Synesthesia, Visual Search, and the N2pc: an ERP Study

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Abstract

Grapheme-color synesthesia is a perceptual condition in which achromatic graphemes (inducer) elicit color perception (concurrent) in an individual. Research has suggested that this unusual perceptual experience provides synesthetes with behavioral advantages in visual search tasks, potentially including the experience of an attentional "pop-out" effect, in which a target with one unique feature stands out from a display of homogeneous distractors. The following study used a visual search paradigm in which a "target" grapheme (e.g. E) appeared embedded within a display containing many instances of a similarly-shaped grapheme (e.g. F), known as the "distractor." The specific number of distractors was varied according to three set sizes. Importantly, we made sure that the target grapheme elicited a different synesthetic color than the distractor grapheme for each individual in our synesthetic sample. Behavioral measures of reaction time and accuracy, along with electrophysiological measures (early ERP components and the N2pc attentional component) were compared between synesthete and control subjects, in order to elucidate group differences and investigate the potential synesthetic "pop-out" effect. Our results suggest that our paradigm failed to elicit an N2pc component, so we were unable to use it as evidence of a "pop-out" effect. However, we were able to demonstrate a synesthetic behavioral advantage in reaction time and accuracy, as well as group differences in early ERP components, suggesting underlying physiological differences. Further research is necessary to investigate group differences in these early ERP components. In addition, modifications to our visual search paradigm may be necessary to successfully elicit an N2pc to investigate the role of attention in the synesthetic experience.

INTRODUCTION

What if I told you that some people physically feel music flowing through the space around them, or know the personalities of the months of the year? That some people experience tastes that go with each word, or different chords always make them think of a certain color? That some musicians (like Lorde and Billie Eilish[1]), artists (such as Van Gogh), and other figures throughout history, literally saw the world differently than everyone else? While these experiences may sound like science fiction, they all fall under the purview of a rare but real perceptual condition called synesthesia.

SYNESTHESIA

Broadly, synesthesia is defined as perceptual associations between disparate senses, where a stimulus (inducer) evokes an unusual perceptual experience (the concurrent), which may cross senses (e.g. an auditory stimulus eliciting a visual experience) or it may elicit a secondary experience within the same modality (e.g. a black and white letter eliciting a specific color). Both the inducer and the concurrent experience can take a variety of forms, and the limit to their combinations or types of synesthesia has not be found as of yet. As a condition, synesthesia is not classified as a pathology and is not known to have general negative effects on standard of living, and indeed many synesthetes go most of their lives unaware of the fact that their sensory experiences are unusual. Large-scale research estimates that approximately 4% of the population are synesthetes (Simner, J., Mulvenna, C., Sagiv, N., Tsakanikos, E., Witherby, S. A., 2006), with many more probably unidentified. The effects of synesthesia have not been fully

[1] Lorde experiences music-color synesthesia (Geggel, L., 2017), while Billie Eilish has talked about various forms of synesthetic experience, including music-color synesthesia and music-texture synesthesia (Schiller, R., 2019). Both artists have spoken extensively about how their synesthesia informs their work, and Eilish created an immersive museum experience to manifest aspects of her synesthesia related to her album (Schiller, R., 2019).

investigated, but research has shown that it may assist the synesthetes in memory tasks (Rothen, N., Meier, B., Ward, J., 2012), or finding embedded figures (Rich, A., Karstoft, K., 2013). They also have scored higher on some measures of "creativity, personality traits of absorption and openness, and cognitive abilities of verbal comprehension and mental imagery" (Chun, C.A., Hupé, J., 2016 p.1) These advantages may be generalizable to synesthesia as a whole, it is also possible that a specific type of synesthesia aids in specific tasks. Although the specific associations of synesthesia have been found to be primarily unique to each individual, and case studies of unique types of synesthesia are published frequently, there are some general theories about the origin of this perceptual abnormality.

THEORIES ON THE NEURAL MECHANISM OF SYNESTHESIA

Despite documentation for its existence going back hundreds of years[2], rigorous scientific research examining the potential neural mechanisms of synesthesia is relatively recent. No unifying theory has been agreed upon, but several major theories have emerged: the cross-activation hypothesis (Ramachandran, V.S., Hubbard, E.M., 2001), the disinhibited-feedback model (Grossenbacher, P.G., Lovelace, C. T., 2001), the reentrant processing model (Smilek, D., Dixon, M.J., Cudahy, C., Merikle, P.M., 2001) and the cascading cross-tuning theory (Brang, D., Hubbard, E., Coulson, S., Huang, M., & Ramachandran, V., 2011). Theories of neural pruning, disinhibited feedback, and hyper-binding are considered in supplement to these main theories. See Figure 1 for a schematic representation of these four theories.

[2] Ancient Greeks originally sought to describe the timbre of music using color (Gage, J., 1995), Isaac Newton theorized of a relationship between musical frequency and color frequency (Taylor, A., 2017), and an early pioneer of psychophysics conducted an empirical study of 73 (grapheme-color) synesthetes in 1871 (Fechner, G., 1876).

