positive schizotypy involves unusual perceptual experiences,

hallucinations, and magical thinking. Disorganized schizotypy involves difficulties with attention, decision-making, and social anxiety. This heightened positive schizotypy may explain why synesthesia has been linked with such phenomena as out-of-body-experiences (Terhune, 2009), and mitempfindung, the referral of a tactile sensation to a location far away from the stimulation site (Burrack et al., 2006). Furthermore, positive schizotypy has been linked with creativity (Nelson & Rawlings, 2010) as well as vividness of mental imagery (Oertel et al., 2009), so heightened levels of this trait in synesthetes may explain the link between synesthesia and these two constructs. The results of this study suggest the presence of widespread cognitive and perceptual differences in synesthesia that cannot be attributed to the synesthetic experience itself.

In another study (Banissy et al., 2013), 81 grapheme-color synesthetes completed the Empathy Quotient (EQ), Inter-Personal Reactivity Index (IRI), and Big Five Inventory (BFI). The 40-item EQ has been revealed to have three factors: cognitive empathy, emotional reactivity, and social skills (Lawrence et al., 2004, and Muncer & Ling, 2006). The IRI, a 28-item self-report empathy measure (Davis, 1980), has 4 subscales: Perspective Taking, Fantasizing, Empathic Concern, and Personal Distress. The BFI is a 44-item scale designed to measure the Big Five personality traits, namely Extraversion, Agreeableness, Conscientiousness, Neuroticism, and Openness (John et al., 1991). On the BFI, synesthetes were found to score significantly higher on the Openness factor and significantly lower on the Agreeableness factor. No differences were found on the EQ; however, synesthetes did score higher on the Fantasizing subscale of the IRI. It is important to note, though, that the conceptual relatedness between the Fantasizing subscale and empathy in general has been questioned (Baron-Cohen & Wheelwright, 2004).

The results of this study were replicated in part by Chun & Hupé (2016), who administered the OCEAN-F, which assesses the Big Five traits (Goldberg, 1999), as well as the 28-item Tellegen Absorption Scale (TAS)- French Revised Version to 29 synesthetes of various types. The version of the TAS used has 5 factors: Responsiveness to Engaging Stimuli, Enhanced Cognition, Oblivious or Dissociative Involvement, Vivid Reminiscence, and Enhanced Awareness. On the OCEAN-F, synesthetes scored higher on the Openness factor, lending support to the results of Banissy et al. (2013). The

synesthetes also scored higher on the TAS. These results may explain the enhanced mental imagery reported in synesthesia, as the authors found that not only were openness and absorption positively correlated, but each also positively correlated with usage of mental imagery.

Perception of synesthetes

Early perceptual processing

Synesthetes who perceive colors have been shown to display early processing differences to stimuli that do not induce synesthetic percepts. Barnett et al. (2008) presented high (HSF) and low (LSF) spatial frequency Gabors (arrays of lines, with high frequency Gabors having many lines and low frequency Gabors having fewer lines, see Figure 4) and grids of luminance-contrast squares (where contrast of the squares against the background was established by the luminance of the squares, see Figure 5) to 15 grapheme-color synesthetes. Using EEG, the authors found that synesthetes displayed an enhanced C1 component in response to HSF Gabors compared to non-synesthetes. The C1 component, which is the earliest discernable VEP (it peaks around 90 ms post-stimulus), reflects activity in the primary visual cortex (Di Russo et al., 2001). The authors also found that synesthetes displayed an enhanced P1 component (which peaks around 100 ms post-stimulus, see Di Russo et al., 2001) in response to luminance-contrast squares presented from 8% to 64% contrast (but not 4% contrast). In fact, at 4% contrast, synesthetes showed a trend toward decreased cortical responsiveness. These results suggest differences in the activity of a group of neurons called parvocellular neurons in the lateral geniculate nucleus (LGN) of the thalamus in synesthetes, because parvocellular neurons are more sensitive to higher contrasts and higher spatial frequencies, the types of stimuli which were found to result in enhanced visual evoked potential (VEP) components. These results suggest decreases in the activity of magnocellular neurons in the LGN as well, because magnocellular neurons are more sensitive to lower contrasts and lower spatial frequencies, the former of which was found to result in smaller VEP components..
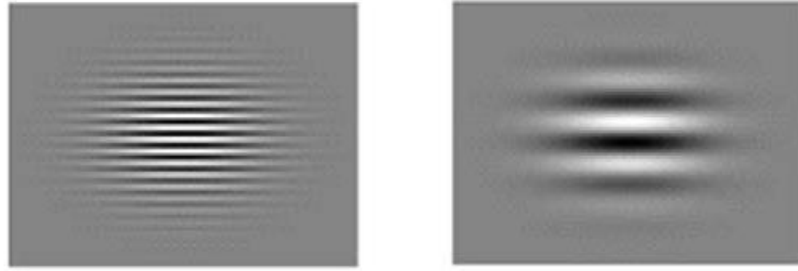
Figure 4. HSF and LSF Gabors.

On the left is an HSF Gabor, and on the right is an LSF Gabor (see Barnett et al., 2008).

Figure 5. Luminance-contrast squares.

On the left are 16% contrast squares, and on the right are 32% contrast squares (see Barnett et al., 2008).

These results are relevant to the current study because processing of HSF stimuli has been correlated with local processing. Specifically, processing of local information seems to depend on its HSF content (Boeschoten et al., 2005), which is processed more medially (vs. laterally) in the visual cortex than low spatial frequency content. Thus, these results suggest that synesthetes may have superior local processing abilities compared to controls.

Facial and emotional processing

Synesthetes have been shown to differ in their processing of faces and emotions. McErlean et al. (2016) administered the Cambridge Face Perception Test (CFPT-Identity) to 20 grapheme-color synesthetes. In this task, a male face is presented at the top of the screen, and six slightly different male faces are presented below. Participants

were asked to sort these six faces in order of least to most like the target face. The authors also administered to the subjects the Cambridge Face Perception Angry Expression (CFPT-Angry) and the Cambridge Face Perception Happy Expression (CFPT-Happy) tests. For these tests, a row of faces was presented, with the faces displaying different degrees of anger (or happiness). Participants were asked to rank the faces from most intense to least intense display of the emotion. Synesthetes were found to outperform controls both on facial identity and facial emotion perception. Since this task assesses ability to make fine-grained discriminations among faces, these results suggest superior local processing abilities in synesthetes.

McErlean et al. (2016) also conducted a second experiment in which they tested 12 grapheme-color synesthetes in a face composite task, considered to be a measure of holistic face processing (Rossion 2013). In this task, a set of composite faces was generated by mixing same-sex top and bottom halves from a set of original faces. The top and bottom halves could either be aligned (to form a novel face) or misaligned. One composite face would be presented, followed by a blank screen, followed by the second composite face. Either both faces would be aligned or both faces would be misaligned. Participants were asked to indicate whether the top halves of the faces were the same or different, while ignoring the bottom halves. No difference was found in the face composite effect between synesthetes and non-synesthetes, suggesting that there are no differences in holistic, or global, processing abilities. Overall, these results, and results from the previous study, suggest that synesthetes may respond preferentially to local elements of a stimulus as opposed to global elements of the stimulus.

Color perception

As mentioned earlier, synesthesia may lead to differences in the activity of parvocellular neurons in the LGN of the thalamus. Parvocellular pathways also contribute to chromatic processing, so perception of color may also be altered in synesthesia. Further evidence for this idea comes from neuroanatomical evidence showing that synesthesia for color (defined as synesthesia in which color is the evoked sensation) is related to greater brain volume in regions of the fusiform gyrus implicated in color processing (Banissy et al. 2012). Banissy et al. (2013) tested this hypothesis by

administering 10 synesthetes for color a visual search task in which colored circles were arranged to form a circle (with the very top and very bottom circle missing). All of these circles were the same except for one, which was the target. The target could differ from the distractors in one of three ways: hue, saturation, or luminance (see Figure 6). Participants were required to indicate which side of the circle (left or right) contained the target. Synesthetes were found to be more accurate on this task, but did not differ from controls in response time.
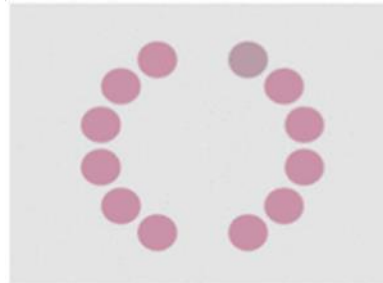
Figure 6. Color visual search task.

One of the circles differs in color from the rest; in this example, it is the circle on the top right (see Banissy et al., 2013)

Banissy et al. (2009) used a different task to assess color perception in synesthetes. They administered the Farnsworth-Munsell Colour Hue Test to 16 synesthetes for color. In this task, participants arrange a series of colored caps such that they transition from one hue to another. In this task as well, synesthetes for color were found to perform superior (as manifested by a lower Total Error Score, which is calculated based on the deviation from the expected ordering) to controls. Yaro & Ward (2007) also used this task and were able to replicate their results.

There is little, if any, research on the relationship between color perception and local/global processing, but it seems likely that performance on this task is partly based on local processing abilities, as it requires the detection of minute changes in hue, saturation, or luminance. If this is the case, these results would predict superior local processing abilities in synesthetes.

Motion perception

As mentioned earlier, synesthesia may be associated with changes in the magnocellular neurons of the LGN. Furthermore, synesthetes have been shown to have decreased brain volume in the middle temporal visual area (MT/V5) (Banissy et al. 2012), which receives input from magnocellular pathways. This area is involved in motion perception, so these results suggest that motion perception may be impaired in synesthesia. Further evidence for this idea comes from evidence that color perception is enhanced in synesthesia for color, and that neural regions involved in color and motion processing typically inhibit one another (Ellison et al., 2003; Morland et al., 1996; Walsh et al., 1998). In a small group study, Banissy et al. (2013) evaluated this hypothesis by testing synesthetes for colors in a random-dot kinematogram paradigm (see Figure 7). For this task, an array of white dots was presented, with a proportion of the dots moving in the same (coherent) direction, and the rest moving in random directions. The participants were instructed to indicate which way (left or right) the coherent dots were moving. Synesthetes were found to have a higher motion-coherence threshold than non-synesthetes; in other words, the proportion of coherent dots needed to accurately detect direction of motion was higher in synesthetes than in non-synesthetes. These results suggest reduced motion perception in synesthetes.
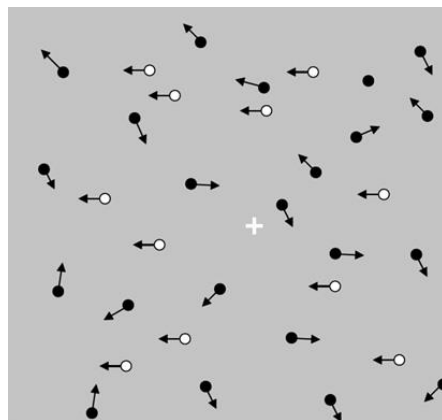

Figure 7. Random-dot kinetogram paradigm.
The white dots represent the coherently-moving dots, while the black dots represent the random-moving dots. Arrows indicate the direction of dot motion (see Kalla et al., 2011).

Motion perception sometimes relies on global processing, and sometimes on local processing (Anstis & Kim, 2011). It is difficult to tell which of these processing levels is altered and causes the reduced motion perception in synesthesia for this particular task, nevertheless; motion perception and global/local processing are definitely related constructs.

Local/Global Visual Processing

Hierarchical Figures

A hierarchical figure is a large form made up of smaller forms. A classic example of a hierarchical figure is a Navon letter, for example, a big H made up of smaller Ss (inconsistent) or a big S made up of smaller Ss (consistent) (Navon, 1977) (see Figure 8). In this task, most people exhibit a global processing bias (Navon, 1977). This means that if the local and global elements of a form are inconsistent, reaction times are faster and accuracy is higher for identifying the global form compared to the local forms. This pattern of results suggests that the local elements do not distract people from identifying the global element, while the global element does distract people from identifying the local element. To put it more simply, there seems to be a "global precedence effect" in which attention is automatically biased toward processing the global element compared to the local elements of a form. The results of this study are relevant to the current experiment because if synesthetes do in fact display a more locally-oriented processing style than controls, then the magnitude of the global precedence effect should be decreased in these synesthetes compared to controls. The current study used a variant of the Navon paradigm, but also eliminated the influence of synesthetic percepts by using non-grapheme-based stimuli, in order to get at more general local/global processing differences not directly related to the synesthetic experience itself.

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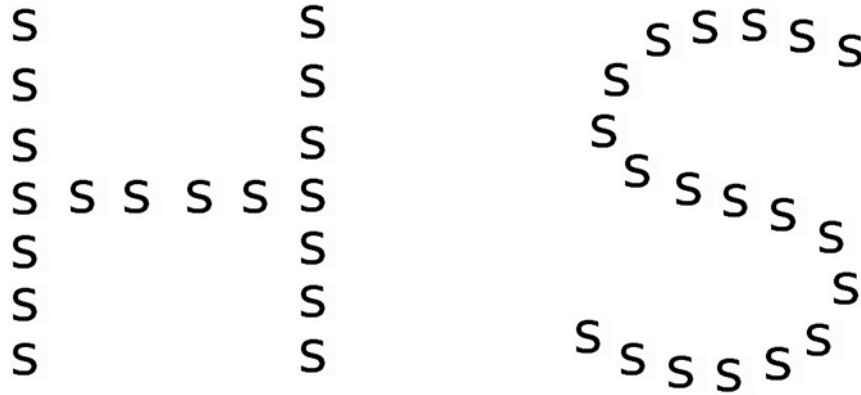
Figure 8. Navon stimuli.