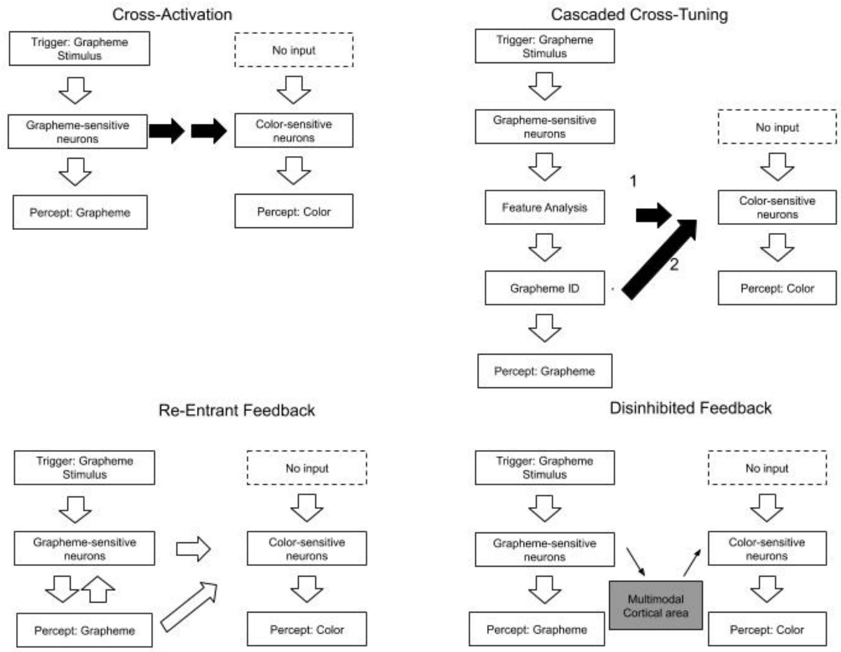

Figure 1. The four main hypotheses on the origin and mechanism of synesthesia (modified from Brang et al., 2011), with arrows indicating flow of activation between the boxes representing processing stages/areas. Solid lines represent regions that are active, while non-active regions/pathways are shown with dotted lines. (Originally adapted from Mulvenna, C.M.; Walsh, V., 2006).

CROSS-ACTIVATION HYPOTHESIS

The cross-activation hypothesis (or structural hypothesis) proposed by Ramachandran and Hubbard (2001) relies on the idea that humans are born with many more neuronal connections than are necessary, and that through childhood and adolescence, these excessive connections are pruned away. In this hypothesis, synesthetes are hypothesized to have had less neuronal pruning and so to possess more neuronal connections between seemingly unrelated areas of the brain. These neuronal connections would then distinguish synesthetes from non-synesthetes structurally, and would physically connect the areas of their brain that form the basis of their associations, such as V4[3] and other areas of the fusiform gyrus[4] in grapheme color synesthetes (Ramachandran et al 2001). Indeed, evidence from DTI[5] studies show that grapheme-color synesthetes show enhanced connectivity in the brain (See Figure 2.), specifically in the inferior temporal cortex and superior frontal cortex (Rouw, R., Scholte, S., 2007).

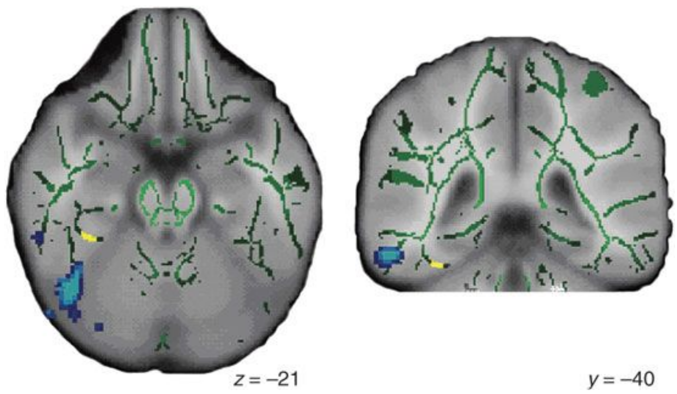

Figure 2. "Increased brain activation and increased anisotropy in the inferior temporal cortex in grapheme-color synesthetes" (Rouw & Scholte 2007, p 794).

DISINHIBITED FEEDBACK MODEL

Another prominent theory, the disinhibited-feedback model, argues that synesthetes have no physiological differences in their brain or number of neuronal connections when compared to non-synesthetes but instead, they have altered functioning that leads to abnormal activation in unrelated areas of their brain. The disinhibited-feedback model, proposed by Grossenbacher and Lovelace (2001), applied the concept of higher cortical areas, such as the parietal lobe, exerting feedback on lower cortical areas of the brain, which is usually inhibited to suppress unrelated neuronal activation.

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[3] V4 is a region of the visual cortex that focuses on higher level processing of color, modulate attention, and has been shown to have increased activation in some types of synesthetes (Brang et al., 2010).

[4] An area of the temporal and occipital lobes known to be involved in color, letter, and word processing, whose activation has been linked to grapheme-color synesthesia.

[5] Diffusion tensor imaging is a technique which uses MRI technology to show white matter, or myelinated axons, in the brain.

Grossenbacher and Lovelace then hypothesized that this feedback, coming from a multisensory nexus, which Rouw and Scholte posit could be "the superior temporal sulcus, posterior parietal lobe, intraparietal cortex or temporoparietal-occipital junction" (Rouw & Scholte 2007 p.1), would be less inhibited in synesthetes, allowing for over-activation of excitatory neurons as compared to inhibitory neurons in unrelated areas of the brain, producing synesthetic experiences.