The large H made of small Ss (left) is inconsistent. The large S made of small Ss (right)
is consistent (modified from Navon, 1977).

Rey-Osterrieth Complex Figure (ROCF) Task

The ROCF task is a task that assesses visuo-spatial memory in addition to
local/global processing. In this task, the participant is given a complex figure. The task
generally has three conditions: Copy, Immediate Recall, and Delayed Recall. In the Copy
condition, the participant is asked to draw a copy of the image as accurately as possible.
After this, the figure is taken away and the participant is asked to draw it from memory.
This is the Immediate Recall condition. The participant then completes other, unrelated
tasks for about half an hour, then draws the figure from memory again. This is the
Delayed Recall Condition. By assessing the order in which the elements are drawn, as
well as the presence, accuracy and placement of the various elements, one can determine
whether that individual has a more globally-oriented or a more locally-oriented
processing style.

Gross et al. (2011) administered this task to grapheme-color synesthetes, and
found that the synesthetes performed better than controls overall on all three conditions
of the ROCF task, particularly in that they had higher accuracy for configural elements
(the larger, more global elements of the figure). These results are interesting in that they
do not seem entirely compatible with the predictions made for this study, so attempting to
replicate their results is very informative.

Visual search

Visual search tasks are generally of two types. In feature search, the target differs from each distractor along a single dimension (for example, a red T hidden among blue Ts). Feature search is often said to be "efficient" and "parallel" (Treisman & Gelade, 1980). On the other hand, in conjunction search, the target differs from some distractors along one dimension, and from the other distractors along another dimension (for example, a purple S among purple Vs and green Ss). Conjunction search is often said to be "inefficient" and "serial" (Treisman & Gelade, 1980). The latter term refers to the feature-integration theory, which states that attention is directed serially to each of the items in a conjunction search in order to determine if it is the target. (Treisman & Gelade, 1980)

Not only do feature and conjunction searches differ in terms of task demands, they also differ in the mechanisms mediating performance on these tasks. Feature searches are often believed to rely on preattentive mechanisms, while conjunction searches are often believed to rely on attentive mechanisms. In other words, conjunction search appears to require active attention, while feature search does not. The reason for this is because feature search tasks often have a set-size slope of approximately 0 (put differently, in feature search tasks, increasing the set size, or number of stimuli, in a trial does not increase response time), and this null slope is thought to be reflective of preattentive mechanisms. In fact, because feature search does not seem to rely on active attention, it can be thought of as "pop-out" search, where the target "pops out" perceptually to the participant. Conjunction search tasks, on the other hand, generally have a positive set-size slope, where response times increase by 10 to 50 ms per distractor item added (Wolfe, 1998).

The distinction between preattentive and attentive levels of processing in visual search can be referred to as the two-stage assumption (Kristjánsson 2015). As widely accepted as this model is, there are some findings that would seem to contradict it. One example is efficient conjunction search, which occurs in certain specific visual search tasks. For instance, McLeod et al. (1988) found that search for a moving X among moving Os and static Xs was parallel. This suggests that the two-stage assumption is not

true for targets defined by a combination of the features movement and form. These results were also significant because, as the moving Os and static Xs were randomly distributed, they suggest that attention can be focused on a spatially dispersed perceptual group. This contradicts previous findings that attention can only be directed to contiguous regions of visual space (Treisman, 1982; Nakayama & Silverman, 1986). Furthermore, Theeuwes & Kooi (1994) found that search for a target defined by a conjunction of contrast polarity and shape was parallel, and Nakayama & Silverman (1986) found that search was also parallel for a target defined either by a conjunction of stereoscopic disparity (the difference in image location of an object seen by the left and right eyes, resulting from the eyes' horizontal separation) and color, or of stereoscopic disparity and motion.

Further evidence refuting the two-stage assumption comes from studies where response time decreased as set size increased. This was found by Bravo & Nakayama (1992) and Santhi & Reeves (2004), and their results suggest that target salience can be increased in certain circumstances by an increasing number of distractors. Alternatively, a larger number of distractors could provide more evidence on which to base a decision (Eckstein, 1998) or simplify the task by facilitating perceptual grouping (Wang et al., 2005). Regardless, all of the aforementioned evidence suggests that the two-stage assumption should not be relied too heavily upon, and that visual search is more complex than previously imagined.

As visual search is generally taken to be a measure of local visual processing ability (a main line of evidence in support of this is that people with ASD reliably outperform controls on visual search tasks, Kaldy et al., 2013, and also have superior local processing abilities, van der Helm, 2016), it seems that grapheme-color synesthetes would outperform controls on such tasks. However, the literature on the effects of grapheme-color synesthesia on visual search performance is mixed.

Palmeri et al. (2002) presented one synesthete with visual search arrays in which participants were asked to find the 2 hidden among the 5s, or to find the 8 hidden among the 6s. Displays consisted of either 16, 25, or 36 digits. Participants were instructed to respond PRESENT if the target was present and ABSENT if the target was absent. As expected, non-synesthetes' response times increased as the set size increased. This

pattern occurred in the synesthete as well, but the slope of the visual search function was flatter than was the non-synesthetes' for the 2 in 5s condition. However, in the 8 in 6s condition, the synesthete's response pattern was very similar to the non-synesthetes'. This is because the synesthete perceived both 8 and 6 as blue, thus lessening his synesthetic advantage by reducing the pop-out effect. The authors also presented to the synesthete arrays where he had to find a 2 or a non-grapheme hidden among a field of a different non-graphemes. For this condition results did not differ from non-synesthetes. This is particularly interesting as it would seem that a 2 (which the synesthete perceived as orange) should pop-out from the field of non-graphemes (which had no color). However, overall, the results suggest that performance on a grapheme-based visual search task is enhanced in synesthetes, assuming the graphemes used have different colors. When the graphemes were uniform in color, no such enhancement was seen. In combination with the lack of a difference between groups for the purely non-graphemic task, these results suggest that there would probably not be superior performance in synesthetes on a non-grapheme-based task. A limitation of this study is that it only had 1 synesthete, which greatly limits the generalizability of the results. Laeng et al. (2004) conducted a similar study, with similar results. Their experiment was also a case study.
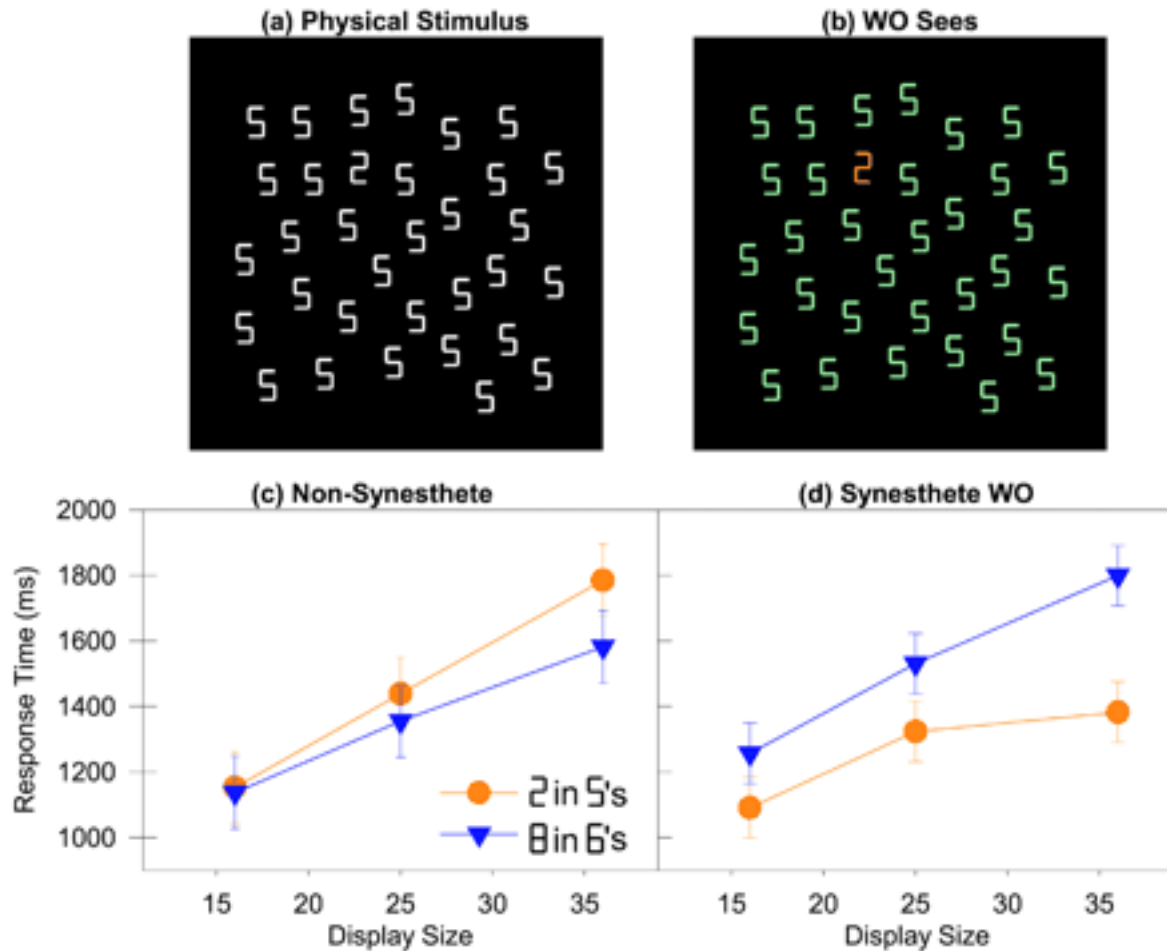
Figure 9. The effect of synesthetic color on visual search performance.
The synesthete displays a shallower search slope than controls for the 2 in 5s condition
because he perceives each grapheme in a different color, allowing the target to
perceptually "pop out" to him. However, his search slope for the 8 in 6s condition was
very similar to controls because he perceived both graphemes to be blue, thus eliminating
the color pop-out effect.

The idea that synesthetes would be no better than controls on a non-grapheme-
based task is supported by the results of Banissy et al. (2013), who administered an
orientation visual search task to grapheme-color synesthetes and controls. In this task,
tilted lines were organized to form a circle (with the top and bottom lines missing). One
line was oriented differently from the others, and the participant was asked whether this
line was on the left or right of a circle see Figure 9). There was no difference in
performance (either in accuracy or response time) between these two groups.

Figure 10. Orientation visual search task.

One line differs in orientation from the rest; in this example, it is on the left side, second from the top (see Banissy et al., 2013)

However, the fact that there was no color (all black or white) in these two non-graphemic tasks (Banissy et al.'s 2013 task and Palmeri et al.'s 2002 task) could have minimized the involvement of the parvocellular 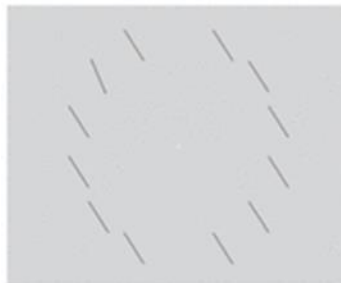pathway (which processes color) and thus influenced the results, so we cannot say for certain no effect would be found in a non-grapheme-based task that uses color or other stimulus attributes to induce a shift to parvocellular processing. As noted earlier, grapheme-color synesthetes showed superior performance on a color visual search task, which thus relied heavily on parvocellular processing. However, due to the specific nature of this task, the very likely possibility that these synesthetes have increased sensitivity to differences in color relative to controls makes it difficult to determine the extent to which general visual search ability played a role in the results.

However, the trend in group studies seems to be different. Edquist et al. (2006) and Gheri et al. (2008) both failed to find differences between synesthetes and controls on visual search tasks. Their findings may suggest that synesthetic experiences arise from the cognitive, and not the perceptual, level. Alternatively, they may indeed arise from the perceptual level, but not early enough in visual processing to affect task performance.

By administering a non-grapheme-based visual search task, we may be able to use the results of the current study to resolve some of the discrepancies in the existing research in visual search and synesthesia. More importantly, though, we may be able to address the broader issue of whether grapheme-color synesthetes have general perceptual differences, not just those related to their synesthetic experiences. By eliminating the

confound of synesthetic percepts induced by graphemes, we can gain insight into whether synesthetes do in fact have such general perceptual differences.

Current Study

Given the results of the aforementioned studies, particularly those that suggest cognitive and perceptual differences in synesthesia, the current study was designed to test whether synesthetes differ from non-synesthetes in terms of local versus global processing abilities. The general prediction was that synesthetes may have a local bias in perceptual processing, or alternatively a reduced global bias compared to non-synesthetes. While most previous experiments on grapheme-color synesthesia used grapheme stimuli to measure differences in perception and cognition, the current study intentionally avoided such stimuli in order to focus more broadly on perceptual and attentional differences between synesthetes and non-synesthetes. Three different tasks were employed to measure potential differences in local/global processing in a group of synesthetes versus a group of gender- and age-matched controls: (1) The Rey-Osterrieth Complex Figure Task, (2) a hierarchical figure task, and (3) a visual search task. In each case, between-subjects comparisons were made to determine if perceptual and/or attentional processing differs between the two groups. Specifically, it was predicted that synesthetes would score higher on the detailed drawing aspects of the ROCF task, show less of a global precedence effect on the hierarchical figure task, and show less steep search slopes on conjunction visual search tasks compared to controls.

Methods

Participants

9 grapheme-color synesthetes were recruited, along with 9 age- (+/- 1 year) and gender-matched controls. The sample included 10 males (55.56%) and 8 females (44.44%) (*M* age = 19.61, *SD* age = 1.24). All participants provided informed consent, and all were compensated with $15. This study was approved by the Reed College Institutional Review Board.

Procedure

The first task completed by all participants was the Copy condition of the Rey-Osterrieth figure, followed by the Immediate Recall condition. After this, they completed either the hierarchical figures task or visual search task (which included both the feature and conjunction sub-tasks). The order of the computerized tasks was counterbalanced. After this first computerized task, participants completed the Delayed Recall condition of the Rey-Osterrieth figure. Finally, they completed the second computerized task. Additionally, visual acuity was tested using an eye chart.

Tasks

Hierarchical figures

The hierarchical figures task was non-grapheme-based, to prevent any confounding effects induced by the synesthetic percepts, and to investigate more general processing differences between synesthetes and controls. Five different false fonts (which

involve the manipulation of elements of actual graphemes to produce unfamiliar forms) were used to construct the stimuli (see Figure 10).

Figure 11. False Fonts
The five false fonts used for construction of hierarchical stimuli

The basic logic behind stimulus design was to create large false font stimuli composed of smaller false font elements. The stimuli consist of the false fonts in all their possible combinations, with the following rule: that the global and local elements of a given stimulus cannot be identical. Two such stimuli were presented simultaneously on each trial, and the participant was required to indicate whether the forms at either the local level or global level (during separate "local" and "global" attention blocks) were the same or different using two alternative key presses.

There were three types of trials: *mismatch* (in which the global and local elements of each of the two forms are all different, so there are 4 different false fonts on the screen), *global match* (in which the elements at the global levels of the two forms match; the local elements of the two forms differ from the global elements as well as from each other, so there are 3 different false fonts on the screen), and *local match* (same as the same/global trials, except that the match is at the local level instead).

There were 2 blocks of trials where participants must focus on the local level, and 2 blocks of trials where participants must focus on the global level. Each local block consisted of 30 *local match* combinations and their reversals (i.e. the form on the left becomes the form on the right, and vice versa; 60 trials in total), 15 *global match* combinations and their reversals (30 trials in total), and 15 *mismatch* combinations and their reversals (30 trials in total). Thus, each local block consisted of 120 trials. Each global block consisted of 30 *global match* combinations and their reversals (60 trials in total), 15 *local match* combinations and their reversals (30 trials in total), and 15 *mismatch* combinations and their reversals (30 trials in total). Thus, each global block consisted of 120 trials. This task was designed such that within a given block, the number

of matches and non-matches (at the instructed level only) will be the same. The local and global blocks alternated. Thus, participants completed the blocks in one of 2 orders: local, global, local, global, or global, local, global, local. The order of the blocks was randomized for each participant. In total, participants completed 480 trials.

The global element subtended 5° by 5° of visual angle, and the local element subtended 0.6° by 0.6° of visual angle. During stimulus presentation, the two stimuli were located 0.5° from a central fixation cross (which subtended 0.5° by 0.5° of visual angle). Trials began with a central fixation cross presented for anywhere between 800 to 1200 ms (randomized for each trial), after which the Navon stimuli were presented (with fixation cross) for 200 ms, followed by another fixation cross which lasted until the response was made (see Figure 11). Thus, the fixation cross was on screen the entire length of each trial. Participants were seated approximately 30 inches away from the computer screen.

This was a speeded task, with the participant asked to answer as accurately and as quickly as possible. Response time and accuracy were compared between the local and global conditions. I predicted that controls will be more accurate and have faster response times in the global condition compared to the local condition (in other words, that their performance will reflect the "global precedence effect". I also predicted that synesthetes will show the same pattern of results as controls in the global condition, but that they will also be more accurate and have faster response times in the local condition compared to the controls (which would result in a diminished "global precedence effect").

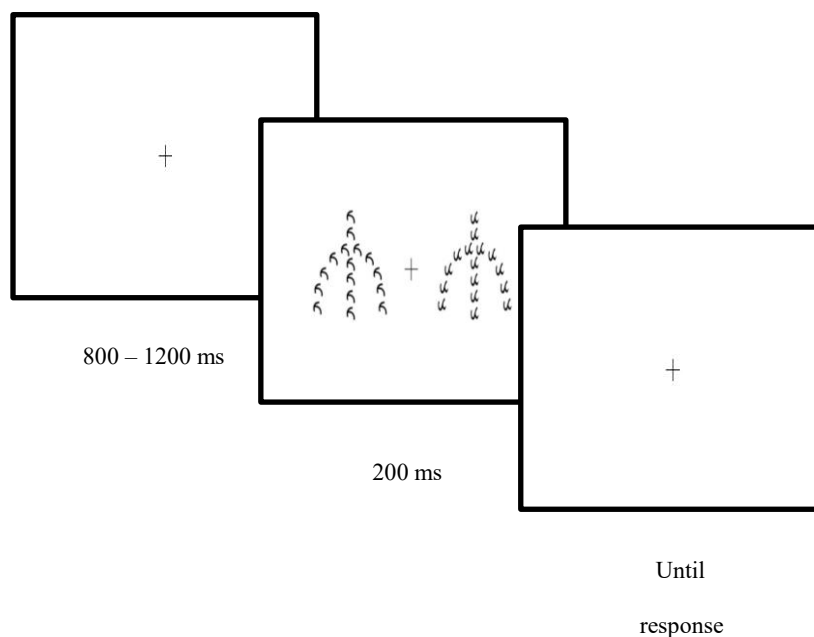800 – 1200 ms

200 ms

Until

response

34

Figure 12. A sample hierarchical figures trial.

A fixation cross was presented for 800-1200 ms (randomized for each trial), after which the stimulus was presented for 200 ms, and then another fixation cross was presented until a response was made. This trial belongs to the "global match" condition.

ROCF task
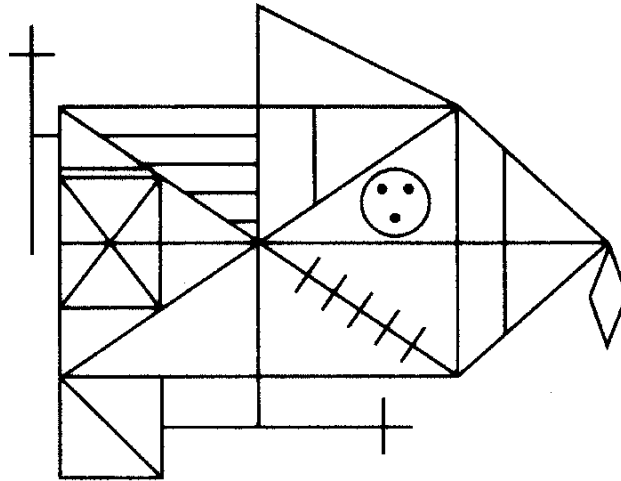
Figure 13. The Rey-Osterrieth figure.

This task can be used to evaluate visuo-spatial memory and perceptual processing style.

The Rey-Osterrieth task consisted of three conditions: Copy, Immediate Recall, and Delayed Recall. In the Copy condition, participants were presented with the figure (see Figure 12) and asked to reproduce it as accurately as possible. The participants were not told that they were to reproduce it from memory later. As soon as the Copy condition was completed, the figure was removed, and the participants were asked to draw it from memory. This was the Immediate Recall condition. They then completed the first computerized task, after which they were instructed to draw it from memory again. This is the Delayed Recall condition. No time constraints applied to any of the three

conditions, although it was noted how long the participant took to complete each drawing. As the participant drew the reproductions, notes were taken in order to ascertain the way in which the design was approached (e.g. which elements were drawn first). Reproductions from all three conditions were scored using the comprehensive method of the Boston Qualitative Scoring System, which categorizes each element of the figure into either a configural element (global element), cluster (mid-level element), or detail (local element). Total score (calculated as sum of all 16 subscores), configural scores (calculated as sum of configural element presence and accuracy), cluster scores (calculated as sum of cluster presence, accuracy, and placement), and detail scores (calculated as sum of detail presence and placement) as well as all 6 summary scores, were compared between synesthetes and controls. (See Appendix E for a list of the 16 subscores and 6 subscores and how they are calculated, as well as a diagram identifying all the individual configural elements, clusters, and details.) I predicted that synesthetes would score higher on Details Presence and Details Placement, and lower on Organization, compared to controls.

Visual search tasks

Additionally, participants completed both a feature visual search task and a conjunction visual search task. For each task, 3 search sizes (4, 16, and 32) were used. Both tasks were non-grapheme-based, to prevent the influence of any synesthetic colors. The stimuli consisted of horizontal or vertical bars colored either red or green. The target was always a red vertical bar, in both conditions. In the feature condition, the distractors were vertical and horizontal green bars. In the conjunction condition, the distractors were horizontal red bars and vertical green bars. On half the trials, the target was present, and on the other half, the target was absent. Participants were asked to indicate whether or not the target was present via two alternative key presses. The horizontal bars were 0.53° by 0.15° of visual angle, and the vertical bars were 0.15° by 0.53° of visual angle. Each trial consisted of a fixation cross presented for 500 ms, followed by the stimuli for either 10000 ms or until a response was made (see Figure 13). Participants were seated approximately 30 inches away from the computer screen. Accuracies and response time search slopes were compared between the two groups. I predicted that synesthetes' search

slope in the conjunction task will be flatter than that for controls and that overall response times for accurate trials in the conjunction task will be lower than in controls. I also predicted that search slope in the feature task will be the same for synesthetes and controls but that the overall response times for accurate trials will be lower than in controls.
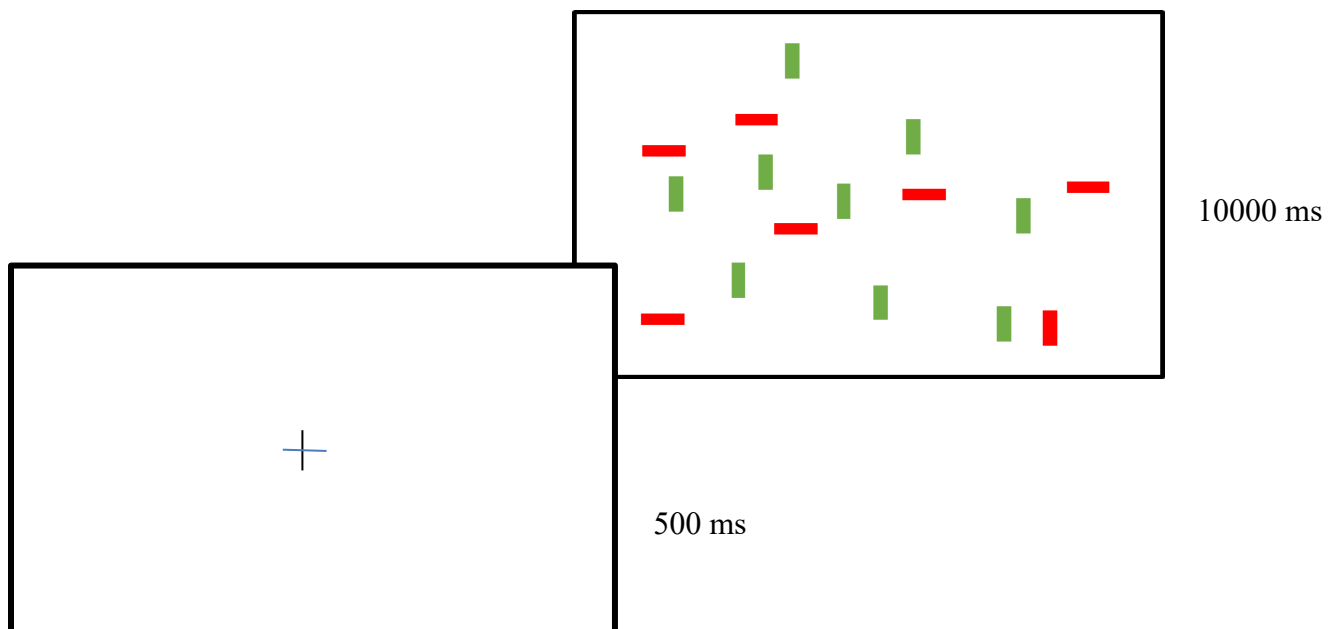

10000 ms

500 ms

Figure 14. A sample feature visual search task trial.
A fixation cross is presented for 500 ms, after which the visual search array is presented for 10000 ms or until a response is made. In this conjunction trial, there are 16 items and the target (a red vertical bar) is present.