REENTRANT PROCESSING MODEL

While the disinhibited feedback model is concerned with feedback originating from a multisensory nexus, grapheme-color synesthesia reentrant processing is defined as feedback coming from areas specifically involved in processing the meaning of graphemes (Rouw & Scholte 2007). Smilek et al. (2001) outlined the sequence of processing of chromatically-displayed graphemes, from processing of color by generalized "blob areas" (Smilek et al., 2001, p. 933) in V1 and V2 areas of the primary visual cortex, to the color-specific areas of the fusiform gyrus in V4. Then, "the form of the digit is segregated from the background" (Smilek et al., 2001, p. 933) and areas of the primary visual cortex that process shape are activated, as are some areas of V4. The form (line segments) of the digit is processed in the anterior fusiform gyrus[4] and PIT[6] gyri where the meaning is activated, and where Smilek et al. (2001) argue that synesthetic processing differs. They believe that meaning processing of the digit (in this case the inducer for the synesthesia), which causes PIT activation, then influences their V4 color processing, resulting in the concurrent experience of color with the grapheme. Once the meaning of the grapheme has been processed, the color information that is incorporated into the feedback from PIT back to V4 would be the concurrent color, rather than the color that the grapheme is actually presented in. This model fits within the broader framework of Grossenbacher's model of disinhibited feedback, with the multisensory nexus in this case being the PIT area and the feedback pathway leading to V4.

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[6] Posterior area of the inferior temporal gyrus, associated with processing of visual stimuli and recognition of visual objects (Kolb, B., Whishaw, I.Q., 2014)

THEORY OF CASCADED CROSS-TUNING

Similar to the model of reentrant processing, the hybrid theory of cascaded cross-tuning (Brang et al., 2010) also relies on evidence showing increased V4 activation in synesthetes compared to controls, and near simultaneous activation of the PTGA[7] and V4 in synesthetes. This finding supports the cross-activation theory and does not strongly support the disinhibited-feedback theory, as that theory would have predicted a delay of activation of V4 until after some preliminary stages of grapheme processing. Additionally, as discussed in Brang et al. (2010), theories of grapheme identification had been updated since the inception of both synesthesia theories, from a template-matching model to a hierarchical feature integration model involving competitive activation (Dehaene, S., Cohen, L., Sigman, M., & Vinckier, F., 2005; Grainger, J., Rey, A., & Dufau, S., 2008), similar to the Pandemonium model of letter recognition (Selfridge, 1959). New understandings of grapheme identification proposed that as components of a grapheme are processed, all graphemes with those components are activated at a low level, and activation is propagated through the hierarchical network that proceeds more components of the grapheme are processed and the identification becomes more specified. Therefore, Brang et al. (2010) proposed that the earlier and increased activation of V4, simultaneous with activation in the PTGA, indicated that local connectivity between V4 and the PTGA caused low-level activation of color and grapheme processing via cascaded activation. Rather than the inducer being limited to the full grapheme, the hierarchical feature integration model suggests that features of the grapheme may activate V4 at some level. This would suggest that graphemes that share similar features are more likely to elicit similar concurrent colors, a theory which several studies have supported (Brang et al., 2010b; Hubbard et al., 2005).

Hubbard, Brang, and Ramachandran proposed the cascaded cross-tuning model of synesthesia ten years after their initial proposal of cross-activation theory. This theory supports a complex understanding of the activation of synesthetic associations,

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[7] Posterior grapheme temporal area.

combining aspects of cross-activation theory, reentrant processing, and even the disinhibited feedback model. In the cross-activation model, letter input leads to simultaneous activation of both letter areas and color areas (black arrows), leading to percepts of colors and letters. Cascaded cross-tuning further specifies that the color area V4 is activated before color is produced (Arrow 1 in Figure 1), and then again (Arrow 2 in Figure 1) when the grapheme has been identified. The re-entrant feedback model posits that higher order conceptual feedback from conscious percept of the grapheme activates both physical form and color areas, leading to percept of a color once a grapheme has been identified. In the disinhibited feedback model, perceptual information is fed back to color selective areas through a multi-modal cortical area, leading to perception of color once a grapheme's form and meaning has been processed.

Though each theory proposes a difference mechanism for the inducer-concurrent perceptual experience of synesthesia, only the cross-activation theory proposes the simultaneous perception of the form of the grapheme and the concurrent color, claiming that synesthetic color could serve as an grapheme feature independent of grapheme form.

GRAPHEME-COLOR SYNESTHESIA

The form of synesthesia examined in this thesis, grapheme-color synesthesia, is characterized by a synesthete viewing an achromatic letter or number stimulus and associating it with the perception of a color (See Figure 3). The origin of this type of synesthesia, as with all types of synesthesia, is as of yet unknown. However, there are many different hypotheses about how this particular type of synesthesia could be formed or even nurtured. Some research shows that fundamental aspects of language learning may inform grapheme-color synesthesia, through such aspects as order of graphemes in an alphabet. By examining a dataset of five languages, Root et al. 2018 investigated why English-speaking grapheme-color synesthetes often report associating the letter 'A' with red (Root, N. B., Rouw, R., Asano, M., Kim, C., Melero, H., Yokosawa, K., & Ramachandran, V. S. (2018). They found that across a dataset of native English, Dutch, Spanish, Japanese, and Korean speakers, the first grapheme of a synesthete's particular alphabet tended to be associated with red. They then demonstrated that the color associated with the first grapheme in a synesthete's alphabet is more distinct from colors associated with other graphemes in the alphabet, therefore proposing a link between a distinct ordinal position in the alphabet (first) and a distinct color association. Further support for universal principles in grapheme-color synesthesia, is the fact that letters that are shaped similar to each other, are more likely to elicit similar colors (Brang et al., 2010). Recalling the Cascading Cross-tuning model proposed by Brang et al. (2010), Root et al. demonstrated that letters that share shape components are likely to elicit similar colors, especially in projector synesthetes (Brang et al., 2010b; Hubbard et al., 2005; Root et al., 2018).

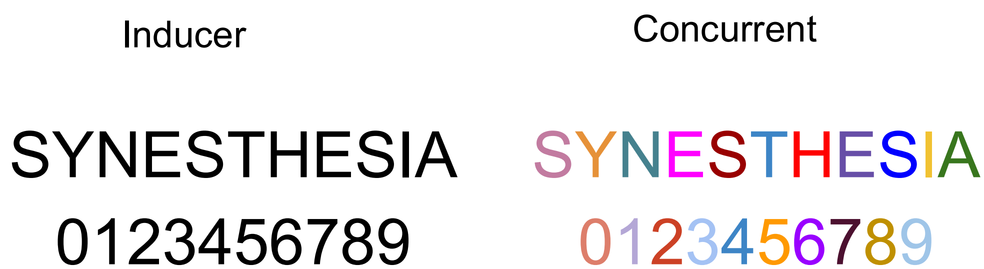

Figure 3. The inducer (achromatic grapheme) and concurrent (associated or projected color) in grapheme-color synesthesia.

PROJECTOR VS ASSOCIATOR, HIGHER VS LOWER

Various subtypes of synesthetes, such as grapheme-color synesthetes, have been further classified in other ways. For instance, those whose color association exists out in space and superimposed onto the black and white grapheme are classified as 'projectors', whereas those whose associations remain in their "mind's eye" are called 'associators' (Dixon, M.J., Smilek, D., Merikle, P.M., 2004). Some differences have been found between projector and associator synesthetes, including that projector synesthetes show increased neuronal connections in the inferior temporal cortex, compared to associator synesthetes (Rouw & Scholte, 2007), and, in the particular case of grapheme-color synesthetes, projectors also show stronger and earlier V4 activation in tandem with PTGA activation (Brang et al., 2010). For either group of synesthetes, these associations can vary in strength, but are consistent over many years and precise down to specific RGB values. RGB values are used to describe the amount of Red, Green, and Blue light present in a particular color, in order to represent the color on a computer screen (See Figure 4). They can be combined in different amounts to represent any color across the visible spectrum with precision.

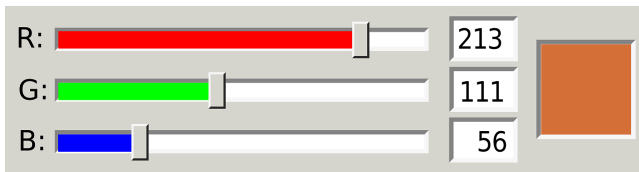

Figure 4. A typical RGB value selector, showing the amount of Red, Green, and Blue light on a scale from 0-255, with the summated color on the right (Public domain image).

Researchers have also argued that synesthetes can be separated based on when in the visual processing pathway, their color associations come into play. 'Higher' synesthetes are said to have color-grapheme associations due to top-down processing and therefore, their color associations enter perception much later in visual processing, whereas 'lower' synesthetes are hypothesized to have their color-grapheme associations enter processing at an earlier stage (Ramachandran & Hubbard, 2001). It has been hypothesized that 'higher' may be another way of describing 'associator' synesthetes and 'lower' synesthetes may be another name for 'projectors.'

While the experience of seeing all letters and numbers in color is part of normal life for grapheme-color synesthetes, their unusual perceptual experience allows for the investigation of fundamental questions about perception, synesthesia, and how the condition changes the way people process the world.

ERP COMPONENTS & THE N2pc

Investigation into the theories proposed about the origin of synesthesia has greatly benefited from using a variety of tools. For example, MEG[8] data have shown that V4 and the PTGA are activated simultaneously in grapheme-color synesthetes (Brang et al. 2010), while fMRI data have provided conflicting results in regards to whether graphemes induce V4 activation in grapheme-color synesthetes (Sperling, J., Prvulovic, D., Linden, D., Singer, W., & Stirn, A., 2006) or not (Hupé, J., Bordier, C., & Dojat, M., 2011). EEG data have been used to demonstrate differences in posterior parietal alpha-band oscillations between projector and associator synesthetes (Cohen, M. X., Weidacker, K., Tankink, J., Scholte, H. S., & Rouw, R., 2015). This technique (ERP) is particularly useful for investigation into the theories of synesthesia due to its temporal precision and variety of ERP components that can be utilized.

Event-related potential (ERP) components are measurable brain responses that are "the direct result of a specific sensory, cognitive, or motor event" (Luck 2005). These components are time-locked to specific event, and are a non-invasive way to measure brain activity. The N2pc component is an ERP component that demarcates a shift in attention towards a target. It is an enhanced negativity occurring around 180–350 ms (Li, C., Liu, Q., & Hu, Z., 2017) contralateral to the location of the attended stimulus that is isolated by subtracting the amplitude of the electrodes ipsilateral to the target from the amplitude of the electrodes contralateral to the target (see Figure 5). It has been studied in many studies of visual search and the "pop-out" phenomenon (explained below). While there is debate over the long-held belief that the N2pc reflects a shift in enhanced attention to a target (Kiss, M., Velzen, J. V., & Eimer, M., 2008), the component is now thought to be specifically linked to target enhancement, rather than distractor suppression (Li et al. 2017).