Results

Hierarchical Figures

Accuracy

Mean accuracy was computed for each subject for the local blocks (the two local blocks were averaged together) and the global blocks (the two global blocks were averaged together). These means were entered into a 2 x 2 mixed ANOVA with group as a between-subjects factor and block type as a within-subjects factor. There was a significant main effect of block type, $F_{(1,16)} = 13.68$, $p = 0.002$, $\eta^2 = 0.46$. There was no significant main effect of group, $F_{(1,16)} = 0.78$, $p = 0.389$, $\eta^2 = 0.05$. There was also no significant interaction between block type and group, $F_{(1,16)} = 0.17$, $p = 0.685$, $\eta^2 = 0.01$. Accuracies, averaged across both groups, were higher overall in global blocks ($M = 94.387$; $SD = 5.60$) than in local blocks ($M = 89.469$, $SD = 5.56$), a difference of 4.918 ($SD = 5.50$, 95% CI = [2.418, 7.418]). Means for each combination of group and block type are shown in Table 1 and Figure 14.

Table 1. Means and standard deviations for accuracy in local and global blocks in synesthetes and non-synesthetes.

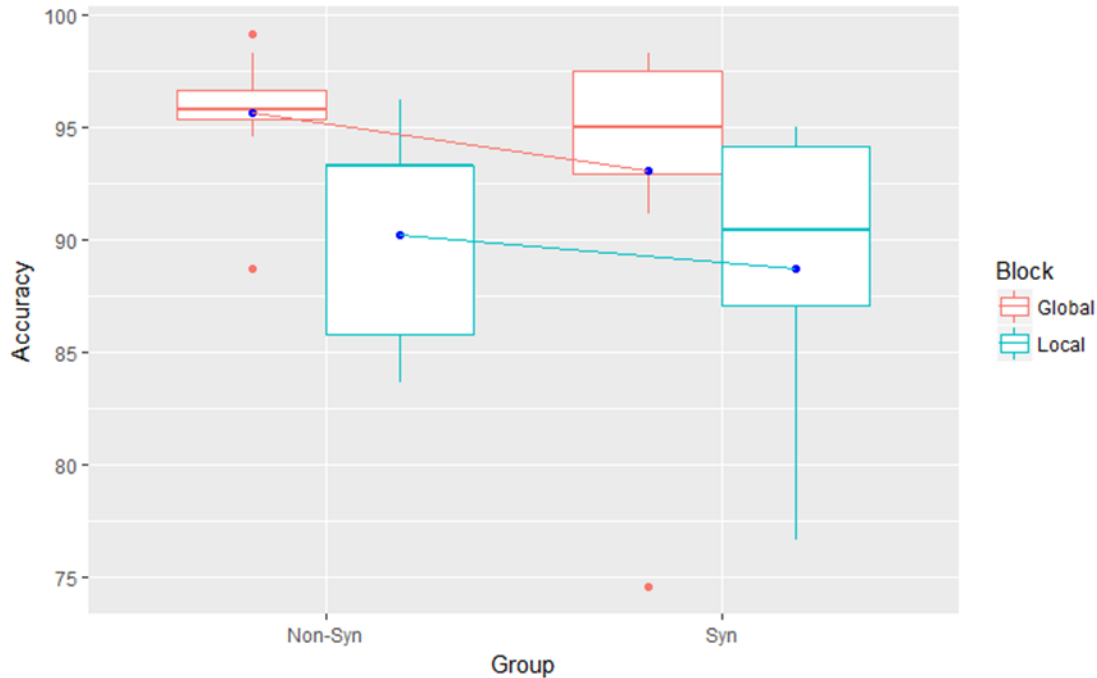| Group	Local Block Accuracy	Global Block Accuracy
	Mean = 88.723	Mean = 93.092
Synesthetes	SD = 6.549	SD = 7.357
Non-Synesthetes	Mean = 90.214	Mean = 95.682
	SD = 4.654	SD = 2.967

Figure 15. Boxplot showing accuracies in local and global blocks in synesthetes and non-synesthetes.

Dark blue dots represent means for each combination of group and block. The red line represents the difference in mean accuracy between synesthetes and non-synesthetes for the global blocks. The teal line represents the difference in mean accuracy between synesthetes and non-synesthetes for the local blocks. While accuracies were significantly higher for global vs. local blocks in each group, the group differences were not significant. Non-Syn = Non-Synesthetes, Syn = Synesthetes.

The previous analysis included all trials regardless of trial type (e.g. target level matches [local block, local match trials and global block, global match trials], opposite level matches [local block, global match trials and global block, local match trials], and mismatches [local block, mismatch trials and global block, mismatch trials]). In order to determine whether group differences in accuracy might be present but restricted to a particular trial type, 2 x 2 mixed ANOVAs with group as a between-subjects factor and block type as a within-subjects factor were run for each of the three trial types (target level matches, opposite level matches, and mismatches). There were significant (or near-significant) main effects of block type for all three trial types. However, there were no significant main effects of group or interaction effects between block type and group for any of the three trial types (see Appendix A).

One possible reason for the lack of group differences might be related to learning throughout the experiment. Perhaps synesthetes started off with an advantage for local blocks, but controls quickly learned to perform the local task just as well. In order to see whether synesthetes and non-synesthetes differed in accuracy in only the first local or global blocks, a 2 x 2 mixed ANOVA was conducted with group as a between-subjects variable and block type as a within-subjects variable, for only the trials in the first local and global blocks. For the first two blocks (the first local block and the first global block) only, there were significant main effects of block type. However, there were still no main effects of group or interaction effects between block type and group (see Appendix B).

Response Time

Mean response times were computed for each subject for the local blocks (the two local blocks were averaged together) and the global blocks (the two global blocks were averaged together). These means were entered into a 2 x 2 mixed ANOVA with group as a between-subjects factor and block type as a within-subjects factor. There was a significant effect of block type, $F_{(1,16)} = 46.86$, $p < 0.001$, $\eta^2 = 0.75$. There was no significant main effect of group, $F_{(1,16)} = 0.17$, $p = 0.687$, $\eta^2 = 0.01$. There was also no significant interaction between block type and group, $F_{(1,16)} = 0.03$, $p = 0.866$, $\eta^2 < 0.01$. Response times, averaged across both groups, were shorter overall in global blocks ($M = 684.211$ ms, $SD = 151.862$ ms) than in local blocks ($M = 836.995$ ms, $SD = 198.288$ ms), a difference of 152.784 ms ($SD = 91.954$ ms, 95% CI = [110.784 ms, 194.784 ms]). Mean response times for each combination of group and block type are shown in Table 2 and Figure 15.

Table 2. Means and standard deviations for response time in local and global blocks in synesthetes and non-synesthetes.

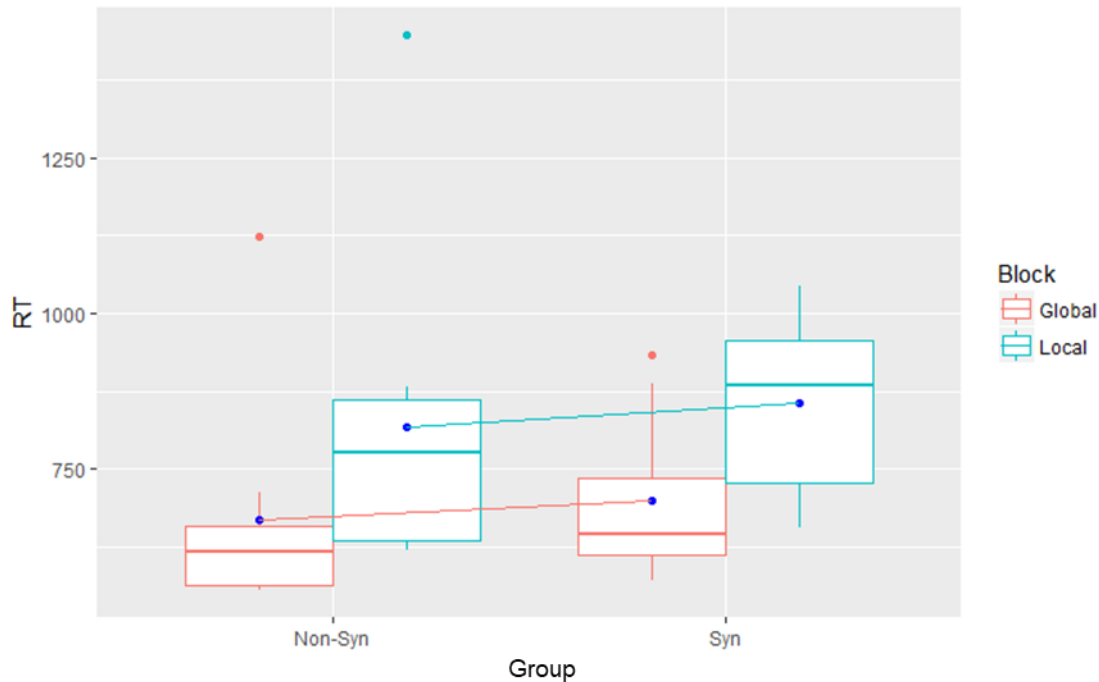| Group	Local Block RT	Global Block RT
	Mean = 855.825	Mean = 699.203
Synesthetes	SD = 133.888	SD = 129.228
Non-Synesthetes	Mean = 818.166	Mean = 669.219
	SD = 242.709	SD = 183.516

Figure 16. Boxplot showing response times in local and global blocks in synesthetes and non-synesthetes.

Dark blue dots represent means for each combination of group and block type. The red line represents the difference in mean response time between synesthetes and non-synesthetes for global blocks. The teal line represents the difference in mean response time between synesthetes and non-synesthetes for local blocks. While the response times were faster for global versus local blocks in each group, the differences between groups were not significant. Non-Syn = Non-Synesthetes, Syn = Synesthetes.

The previous analysis included all trials regardless of trial type (e.g. target level matches [local block, local match trials and global block, global match trials], opposite level matches [local block, global match trials and global block, local match trials], and mismatches [local block, mismatch trials and global block, mismatch trials]). In order to determine whether group differences in response time might be present but restricted to a particular trial type, 2 x 2 mixed ANOVAs with group as a between-subjects factor and block type as a within-subjects factor were run for each of the three trial types (target level matches, opposite level matches, and mismatches). There were significant main effects of block type for all three trial types. However, there were no significant main

effects of group or interaction effects between block type and group for any of the three trial types (see Appendix C).

Additionally, in order to see whether synesthetes and non-synesthetes differed in response times in only the first local or global blocks, a 2 x 2 mixed ANOVA was conducted with group as a between-subjects variable and block type as a within-subjects variable, for only the trials in the first local and global blocks. For the first two blocks (the first local block and the first global block) only, there were significant main effects of block type. However, there were no main effects of group or interaction effects between block type and group (see Appendix D).

Visual Search

Accuracy

Means and standard deviations of accuracy were computed for each combination of group, block type, set size, and target presence (see Table 3).

Table 3. Means and standard deviations for accuracy for each combination of group, block, set size, and target presence in synesthetes and non-synesthetes.

Group	Block	Set Size	Target Presence	Mean	SD
Synesthetes	Feature	4	Present	96.296	3.093
			Absent	98.889	2.357
		16	Present	97.037	3.889
			Absent	99.63	1.111
		32	Present	96.296	4.231
			Absent	98.519	3.379
	Conjunction	4	Present	97.407	3.239
			Absent	95.926	8.127
		16	Present	94.444	7.993
			Absent	98.889	2.357
		32	Present	89.63	5.638
			Absent	98.889	3.333
Non-Synesthetes	Feature	4	Present	98.519	2.422
			Absent	97.037	3.093
		16	Present	96.667	3.333

		Absent	98.889	1.667
	32	Present	94.444	5
		Absent	98.519	2.422
	4	Present	98.148	2.422
		Absent	97.037	2.606
Conjunction	16	Present	91.111	6.455
		Absent	100	0
	32	Present	88.519	6.035
		Absent	98.889	2.357

Response Time

A 2 x 2 x 3 ANOVA was conducted with group as a between-subjects variable and trial type (target present, target absent) and set size (4, 16, 32) as within-subjects variables for the feature block trials. There was no significant main effect of group, $F_{(1,16)} = 0.23$, $p = 0.636$, $\eta^2 = 0.001$. There was a near-significant main effect of set size, $F_{(1,16)} = 4.06$, $p = 0.061$, $\eta^2 = 0.20$. There was also no significant main effect of trial type, $F_{(1,16)} = 2.40$, $p = 0.141$, $\eta^2 = 0.13$. The only interaction that was significant was between set size and trial type, $F_{(1,16)} = 4.88$, $p = 0.042$, $\eta^2 = 0.23$.

A separate 2 x 2 x 3 ANOVA was conducted with group as a between-subjects variable and trial type and set size as within-subjects variables for the conjunction block trials. There was no significant main effect of group, $F_{(1,16)} = 1.28$, $p = 0.274$, $\eta^2 = 0.07$. There was a significant main effect of set size, $F_{(1,16)} = 58.90$, $p < 0.001$, $\eta^2 = 0.79$. There was also a significant main effect of trial type, $F_{(1,16)} = 36.90$, $p < 0.001$, $\eta^2 = 0.70$. The only interaction that was significant was that between set size and trial type, $F_{(1,16)} = 16.13$, $p = 0.001$, $\eta^2 = 0.50$.

Search slopes were calculated for each subject for each of combination of block type and target presence (see Table 4). These slopes were entered into two separate ANOVAs. The first was a 2 x 2 mixed ANOVA with group as a between-subjects factor and target presence as a within-subjects factor, and only included feature block trials. The second was identical, except that it only included conjunction block trials. Figure 16 displays the search slopes for non-synesthetes for each combination of block type and

target presence, and Figure 17 displays the search slopes for synesthetes for each combination of block type and target presence.