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[8] Magnetoencephalography records the magnetic fields that are produced by neural electrical currents, allowing functional neuroimaging (i.e. showing areas of activation associated with a particular process).

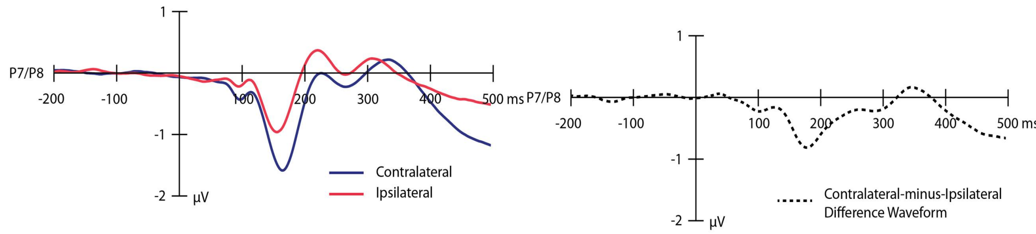

Figure 5. Example of N2pc ERP component, with ERP elicited when target was ipsilateral (same hemisphere as side of vision the target was presented on) subtracted from ERP when target was contralateral (opposite hemisphere from target presentation) (left), and the resulting difference wave (right) showing a negativity at approximately 200ms (Kappenman, E., Farrens, J., Luck, S., Proudfit, G., 2014).

THE ATTENTIONAL "POP-OUT" EFFECT

One perceptual phenomenon that we all experience is called the pop-out effect. It occurs in certain types of visual search, which is broadly described as an active visual scanning of an environment in order to identify a target as distinct from distractor items (Treisman 1980). The pop-out effect occurs during the so-called visual feature search task, where a single target stimulus differs from a number of distractors in one single feature (such as color, shape, size, etc). In other words, the pop-out effect occurs when a target with a unique feature *stands out* among a display of homogenous distractors (Treisman, A., 1985; Wolfe, J. M. 1994). Research has shown that attention is not required for the pop-out effect, though it may require some form of top-down processing (Hsieh, P., Colas, J., Kanwisher, N., 2011). One example of a visual search paradigm in which a 'pop-out' effect may occur is when subjects are asked to do a visual search for a stimulus of a particular color, embedded within a group of distractors, all of them of a different homogeneous color (see Fig. 6, left side).

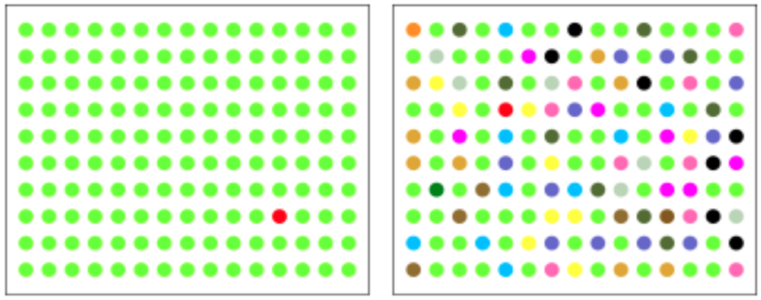

Figure 6. When the target differs from the distractors in one feature (left), then it "pops-out" in parallel search. When there are several combinations of features among the distractors, the target (red circle) no longer stands out as immediately different. (PsyToolKit)

Because the target has one single different feature from the homogeneous distractors, it stands out to the subject. No matter how many objects are added as 'distractor' items (e.g. the green circles), the subject still finds the target easily and their reaction time remains low and constant (see Figure 7 for a visualization). Therefore, it is proposed that the participant is able to process all stimuli simultaneously in parallel fashion. This effect is in stark contrast to what happens when subjects search for a target that has more than one similar feature to the distractors (e.g. find a red circle immersed among circles of many colors). In this case, the task gets longer as more distractors are added, with the reaction time increasing linearly with the number of distractors (Figure 7). That is, the target does not "pop-out" and therefore, it is proposed that in this case, the subject must look at each object individually to find the target, doing what is called a 'serial search.' In sum, this paradigm makes evident two different types of visual search, providing an excellent opportunity to investigate how the color associations are processed in synesthesia.

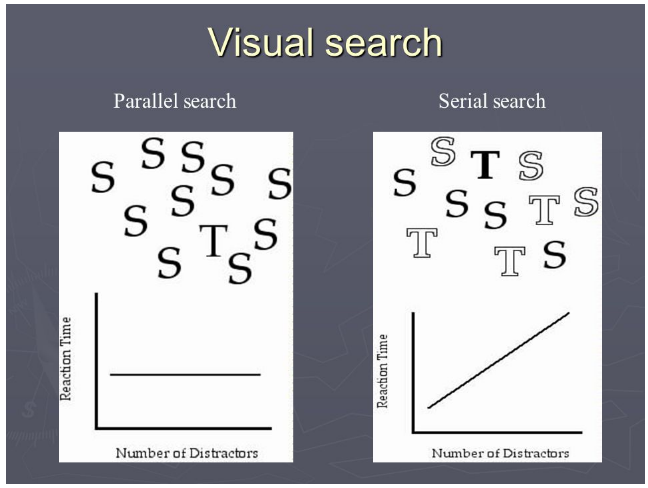

Figure 7. The display on the left would induce a parallel search and possibly a pop out effect. In contrast, the display on the right is likely to induce a serial search. Participants' reaction times reflect this, with the number of distractors having no effect on the parallel search reaction time, but a linear effect on the serial search, with reaction times increasing with more distractors (Friedenber, J., Silverman, G., 2012).

PRESENT STUDY

PREVIOUS RESEARCH

The research on synesthesia has long been dominated by case studies of individual synesthetes, as the topic gradually gained traction as an area of study in neuroscience. As key studies demonstrated the consistency, specificity, and diversity of synesthetic associations (see Watson, M. R., Akins, K. A., Spiker, C., Crawford, L., & Enns, J. T., 2014 for review), research has expanded. Studies with large sample sizes remain difficult due to the relative rarity of the condition and the lack of awareness of some synesthetes about their condition. Therefore, the majority of the large group studies have been done with grapheme-color synesthetes as they are the most common[9] and therefore easiest to recruit.

Rothen and Meier (2009) reviewed the literature on visual search studies with grapheme-color synesthetes and conducted one of their own. Ramachandran and Hubbard (2001) claimed to have found a synesthetic advantage at embedded figure recognition with 2 synesthetes and 40 control subjects, though the difference in number of subjects in each condition undermine these results slightly. They found that when viewing an image (see Figure 8.) that contained a global shape made of graphemes, amongst distractor graphemes that elicited a distinctly different color than the global shape grapheme, the synesthetes were much better than the controls at identifying the global shape. From this, they concluded that the association was "genuinely perceptual and not confabulatory in origin, nor based on memory associations" (Ramachandran & Hubbard, 2001, p. 981).

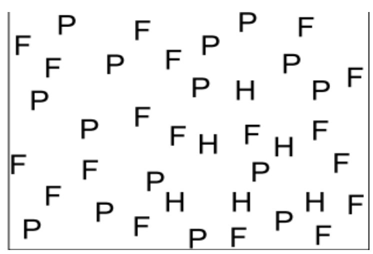

Figure 8. Embedded figure stimuli used in Ramachandran & Hubbard (2001), in which the H's (which elicited green for the synesthete) form a global triangle among the F's (yellow) and P's (red).

In another study with very few synesthetes, Palmeri, Blake, Marois, Flanery, and Whetsell (2002) compared the performance of 1 synesthete and 7 control subjects at a pop-out task (See Figure 9). and found that the synesthete had a much smaller set size effect and significantly faster reaction times, suggesting that "binding in lexical synesthesia occurs during central visual processing and not during later more conceptual processing" (Palmeri et al., 2002, pg. 4130). This would indicate that conceptual processing of the meaning of the grapheme was not necessary to evoke color

[9] According to a survey of 572 reported cases (27% from published literature), 68% of synesthetes report grapheme-color synesthesia (Day, S., 2005)

associations, favoring the cross-activation hypothesis and undermining the reentrant processing model.

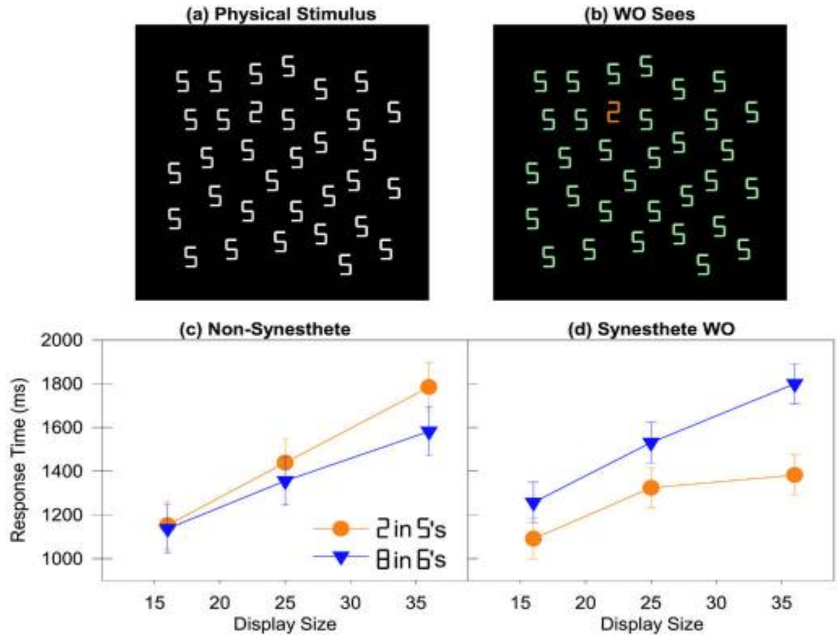

Figure 9. Stimulus display presented to subjects (a), as seen by the synesthete WO based on grapheme-color associations (b), and resulting set size effects (c, d) in Palmeri et al. (2002).

Laeng, Svartdal, and Olemann (2004) also examined the potential pop-out effect with a single synesthete and 8 control subjects, and found that when the target and distractor were similar in form but elicited different synesthetic colors, the synesthete showed less of a set size effect. Researchers also found that while both control subjects and the synesthete had faster reaction times the less the degree of eccentricity of the target stimuli, the effect for the synesthete was much stronger, with targets that were 3° and 6° from the center resulting in synesthetic reaction times 2.5 standard deviations faster than the mean reaction times of the control subjects (Laeng et al., 2004). From this result, these researchers also concluded that conceptual processing was not always necessary, and that focal attention may be the determining factor in finding a synesthetic “pop-out effect”.