For the feature block trials only, there was no significant main effect of trial type, $F_{(1,16)} = 2.849$, $p = 0.101$, $\eta^2 = 0.069$. There was no significant main effect of group, $F_{(1,16)} = 0.442$, $p = 0.511$, $\eta^2 = 0.001$. There also was no significant interaction between trial type and group, $F_{(1,16)} = 0.236$, $p = 0.630$, $\eta^2 = 0.007$.

For the conjunction block trials only, there was a significant main effect of trial type, $F_{(1,16)} = 7.821$, $p = 0.009$, $\eta^2 = 0.077$. There was no significant main effect of group, $F_{(1,16)} = 0.359$, $p = 0.553$, $\eta^2 = 0.018$. There also was no significant interaction between trial type and group, $F_{(1,16)} = 0.233$, $p = 0.633$, $\eta^2 = 0.007$.

Table 4. Search slopes for synesthetes and non-synesthetes for each combination of block and trial type.

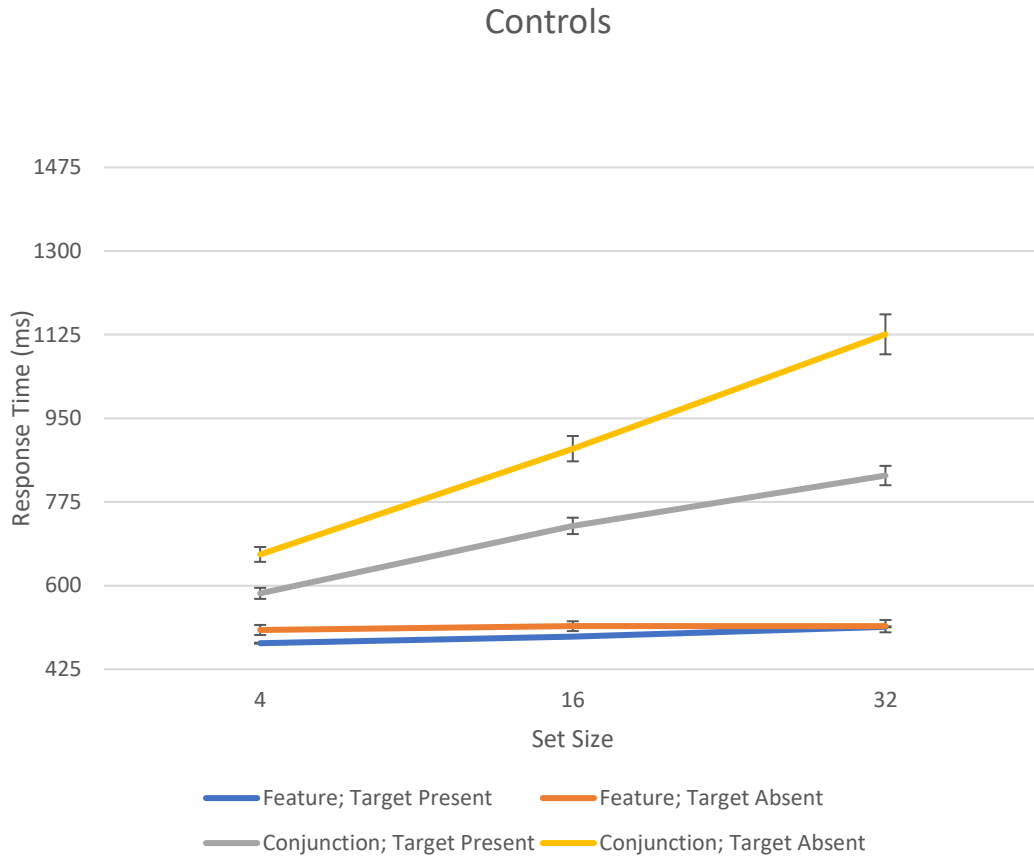| Group	Block	Target Presence	Slope
Synesthetes	Feature	Present	0.8207348
		Absent	0.2146266
	Conjunction	Present	11.01445
		Absent	26.28878
Non-Synesthetes	Feature	Present	1.401044
		Absent	0.3048587
	Conjunction	Present	10.47049
		Absent	21.24834

Controls

Figure 17. Search slopes for non-synesthetes for each combination of block type and target presence.
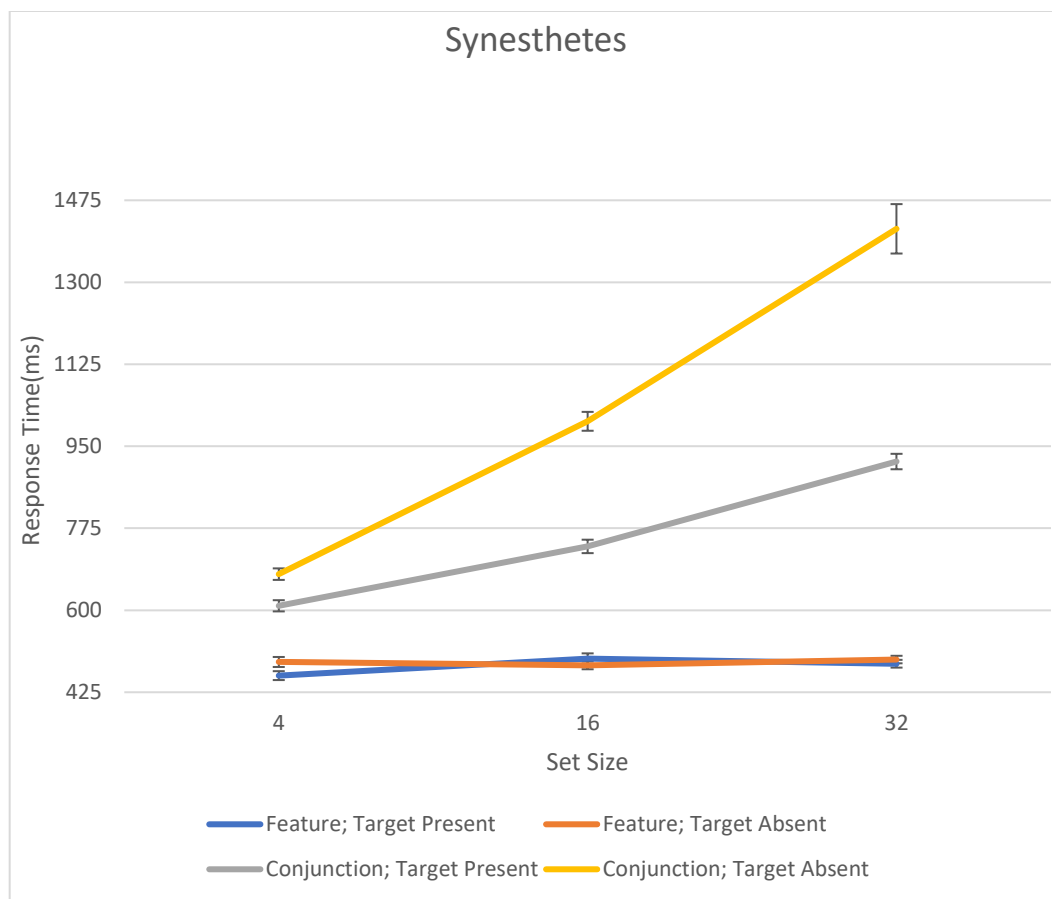
Black bars represent standard errors.

Figure 18. Search slopes for synesthetes for each combination of block type and target presence.

Black bars represent standard errors.

ROCF Task

Total Score

For each subject and for each condition (copy, immediate, delay), the 16 subscores were combined into a total score. These scores were entered into a 2 x 2 mixed ANOVA with group as a between-subjects factor and condition as a within-subjects factor. Means and standard deviations for these scores are shown for each group and condition in Table 5.

There was a significant main effect of condition, $F_{(2,32)} = 37.04$, $p < 0.001$, $\eta^2 = 0.70$. There was no significant main effect of group, $F_{(1,16)} = 0.50$, $p = .488$, $\eta^2 = 0.03$.

There was also no significant interaction between condition and group, $F_{(2,32)} = 1.22$, $p = 0.307$, $\eta^2 = 0.07$. Total score was higher in the copy condition ($M = 58.389$, $SD = 2.933$) than in the immediate recall condition ($M = 53.111$, $SD = 3.596$), which was higher than in the delayed recall condition ($M = 52.556$, $SD = 3.838$). The mean difference in total score between the copy and immediate recall conditions was 5.278 ($SD = 2.906$, 95% CI = [3.978, 6.578]). The mean difference in total score between the immediate recall and delayed recall conditions was 0.556 ($SD = 2.833$, 95% CI = [-0.744, 1.856]). The mean difference in total score between the copy and delayed recall conditions was 5.833 ($SD = 3.761$, 95% CI = [4.133, 7.533]).

Configural Element Score

For each subject and for each condition, the configural presence and configural accuracy subscores were combined into a general configural element score. These scores were entered into a 2 x 2 mixed ANOVA with group as a between-subjects factor and condition as a within-subjects factor. Means and standard deviations for these scores are shown for each group and condition in Table 5.

There was no significant main effect of condition, $F_{(2,32)} = 0.81$, $p = 0.454$, $\eta^2 = 0.05$. There was no significant main effect of group, $F_{(1,16)} = 0.02$, $p = 0.888$, $\eta^2 < 0.01$. There was also no significant interaction between condition and group, $F_{(2,32)} = 1.42$, $p = 0.257$, $\eta^2 = 0.08$. Configural element score was higher in the Copy condition ($M = 7.389$, $SD = 0.608$) than in the Immediate Recall condition ($M = 7.167$, $SD = 0.786$), which was identical to the Delayed Recall condition ($M = 7.167$, $SD = 0.786$). The mean difference in configural element score between the Copy and Immediate Recall conditions was 0.222 ($SD = 1.003$, 95% CI = [-0.238, 0.682]).

Cluster Score

For each subject and for each condition, the cluster presence, cluster accuracy, and cluster placement subscores were combined into a general cluster score. These scores were entered into a 2 x 2 mixed ANOVA with group as a between-subjects factor and

condition as a within-subjects factor. Means and standard deviations for these scores are shown for each group and condition in Table 5.

There was a significant main effect of condition, $F_{(2,32)} = 24.43$, $p < 0.001$, $\eta^2 = 0.60$. There was no significant main effect of group, $F_{(1,16)} = 0.56$, $p = 0.466$, $\eta^2 = 0.03$. There was also no significant interaction between group and condition, $F_{(2,32)} = 0.02$, $p = 0.948$, $\eta^2 < 0.01$. Cluster score was higher in the Copy condition ($M = 10.944$, $SD = 0.873$) than in the Immediate Recall condition ($M = 9$, $SD = 1.328$), which was higher than in the Delayed Recall condition ($M = 8.944$, $SD = 1.162$). The mean difference in cluster score between the Copy and Immediate Recall conditions was 1.944 ($SD = 1.662$, 95% CI = [1.174, 2.714]). The mean difference in cluster score between the Immediate Recall and Delayed Recall conditions was 0.056 ($SD = 0.873$, 95% CI = [-0.344, 0.456]). The mean difference in cluster score between the Copy and Delayed Recall conditions was 2.000 ($SD = 1.372$, 95% CI = [1.37, 2.63]).

Detail Score

For each subject and for each condition, the detail presence and detail placement subscores were combined into a general detail score. These scores were entered into a 2 x 2 mixed ANOVA with group as a between-subjects factor and condition as a within-subjects factor. Means and standard deviations for these scores are shown for each group and condition in Table 5.

There was a significant main effect of condition, $F_{(2,32)} = 27.57$, $p < 0.001$, $\eta^2 = 0.63$. There was no significant main effect of group, $F_{(1,16)} = 0.05$, $p = 0.827$, $\eta^2 < 0.01$. There was also no significant interaction between group and condition, $F_{(2,32)} = 0.52$, $p = 0.600$, $\eta^2 = 0.03$. Detail score was higher in the Copy condition ($M = 7.667$, $SD = 0.686$) than in the Immediate Recall condition ($M = 5.167$, $SD = 1.425$), which was higher than in the Delayed Recall condition ($M = 5.111$, $SD = 1.844$). The mean difference in detail score between the Copy and Immediate Recall conditions was 2.500 ($SD = 1.618$, 95% CI = [1.75, 3.25]). The mean difference in detail score between the Immediate Recall and Delayed Recall conditions was 0.056 ($SD = 1.305$, 95% CI = [-0.544, 0.656]). The mean difference in detail score between the Copy and Delayed Recall conditions was 2.556 ($SD = 1.947$, 95% CI = [1.656, 3.456]).

Copy Presence and Accuracy Score

An independent 2-sample *t*-test was conducted to compare CPA scores between the two groups. There was no significant difference between synesthetes' CPA scores (*M* = 19.111, *SD* = 0.928) and non-synesthetes' CPA scores (*M* = 18.333, *SD* = 1.581), *t* = 1.273, *p* = 0.221. Means and standard deviations of CPA scores for each group are also reported in Table 6.

Immediate Presence and Accuracy Score

An independent 2-sample *t*-test was conducted to compare IPA scores between the two groups. There was no significant difference between synesthetes' IPA scores (*M* = 14.889, *SD* = 2.261) and non-synesthetes' IPA scores (*M* = 14.778, *SD* = 2.108), *t* = 0.108, *p* = 0.916. Means and standard deviations of IPA scores for each group are also reported in Table 6.

Delayed Presence and Accuracy Score

An independent 2-sample *t*-test was conducted to compare DPA scores between the two groups. There was no significant difference between synesthetes' DPA scores (*M* = 15.556, *SD* = 1.810) and non-synesthetes' DPA scores (*M* = 14.667, *SD* = 2.121), *t* = 0.956, *p* = 0.353. Means and standard deviations of DPA scores for each group are also reported in Table 6.

Immediate Recall

An independent 2-sample *t*-test was conducted to compare IR scores between the two groups. There was no significant difference between synesthetes' IR scores (*M* = -21.889, *SD* = 12.604) and non-synesthetes' IR scores (*M* = -19, *SD* = 11.906), *t* = 0.500, *p* = 0.624. Means and standard deviations of IR scores for each group are also reported in Table 6.

Delayed Recall

An independent 2-sample *t*-test was conducted to compare DR scores between the two groups. There was no significant difference between synesthetes' DR scores (*M* = 5.444, *SD* = 10.818) and non-synesthetes' DR scores (*M* = -0.111, *SD* = 11.826), *t* = 1.040, *p* = 0.314. Means and standard deviations of DR scores for each group are also reported in Table 6.

Organization

An independent 2-sample *t*-test was conducted to compare Organization scores between the two groups. There was no significant difference between synesthetes' Organization scores (*M* = 5.556, *SD* = 1.590) and non-synesthetes' Organization scores (*M* = 6.667, *SD* = 1.323), *t* = 1.612, *p* = 0.127. Means and standard deviations of Organization scores for each group are also reported in Table 6.

Table 5. Means and standard deviations for total scores, configural scores, cluster scores, and detail scores for each group and condition.

Composite score	Condition	Group	Mean	Standard deviation
Total Score	Copy	Synesthetes	58.444	2.789
		Non-Synesthetes	58.333	3.24
	Immediate Recall	Synesthetes	52	4.183
		Non-Synesthetes	54.222	2.682
	Delayed Recall	Synesthetes	52.111	4.4
		Non-Synesthetes	53	3.391
Configural Score	Copy	Synesthetes	7.556	0.527
		Non-Synesthetes	7.222	0.667
	Immediate Recall	Synesthetes	7	0.866
		Non-Synesthetes	7.333	0.707
	Delayed Recall	Synesthetes	7.111	0.782
		Non-Synesthetes	7.222	0.833
Cluster Score	Copy	Synesthetes	11.111	0.782
		Non-Synesthetes	10.778	0.972
	Immediate Recall	Synesthetes	9.111	1.269
		Non-Synesthetes	8.889	1.453
	Delayed Recall	Synesthetes	9.111	0.782
		Non-Synesthetes	8.778	1.481
Detail Score	Copy	Synesthetes	7.778	0.667
		Non-Synesthetes	7.556	0.726

		Synesthetes	5	2
	Immediate Recall	Non-Synesthetes	5.333	0.5
		Synesthetes	5.333	2.121
	Delayed Recall	Non-Synesthetes	4.889	1.616

Total score is out of 64, configural score is out of 8, cluster score is out of 12, and detail score is out of 8.

Table 6. Means and standard deviations for the six summary scores for each group.

Summary Score	Group	Mean	Standard deviation
Copy Presence and Accuracy	Synesthetes	19.111	0.928
	Non-Synesthetes	18.333	1.581
Immediate Presence and Accuracy	Synesthetes	14.889	2.261
	Non-Synesthetes	14.778	2.108
Delayed Presence and Accuracy	Synesthetes	15.556	1.81
	Non-Synesthetes	14.667	2.121
Immediate Recall	Synesthetes	-21.889	12.604
	Non-Synesthetes	-19	11.906
Delayed Recall	Synesthetes	5.444	10.818
	Non-Synesthetes	-0.111	11.826
Organization	Synesthetes	5.556	1.59
	Non-Synesthetes	6.667	1.323

Discussion

Outline

On the hierarchical figures task, both synesthetes and non-synesthetes were more accurate, and were faster to respond, in the global blocks than in the local blocks, thus replicating the standard global precedence effect. The two groups, however, did not significantly differ in accuracy or response time in any of the blocks. On the visual search task, both synesthetes and non-synesthetes' response times did not differ across set sizes in the feature block. On the other hand, their response times did increase with set size in the conjunction block. Additionally, both groups took longer to respond to target-absent trials, but only in the conjunction block. Thus, the results of years of research into visual search were replicated. However, no differences were found between groups in response time for either block. On the Rey-Osterrieth (ROCF) task, both groups performed best in the Copy condition, followed by the Immediate Recall condition, followed by the Delayed Recall condition. However, no difference between groups was found on a wide variety of aspects of ROCF performance. The results obtained from this experiment are thus in conflict with those of several previous studies, which suggest enhanced local processing in grapheme-color synesthetes. In this section I begin by summarizing the evidence for local processing differences in these synesthetes. I then discuss possible explanations for why we failed to find any such differences, and I end by describing potential tasks for use in follow-up studies.

Previous synesthesia research

Unlike the present study, a multitude of previous studies have shown differences between synesthetes and controls on a wide variety of cognitive (for example, memory

and verbal comprehension) and perceptual (for example, facial and emotional processing) tests. Some of these studies would seem to suggest a local bias, as manifested by larger-amplitude neural responses to stimuli associated with local processing, as well as enhanced performance in local processing tasks (compared to controls), in synesthetes.

For example, grapheme-color synesthetes were found to outperform controls in a task that assesses one's ability to make fine-grained discriminations among faces for both identity and emotion (McErlean et al., 2016). This study also showed that these same synesthetes performed similarly to controls in the face composite task, a task which is considered to measure holistic face processing. The results of McErlean et al. (2016) thus suggest that grapheme-color synesthetes have superior local processing abilities, but similar global processing abilities to non-synesthetes.

In another study, grapheme-color synesthetes showed an enhanced neural response to high-spatial-frequency (HSF) Gabors (patches of tilted lines, with higher spatial frequencies meaning thinner lines with higher line density) compared to non-synesthetes, as manifested by an enhanced (more negative) C1 component in response to these Gabors compared to controls (Barnett et al., 2008). The C1 component is the earliest visual evoked potential (it peaks ~90 ms post-stimulus), so these results are highly suggestive of very early sensory processing differences in synesthetes compared to controls. These results also suggest that synesthetes have a processing bias towards local-level stimuli, since the C1 difference was observed for high-spatial frequency patterns (local bias), but not for low-spatial frequency (LSF) patterns (global bias).

Neural basis of local processing

What are the neural mechanisms underlying local visual processing? First, evidence suggests that a hemispheric asymmetry may play a role, with the left hemisphere having a local processing bias and the right hemisphere a global processing bias. Barnett et al. (2008) found that synesthetes had higher amplitude event-related potentials (ERPs) to both LSF and HSF Gabors in the left hemisphere relative to the right. Controls, on the other hand, had higher amplitude ERPs to both LSF and HSF Gabors in the right hemisphere. This hemispheric asymmetry could be merely a

coincidence (due to random individual differences in cortical anatomy), but it seems more likely that the results reflect different mechanisms of Gabor processing in synesthetes and controls. In other words, it is possible that the Gabor stimuli are processed to a greater extent in the left hemisphere of synesthetes than in the right, and that this hemispheric difference contributed to the overall effect of a larger C1 amplitude for synesthetes compared to controls for HSF Gabors. Consistent with this notion, Iidaka et al. (2004) showed that the left fusiform gyrus and left inferior occipital gyrus showed greater activation in response to HSF stimuli compared to LSF stimuli. Thus, it may be that the left hemisphere is specialized to process local-level information.

Summary of evidence for local processing differences in grapheme-color synesthesia

More generally, the connection between grapheme-color synesthesia and potential local processing biases can be summarized as follows:

1. The color-processing regions, V4 and V8 (for which the cross-activation theory predicts increased connections), are located in the fusiform gyrus.
2. The visual word form area (for which the cross-activation theory predicts increased connections), is located in the left fusiform gyrus.
3. The fusiform face area, which is specialized to detect and interpret facial expressions, is located in the fusiform gyrus.
4. Grapheme-color synesthetes have an enhanced ability to make fine-grained visual discriminations of facial identity and emotion.
5. Grapheme-color synesthetes have an increased cortical response to HSF stimuli.
6. The left fusiform gyrus seems to be associated with HSF processing.
7. Processing of local-level stimuli depends on HSF content.

When taken collectively, this evidence suggests that the left fusiform gyrus has greater functional connectivity in grapheme-color synesthetes than in controls, and this causes not only synesthetic percepts, but also superior local processing abilities in grapheme-

color synesthetes compared to controls. However, no evidence for a local processing enhancement was found in the current study. The following section outlines possible explanations for this discrepancy.

Current Study

Hierarchical Figures Task

On the hierarchical figures task, synesthetes were no more accurate than non-synesthetes, nor were they faster in their responses. Furthermore, the two groups did not respond differentially to the two types of blocks (local vs. global). To ensure that there weren't any effects restricted to a particular trial type (which might have been obscured in an analysis which included all trial types), additional analyses were conducted separately for each trial type. Still, no group effects were evident. Additionally, there is the possibility that controls were able to learn how to perform the task better over time while synesthetes had already reached a performance ceiling. If this was the case, it is likely that this would have resulted in similar performance between groups in the second half of the experiment, but differential performance in the first half. To test this possibility, an additional analysis was done separately for the first two blocks. Again, the results of these analysis suggested a lack of group differences.

So how can the lack of group differences on this task be explained? One possible explanation for this is a type II error, due to low statistical power. The power for the all trials accuracy analysis (for group) was calculated to be 0.185. The power for the all trials response time analysis (for group) was calculated to be 0.067. Both of these values are low, so we cannot be entirely sure that there is in fact no difference between grapheme-color synesthetes and non-synesthetes in accuracy or response time for this task.

However, it is important to consider the possibility that there truly is no difference between these two groups on accuracy or response time for this particular task. If confirmed, this would be an important finding as it would help rule out a leading explanation for neural and behavioral differences between synesthetes and controls (namely, that these differences arise out of local processing differences). Similarly, if the

group differences in local processing are so small as to only be observable with much larger sample sizes, there must be other factors that explain more of the variance in studies showing neural and/or behavioral differences between the two groups.

Another possibility to consider is that a genuine (moderate to large sized) difference does exist for local processing between synesthetes and non-synesthetes, but that the particular task used in the current study was either flawed or did not rely on local processing to a sufficient extent to be able to detect group differences. It is unlikely that the hierarchical figures task used was fundamentally flawed, as I was able to replicate the standard "global precedence effect". However, it is possible that the task insufficiently measured local processing abilities. The hierarchical figures task used in this study consisted of two figures presented simultaneously on the screen, flanking a fixation cross. Thus, processing of the hierarchical figures, both at the global and local levels, occurred in somewhat peripheral vision, as opposed to foveal (or central) vision. This may not have been conducive to detecting differences in local processing between the two groups. This is because the parvocellular pathway, which processes HSF information, originates from cones connected to midget ganglion cells, and the density of these cells is greatest in the fovea. The magnocellular pathway, which processes LSF information, on the other hand, originates from cones connected to parasol ganglion cells, and the density of these cells increases with foveal eccentricity (essentially, the density of these cells increases the further away from the fovea, which means it is greatest in the periphery). Consistent with this anatomical evidence, Henriksson et al. (2007) presented subjects with achromatic Gabors, and found that as foveal eccentricity increased, LSF selectivity was observed in the corresponding retinotopic area of the occipital cortex. This retinotopic organization of global/local processing was observed in a non-grapheme based hierarchical figures task as well (Sasaki et al., 2001), suggesting that the particular design used for the hierarchical figures task in this study was less than optimal, and that it could potentially be to blame for the lack of significant group differences in this task for either accuracy or response time.

Another factor that may have contributed to the lack of group effects on the hierarchical figures task is that the task was too easy and performance was near ceiling. The presentation time used in this study was twice as long as the presentation time used

in the study that originally used this particular task design (due to concerns about task difficulty during pilot testing). Retrospective analysis of the accuracy values suggests this was an unnecessary (and possibly detrimental) alteration to the design, as accuracies for most subjects were very high, even in the local blocks. This, in combination with the foveal versus peripheral issue, may help explain the results of the hierarchical figures task in the current study.

Again, it remains possible that grapheme-color synesthetes are no better at local processing than controls. The results of McErlean et al. (2016) could alternatively be interpreted to be a manifestation of superior facial and emotional processing arising from increased activity in the fusiform face area, rather than a reflection of increased local processing abilities arising from enhanced parvocellular activity. But what about the results of Barnett et al. (2008)? Why did they find early sensory processing differences, suggestive of local-level processing enhancements, in grapheme-color synesthetes? One possibility is that while grapheme-color synesthetes may have increased cortical responses to HSF stimuli, this increase may be unrelated to local vs. global processing. After all, although there is a correlation between HSF and local-level stimuli, this does not conclusively prove that if there is an enhancement in processing of one, then there is an enhancement in processing of the other. Processing of local-level stimuli depends on its HSF content (Boeschoten et al., 2005), but it likely depends on other factors as well, such as relative size. The increase in HSF stimuli responsiveness may not be enough to generalize to an increase in local-level stimuli responsiveness.