Hubbard, Arman, Ramachandran, and Boynton (2005) conducted a group study with 6 synesthetes and 6 control subjects, in which the subjects performed an embedded figure detection task, which would determine the efficiency of synesthesia assisting in ‘texture segregation’ between the target graphemes making up a global shape, and distractor graphemes. Results showed that five out of six synesthetes outperformed their matched controls, but did not perform as well as control subjects who viewed a chromatic version of the embedded figure display. This study also demonstrated that activation in the color-selective area of hv4[10] was elicited significantly more ($p < 0.05$) by synesthetes (but not control subjects) viewing graphemes compared to viewing non-grapheme symbols, correlating with synesthetes’ superior behavioral performance. Hubbard et al. suggests that the variable results found in the literature in regards to the potential pre-attentive nature of synesthetic color perception may be due to heterogeneity among synesthetes, with some being “higher” (or associator) synesthetes whose associations require conceptual processing of the grapheme, and some being “lower” (or projector) synesthetes, whose associations take place pre-attentively. Hubbard therefore cautions against firm conclusions drawn from case studies of synesthetes, and even studies in which relatively few synesthetes are used.

In contrast to the small number of synesthetes usually studied, Edquist, Rich, Brinkman, and Mattingley (2006) compared the performance of 14 synesthetes to 14 control subjects in a visual search pop-out paradigm. They found no synesthetic advantage, with both the controls and synesthetes displayed set size-reaction time indicating the pop-out effect when the graphemes were presented chromatically, but neither group showed significantly efficient search to indicate the pop-out effect when the graphemes were presented achromatically (see Figure 10).

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[10] Located in the lingual gyrus of the ventral occipital lobe, the human V4 has also been implicated in processing of shape, orientation, and curvature (Roe et al., 2012).

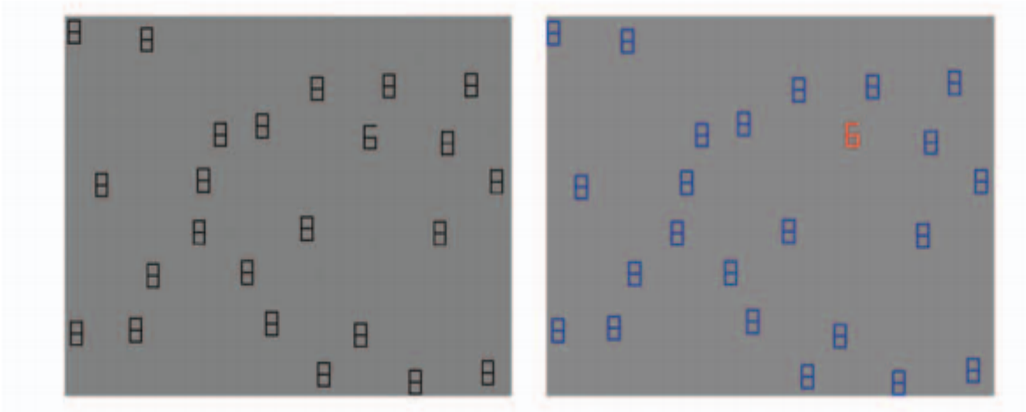


Figure 10. Example of achromatic (left) and chromatic (right) display with the largest set size of 24 items (Edquist et al., 2006).

This result supports the reentrant processing model, and contrasts with the previously discussed results of Palmeri et al. (2002) and Laeng et al. (2004), whose results supported the existence of a synesthetic pop-out effect. However, both Palmeri et al. (2002) and Laeng et al. (2004) compared the results of only one synesthete to many more (7 and 8 respectively) control subjects. Given the heterogeneity suggested by Hubbard et al. (2005) and the potential variability that suggests, results found using only one synesthete are likely not as reliable as a larger study.

After reviewing this body of literature, Rothen et al. (2009) tested 13 associator synesthetes and matched controls on a embedded-shape visual search task and an episodic memory task, and found no significant advantage for synesthetes (see Figure 11). There was a trend toward superior performance in synesthetes versus control subjects, but this was found to be caused by three synesthetes outperforming their yoked controls. As Rothen et al. (2009) remarked, this result supports heterogeneity among mechanisms of synesthetic associations, with distinctions of “higher” and “lower” synesthesia perhaps untethered to projector and associator categories.

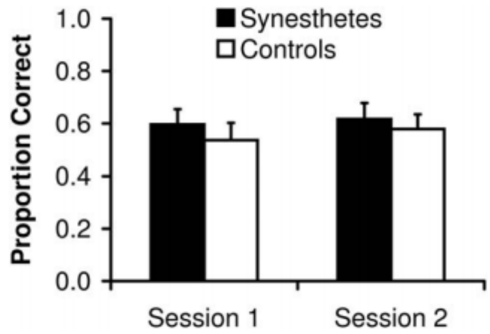


Figure 11. Performance of synesthetes and controls in the embedded-shape visual search task summarized across two sessions, two to three weeks apart (Rothen et al., 2009).

Ward, Jones, Dienes, and Seth (2010) then conducted the largest of such studies on visual search performance (N=36 synesthetes). They found a significant synesthetic advantage over controls on an embedded-shape task using 5's and 2's, but variability in self-reported color perception during the experiment. All of the projector synesthetes in the study reported seeing some color, along with approximately one third of the remaining synesthetes, therefore resulting in a bimodal distribution of results. Synesthetes that did claim to see color on average reported about a third of the graphemes as having color (see Figure 12), and reported that the colors 'appeared' piecemeal as the synesthete attended to that area of the display.