Visual Search Task

For the visual search task, the results suggested that synesthetes are not faster or more accurate than non-synesthetes, and that changes in reaction times as a function of set size do not differ, i.e. the search slopes of the two groups were statistically equivalent.

Why was there no difference in performance between synesthetes and non-synesthetes in visual search? Again, one possible explanation is that the current study

made a type II error, and failed to detect a genuine difference due to low statistical power. However, the visual search data was very consistent with standard findings reported in the literature and in textbooks (e.g. REFS), a large number of trials were run for each condition, and the variability in reaction times for each set size was within a reasonable range. This suggests that if a group difference does exist in basic color-orientation conjunction search, it is likely to be very small.

Another possibility, of course, is that there genuinely is no difference between grapheme-color synesthetes and non-synesthetes on this particular task (or close variants of this task). Would this imply that grapheme-color synesthetes do not differ in local/global processing style from controls? Not necessarily.

The specific variant of the visual search task used here (red and green vertical and horizontal bars) may not have tapped into the right construct (local processing) in grapheme-color synesthetes. The main evidence for this comes from several studies that have looked at the function of the magnocellular and parvocellular pathways.

Firstly, Cheng et al. (2004) found that the serial processing required for the conjunction visual search task relies heavily on the magnocellular pathway. Furthermore, the results of Barnett et al. (2008) suggest decreased magnocellular function in grapheme-color synesthetes. Therefore, controls should have outperformed the synesthetes on the conjunction block of the visual search task. But no such difference in performance was found. Thus, the results of this study are inconsistent with Barnett et al.'s (2008) results. This inconsistency could, however, perhaps be resolved if we could identify another pathway that could have contributed to the decreased neural responsiveness to LSF stimuli in Barnett et al.'s (2008) study instead of the magnocellular pathway. What is more important to note here, however, is that the extent to which the parvocellular pathway (which processes local-level information) was involved in the conjunction visual search task is questionable..

There's more evidence to support that this particular variant of the task relied heavily on magnocellular function. The magnocellular pathway, for example, processes orientation (Hebart & Hesselmann, 2012), one of the distinguishing physical characteristics of the targets and distractors used in this task. Furthermore, the magnocellular pathway has high luminance sensitivity (Pokorny, 2011). Although

brightness was not intended to be a distinguishing physical characteristic of the targets and distractors used in this task, color was, and the two colors selected (red and green) differed drastically in luminance (with the green luminance value being much higher). In other words, subjects may have been relying on brightness differences between red and green stimuli to perform the visual search task, in addition to color differences, and the former relies heavily on magnocellular processing. Thus, it seems that the magnocellular pathway may have played a rather large role in performance on this task. In a follow-up experiment, it would be important to make the red and green stimuli equiluminant in order to tap into the parvocellular pathway while controlling for magnocellular input.

However, the parvocellular pathway also played a large role. The parvocellular pathway is sensitive to color (Xu et al., 2004), but the magnocellular pathway is not. Color was a distinguishing physical characteristic of the targets and distractors used in this task, so parvocellular processing mediated, to a large extent, performance on this task. So, since the results of Barnett et al. (2008) suggest that grapheme-color synesthetes have enhanced parvocellular function (corresponding to enhanced local processing) and impaired magnocellular function (corresponding to impaired global processing) compared to controls, the fact that both magnocellular and parvocellular pathways contributed to performance on this task means that any differences might have canceled themselves out.

Alternatively, it could simply be that grapheme-color synesthetes are in fact no better at visual search than non-synesthetes. This is very possible in light of the results of one of the tasks conducted by Paulesu et al. (2002). In this task, a synesthete was asked to locate the 8 hidden among 6s, for various set sizes. Because the synesthete perceived both the 8 and 6 as blue, there was no color pop-out effect, thus he performed comparably to controls. However, the results' utility was limited because it was a case study based on only one synesthete. The authors also conducted a task in which the synesthete was asked to locate a 2 or a non-grapheme among different non-graphemes. Again, the synesthete performed comparably to controls. However, because this task did not use color (which is processed by the parvocellular pathway), it may have been less sensitive to local processing differences. Still, Paulesu et al.'s (2002) results are clearly consistent with the current findings, despite the limitations of both. Furthermore, Banissy et al. (2013) found

that there was no difference in performance between synesthetes and controls on an orientation visual search task. These results support our findings (since the current study used a color-orientation visual search task), and also suggest that synesthesia does not result in improved visual search performance compared to non-synesthetes in the absence of synesthetic percepts. On the other non-grapheme task used by Banissy et al. (2013), which was a color visual search task, synesthetes did perform better than controls. Our study also used color as a stimulus dimension, so why did they perform better on one color visual search task and not another? Perhaps the reason is that in the current experiment, the visual search task involved discriminating between highly distinguishable colors (red vs. green), while Banissy et al.'s (2013) study involved discriminating between fine differences in either hue, saturation, and luminance. Thus, it might be informative to conduct a future study in which one of the stimulus dimensions is hue, but in which the difference between target and distractors is more subtle than that present in the current study.

Rey-Osterrieth Complex Figure Task

Finally, for the Rey-Osterrieth task, response patterns across conditions did not differ between groups. Similarly, *t*-tests comparing the six summary scores between groups did not yield any significant differences.

Why were no differences found between synesthetes and non-synesthetes in Rey-Osterrieth performance? In addition to the low statistical powers of the analyses, again, it may be that grapheme-color synesthetes and non-synesthetes do not differ in the extent of local/global processing. Perhaps the results of Gross et al. (2011), who did find enhanced performance on the ROCF in synesthetes (particularly on the configural elements) were restricted to that particular subject pool. Or perhaps there were experimenter biases at play when scoring the reproductions of the two groups (the current study did not use blind scoring procedures, and it was unclear whether Gross et al. (2011) did so).

Another explanation is that the Boston Qualitative Scoring System may not be sensitive enough to detect any local/global processing differences between synesthetes and non-synesthetes. The scoring criteria can at times be somewhat vague, and sometimes the numerical ranges for measurements are rather broad. Other times, the criteria are fairly generous. For example, in scoring Cluster 6 placement (the vertical line with the horizontal crossbar to the left of the Rey-Osterrieth figure), only 1 of the following criteria needs to be met: a) the bottom of the vertical line is approximately at the midpoint of Configural Rectangle A, b) the vertical line extends above Configural Rectangle A to a distance that is 10 to 30% the height of the rectangle, or c) the top of the vertical line is roughly at the height of Cluster 3. In the actual figure, all 3 are satisfied. So, let's say that the synesthetes on average had superior local processing, and paid more attention to detail (although the overall Clusters would seem to rely more on global processing, some of the specifics within each Cluster would seem to rely more on local processing). If this is the case, they may have consistently satisfied 2 or even 3 of the criteria, while the non-synesthetes on average may have consistently satisfied only 1 of the criteria. In this scenario, the Cluster 6 for both groups would be marked as correctly placed, that is, they would be considered by the BQSS to have performed the same on this element, even if this is not the case. It is not being argued here that this precise situation occurred; rather, it serves merely to show the possibility of such a situation occurring, and there are many other examples of how the specific scoring criteria used here may have failed to detect a local/global processing difference between grapheme-color synesthetes and non-synesthetes.

Future directions

Further research, ideally with a much larger sample size (due to the lack of statistical power in the analyses) is needed to determine whether there really is a difference in local/global processing abilities between grapheme-color synesthetes and non-synesthetes. Based on an extensive literature review, it seems that the particular variants of tasks used in this experiment may not have been adequate measures of local

processing . Therefore, in this section I discuss possible tasks that may help resolve the issues present in this experiment, for use in follow-up studies.

I propose two possible different hierarchical figures tasks for use in a follow-up study, along with their pros and cons. Each of these tasks is designed to address some of the key limitations of the current study. Then, I propose a new type of visual search task, an embedded figures task, to remedy some of the limitations of the visual search task used in the current study. Finally, I discuss some potential improvements to the scoring system of the Rey-Osterrieth Complex Figure task.

Hierarchical Shape Identification Task

In this task, stimuli will be composed of familiar shapes. There will be one shape (e.g. a square) at the global level, and a different shape (e.g. a circle) at the local level. An example stimulus is presented in Figure 18. There will be two types of blocks, global and local. In the global blocks, one figure will be presented in the center of the screen for a short period of time, after which participants will be asked to identify which shape they saw at the global level. In the local blocks, the procedure is the same except that participants will be asked to identify which shape they saw at the local level. The advantages of this task over the task used in this study are two-fold: one, it uses very familiar elements as stimuli, as opposed to novel false-fonts, and two, figures are always presented in the center of the screen, which addresses the retinotopic issue (discussed above).
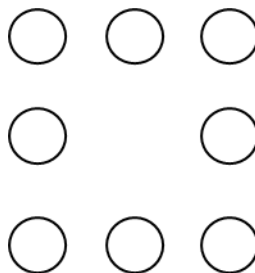
Figure 19. A sample hierarchical figure for the Hierarchical Shape Identification and Same/Different Tasks.

A global level shape (in this example a square) is composed of multiple local level shapes (in this example a circle).

Hierarchical Shape Same/Different Task

In this task, the same types of stimuli are used as in the shape identification task (see Figure 12), but the task design is different. Again, there are two types of blocks, global blocks and local blocks. In global blocks, participants are briefly presented with one figure in the center of the screen, followed by a second. They must then determine whether the figures matched at the global level, just like in the task used in this experiment. In local blocks, the procedure is the same except that the participants must determine whether the figures matched at the local level instead. This task, like the shape identification task, addresses both the unfamiliarity of stimulus problem and the retinotopic problem. However, it poses a new problem: potential memory effects. If this task were to be conducted, it would be important to select an inter-stimulus interval very carefully in order to make the task sufficiently challenging (but not too challenging) and to minimize the memory load imposed by having to remember the first figure while processing the second.

Embedded Figures Task

In lieu of the standard visual search paradigm (either feature or conjunction), I propose that a follow-up study use a highly specialized visual search task called the embedded figures task, as this task is often used to study local/global processing (Pring et al., 2010). In this task, the participant is presented with a complex figure and must locate a specific simple figure hidden within the complex figure (see Figure 19). The prediction here is that grapheme-color synesthetes will be faster to find the simple figure than non-synesthetes. This task may be better suited to identifying differences in local processing abilities between synesthetes and non-synesthetes by driving a shift to parvocellular pathway processing. After all, this task eliminates the use of orientation, and does not involve a classic serial-type search as in conjunction search. However, search strategies likely vary on this task, and people may search one region of the complex figure at a time, constituting a different type of serial search. Thus, the influence of magnocellular pathway processing may not be completely eliminated in this task, but it might (though

not necessarily) be an improvement over a conjunction task. More research is needed to determine the extent of magnocellular and parvocellular processing involved in this task. To increase the activation of the parvocellular pathway during this task, isoluminant chromatic stimuli could be used.
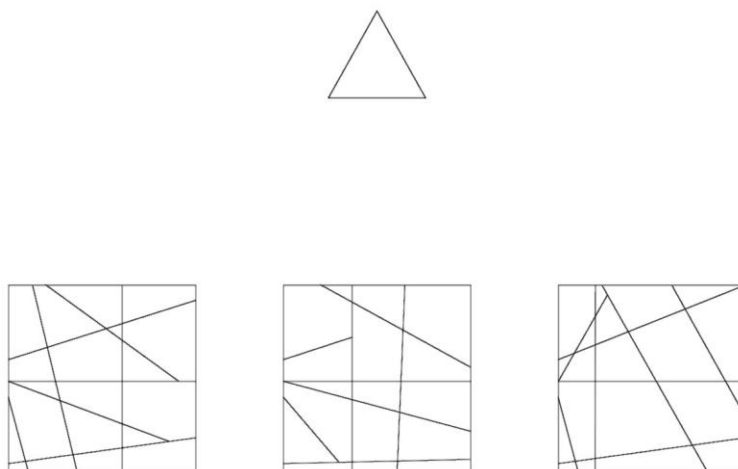
Figure 20. The embedded figures task.

In this variant of the embedded figures task, participants must select which of the three complex figures at the bottom contains the simple figure at the top. In this example, the simple figure is hidden within the right-most complex figure (de-Wit et al., 2017).

Revised scoring system for Rey-Osterrieth

I propose that a novel scoring system be developed for the Rey-Osterrieth Complex Figure task, one specifically designed to evaluate local/global processing abilities. Ideally this scoring system would be valid, reliable, and more sensitive than the Boston Qualitative Scoring System for detecting differences in local/global processing style between groups. The criteria should be more specific and somewhat stricter. For example, the size of gaps and overshoots could be taken into consideration, and the category of perseveration (which counts the total number of repetitions of elements or parts of elements in the figure) could be removed in favor of factoring in repetition of an element or part of an element into the score for that element. In cases where only one of a set of criteria needs to be met, scores should be higher the more criteria are met, instead of assigning a fixed score as long as at least one is met. Changes such as these would allow for clearer boundaries between local and global aspects of the figure as well as

more sensitive scoring, which would allow us to detect subtle changes in the drawings between synesthetes and non-synesthetes (precisely the sort of changes one would expect if synesthetes exhibit local processing differences from controls).

Conclusion

Although no evidence of increased local processing abilities (or decreased global processing abilities) in grapheme-color synesthetes was found in the current experiment, the results must be interpreted with caution. First, an extensive literature review suggests that the specific variants of tasks used in this experiment may not have been adequately sensitive to local processing differences between grapheme-color synesthetes and non-synesthetes. Second, statistical power was likely lacking due to inadequate sample size. Thus, more research is needed, using a larger sample size and alternative task variants, to determine if such a difference is in fact present. Furthermore, more research into the neural mechanisms underlying synesthesia is necessary to identify if any pathways involved in local/global processing are altered in grapheme-color synesthetes. By integrating the results of such research, we can truly gain a better understanding of the how's (and the why's) of visual perception in synesthesia.

Appendix A: Hierarchical Figures Accuracy Analysis for the 3 Trial Types

For the target level matches only (e.g. global block, global match trials and local block, local match trials), there was a near-significant main effect of block type, $F_{(1,16)} = 4.05$, $p = 0.061$, $\eta^2 = 0.20$. There was no significant main effect of group, $F_{(1,16)} = 0.39$, $p = 0.542$, $\eta^2 = 0.02$. There was also no significant interaction between block type and group, $F_{(1,16)} = 1.83$, $p = 0.195$, $\eta^2 = 0.10$. Accuracies were higher overall in global blocks ($M = 92.296$, $SD = 7.475$) than in local blocks ($M = 89.139$, $SD = 6.063$), a difference of 3.157 ($SD = 6.813$, 95% CI $= [0.057, 6.257]$).

For the opposite level matches only (e.g. global block, local match trials and local block, global match trials), there was a significant main effect of block type, $F_{(1,16)} = 14.08$, $p = 0.002$, $\eta^2 = 0.47$. There was no significant main effect of group, $F_{(1,16)} = 0.97$, $p = 0.339$, $\eta^2 = 0.06$. There was also no significant interaction between block type and group, $F_{(1,16)} = 0.32$, $p = 0.579$, $\eta^2 = 0.02$. Accuracies were higher overall in global blocks ($M = 95.172$, $SD = 6.161$) than in local blocks ($M = 88.225$, $SD = 7.044$), a difference of 6.948 ($SD = 7.697$, 95% CI $= [3.348, 10.548]$).

Finally, for the mismatches only (e.g. global block, mismatch trials and local block, mismatch trials), there was a significant main effect of block type, $F_{(1,16)} = 8.05$, $p = 0.012$, $\eta^2 = 0.33$. There was no significant main effect of group, $F_{(1,16)} = 0.49$, $p = 0.496$, $\eta^2 = 0.03$. There was also no significant interaction between block type and group, $F_{(1,16)} = 1.04$, $p = 0.324$, $\eta^2 = 0.06$. Accuracies were higher overall in global blocks ($M = 95.741$, $SD = 3.844$) than in local blocks ($M = 91.379$, $SD = 7.109$), a difference of 4.361 ($SD = 6.530$, 95% CI $= [1.361, 7.361]$).

Appendix B: Hierarchical Figures Accuracy Analysis for the First 2 Blocks

For trials within the first two blocks (the first local block and the first global block) only, there was a significant main effect of block type, $F_{(1,14)} = 17.28$, $p = 0.001$, $\eta^2 = 0.55$. There was no significant main effect of group, $F_{(1,14)} = 0.07$, $p = 0.801$, $\eta^2 < 0.01$. There was also no significant interaction between block type and group, $F_{(1,14)} = 0.57$, $p = 0.463$, $\eta^2 = 0.04$. Accuracy was higher in the first global block ($M = 94.361$, $SD = 4.355$) than in the first local block ($M = 87.127$, $SD = 6.388$), a difference of 7.234 ($SD = 6.860$, 95% CI = [3.834, 10.634]).

Appendix C: Hierarchical Figures Response Time Analysis for the 3 Trial Types

For the target level matches only (e.g. global block, global match trials and local block, local match trials), there was a significant main effect of block type, $F_{(1,16)} = 65.10$, $p < 0.001$, $\eta^2 = 0.80$. There was no significant main effect of group, $F_{(1,16)} = 0.17$, $p = 0.684$, $\eta^2 = 0.01$. There was also no significant interaction between block type and group, $F_{(1,16)} = 0.05$, $p = 0.829$, $\eta^2 < 0.01$. Response times were shorter overall in global blocks ($M = 652.722$ ms, $SD = 144.817$ ms) than in local blocks ($M = 813.357$ ms, $SD = 187.055$ ms), a difference of 160.635 ms ($SD = 82.067$ ms, 95% CI = [122.635 ms, 198.635 ms]).

For the opposite level matches only (e.g. global block, local match trials and local block, global match trials), there was a significant main effect of block type, $F_{(1,16)} = 35.79$, $p < 0.001$, $\eta^2 = 0.69$. There was no significant main effect of group, $F_{(1,16)} = 0.16$, $p = 0.695$, $\eta^2 = 0.01$. There was also no significant interaction between block type and group, $F_{(1,16)} = 0.00$, $p = 0.967$, $\eta^2 < 0.01$. Response times were shorter overall in global blocks ($M = 696.496$ ms, $SD = 140.895$ ms) than in local blocks ($M = 864.493$ ms, $SD = 215.093$ ms), a difference of 167.997 ms ($SD = 115.59$ ms, 95% CI = [114.997 ms, 220.997 ms]).

Finally, for the mismatches only (e.g. global block, mismatch trials and local block, mismatch trials), there was a significant main effect of block type, $F_{(1,16)} = 41.25$, $p < 0.001$, $\eta^2 = 0.72$. There was no significant main effect of group, $F_{(1,16)} = 0.21$, $p = 0.653$, $\eta^2 = 0.01$. There was also no significant interaction between block type and group, $F_{(1,16)} = 0.04$, $p = 0.844$, $\eta^2 < 0.01$. Response times were shorter overall in global blocks ($M = 695.327$ ms, $SD = 153.07$ ms) than in local blocks ($M = 858.262$ ms, $SD = 209.713$ ms), a difference of 162.935 ms ($SD = 104.546$ ms, 95% CI = [114.935 ms, 210.935 ms])

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Appendix D: Hierarchical Figures Response Time Analysis for the First 2 Blocks

For the trials within the first two blocks (the first local block and the first global block) only, there was a significant main effect of block type, $F_{(1,14)} = 66.42$, $p < 0.001$, $\eta^2 = 0.83$. There was no significant main effect of group, $F_{(1,14)} = 0.01$, $p = 0.918$, $\eta^2 < 0.01$. There was also no significant interaction between block type and group, $F_{(1,14)} = 0.35$, $p = 0.563$, $\eta^2 = 0.02$. Response times were shorter in the first global block ($M = 692.462$ ms, $SD = 155.042$ ms) than in the first local block ($M = 913.156$ ms, $SD = 203.684$ ms), a difference of 220.693 ms ($SD = 105.950$ ms, 95% CI = [168.693 ms, 272.693 ms]).

Appendix E: ROCF Scoring

Subscores

1. Configural Presence: raw score = # of configural elements present, converted to scaled score
2. Configural Accuracy: raw score = # of configural elements accurate, converted to scaled score
3. Cluster Presence: raw score = # of clusters present, converted to scaled score
4. Cluster Accuracy: raw score = # of clusters accurate, converted to scaled score
5. Cluster Placement: raw score = # of clusters properly placed, converted to scaled score
6. Detail Presence: raw score = # of details present, converted to scaled score
7. Detail Placement: raw score = # of details properly placed, converted to scaled score
8. Fragmentation: raw score = # of fragmentations present, converted to scaled score
9. Planning: takes into account factors such as order of element drawing, recognizability and placement of figure on page
10. Neatness: takes into account factors such as gaps and overshoots
11. Vertical Expansion: measures degree to which figure is expanded vertically
12. Horizontal Expansion: measures degree to which figure is expanded horizontally
13. Reduction: measures degree to which figure is reduced in size
14. Rotation: measures degree to which figure is rotated
15. Perseveration: measures degree to which certain elements are (incorrectly) repeated
16. Confabulation: measures degree to which novel elements are (incorrectly) added

Summary Scores

1. Copy Presence and Accuracy: calculated as Copy Configural Presence + Copy Configural Accuracy + Copy Cluster Presence + Copy Cluster Accuracy + Copy Detail Presence

2. Immediate Presence and Accuracy: calculated as Immediate Recall Configural Presence + Immediate Recall Configural Accuracy + Immediate Recall Cluster Presence + Immediate Recall Cluster Accuracy + Immediate Recall Detail Presence

3. Delayed Presence and Accuracy: calculated as Delayed Recall Configural Presence + Delayed Recall Configural Accuracy + Delayed Recall Cluster Presence + Delayed Recall Cluster Accuracy + Delayed Recall Detail Presence

4. Immediate Retention: calculated as ((Immediate Presence and Accuracy – Copy Presence and Accuracy) / Copy Presence and Accuracy) * 100

5. Delayed Retention: calculated as ((Delayed Presence and Accuracy – Immediate Presence and Accuracy) / Immediate Presence and Accuracy) * 100

6. Organization: calculated as Planning + Fragmentation

ROCF Elements

— Configural Rectangle A		— Cluster 1		— Detail A	
— Configural Vertical Bisector B		— Cluster 2		— Detail B	
— Configural Horizontal Bisector C		— Cluster 3		— Detail C	
— Configural Diagonal D		— Cluster 4		— Detail D	
— Configural Diagonal E		— Cluster 5		— Detail E	
— Configural Triangle F		— Cluster 6		— Detail F	
		— Cluster 7			
		— Cluster 8			
		— Cluster 9			
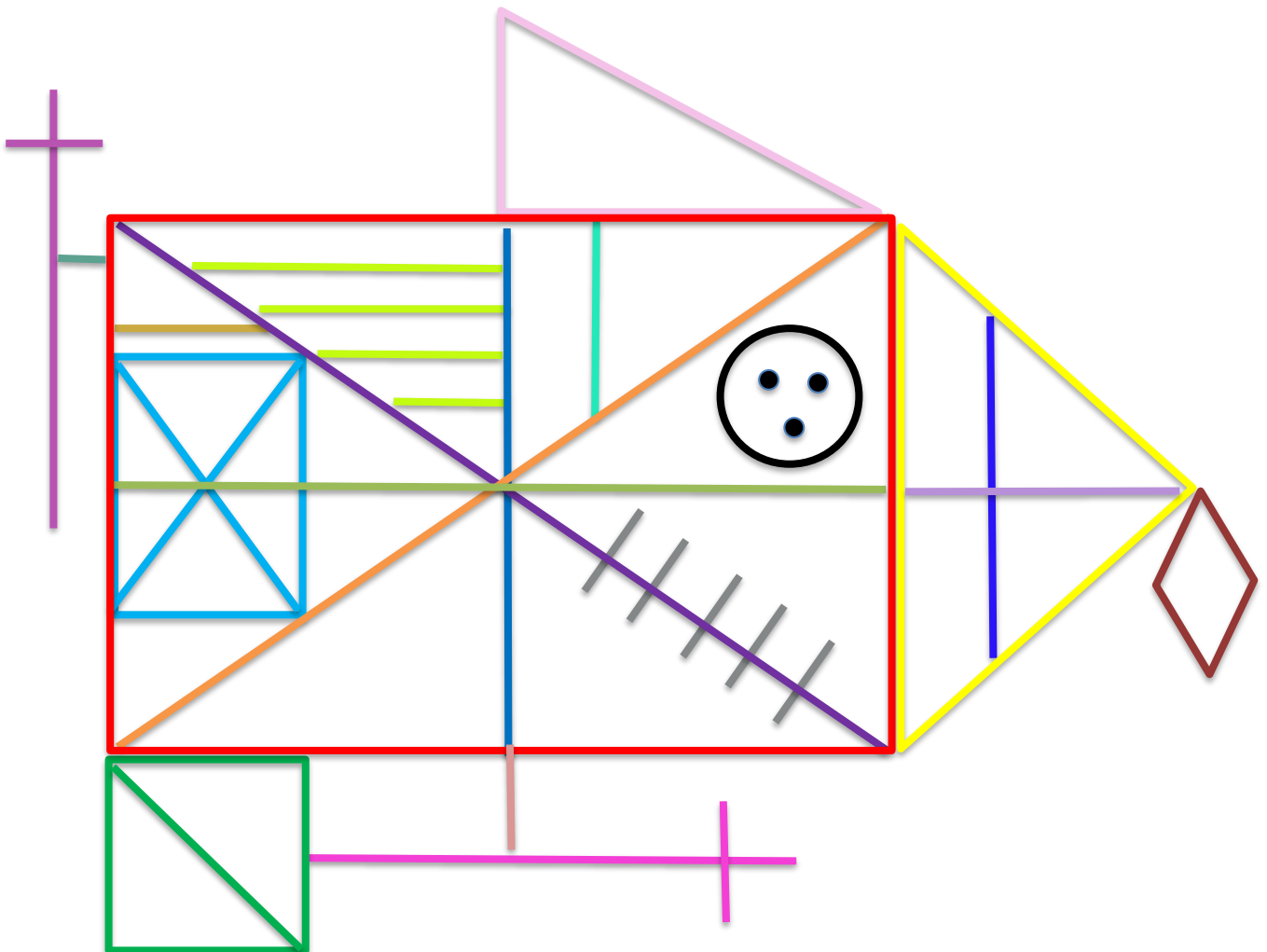
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