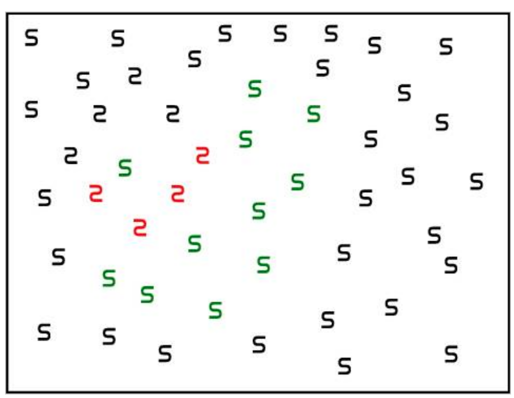


Figure 12. Example of what a synesthete in Ward et al., (2010) might have perceived.

The results also showed that projector synesthetes were more likely to view the graphemes as having color on a given trial but did not on average report more of the graphemes as chromatic. This does not support the hypothesis that projector synesthetes experience grapheme-color associations pre-attentively, as that would result in more of the graphemes being perceived chromatically than non-projector synesthetes. However, this result did support the theory that rather than the associations occurring pre-attentively, they occur in the locus of the synesthete's attention. The synesthetes that did perceive a large number of the graphemes chromatically did outperform those who reported little or no perception of color, confirming again that color serves as an advantage in a visual search embedded-shape task.

These studies cover a wide range of participant numbers and present a large variety of results. Due to the highly unique nature of synesthesia, results based on case studies of a single synesthete cannot be considered conclusive and group studies provide more reliable results. Although efforts were made in Ward et al (2010) to gauge synesthetes phenomenological experience during the study, even then the consistency and strength of synesthetic associations did not inform the stimuli choices. This introduces another dimension of variability, given that synesthetic associations are highly idiosyncratic and the strength of the associations might have a potent impact on the contrast between the color perception of the stimuli. Additionally, none of these studies provide any neural data, which may provide a more conclusive answer to the question about synesthetic performance on visual search tasks, and specifically in regards to temporal relationship between the synesthetic associations and the potential "pop-out effect".

RESEARCH QUESTIONS

There are obvious tensions between the results summarized above. Case studies originally indicated the possibility of a synesthetic behavioral advantage at embedded-shape and pop-out visual search tasks (Ramachandran & Hubbard, 2001; Palmeri et al., 2002; Laeng et al., 2004) but this result was replicated in only one group study (Ward et al., 2010), and not in others (Edquist et al., 2006; Rothen et al., 2009). If grapheme-color synesthetes do experience a pop-out effect with conducting a visual search of achromatic stimuli, that would indicate that their synesthetic color associations were being processed very early on, and perhaps even before the meaning of the graphemes were consciously processed.

In the literature on synesthetic associations and awareness, these tensions are reflected. In a review of the existing literature on the subject, Mattingley (2009) says about synesthetic induced colors:

> First, although they seem to arise automatically, without the need for voluntary control, they are strongly modulated by selective attention. Second, they attain salience relatively early in visual processing, and so can influence perceptual judgments and guide focal attention in cluttered, achromatic displays (Mattingley, J., 2009, pg 141)

The studies reviewed demonstrated the attenuating effect of secondary tasks on synesthetic color perception (Mattingley, J. B., Payne, J. M., & Rich, A. N., 2006), in which focus on a task unrelated to the identification of the synesthetic color led to a decreased perception of the induced color. Another study provided suggested that the location of the grapheme in relation to the focal attention of the subject was significant, finding that "When the inducers were outside the window of attention, they were less likely to induce their colors than when they were inside the window of attention" (Sagiv, N., Heer, J., & Robertson, L., 2006, pg. 239). The lack of evidence for a synesthetic pop-out effect, but evidence for behavioral advantages in visual search discussed earlier might indicate that "mechanisms of attention play a causal role in synesthesia by acting to bind, in an obligatory fashion, visual representations of graphemic form and color. Whether synesthetic colors can be triggered without explicit awareness of the inducing stimulus is still debated, but currently the evidence suggests that inducers must be consciously perceived to exert a measurable influence on behavior" (Mattingley 2009, pg 164). Feature binding (such as discussed here of graphemic color and form), as discussed by Anne Treisman (1985) is a central aspect of the visual processing that takes a scene from an overwhelming amount of visual information to pieces of information that can be integrated into a meaningful picture.

Mattingley (2009) also reviews several of the existing ERP studies on synesthesia. An early study found that in a task which asked subjects to respond to a subset of achromatic graphemes displayed on screen, there was "significant enhancement in the P300 response over frontal electrode sites in the synesthetes compared with a group of non-synesthetic controls" (Schiltz, K., Trocha, K., Wieringa, B., Emrich, H., Johannes, S., Münte, T., 1999). Congruency effects for synesthetes have also been observed as early as the N1 (Sagiv et al., 2006), suggesting a very early emergence of synesthetic experience. Further examination of these differences via EEG allows for temporal precision in neural correlates, and can complement the behavioral data (response time and accuracy). EEG, while providing temporal specificity, can also reflect functioning that happens unconsciously and therefore is not susceptible to demand characteristics in the same way as a questionnaire. Because EEG measures a constant oscillation in brain waves that is not under voluntary control, it can be used a tool to distinguish between stages of unconscious and conscious processing more effectively than a motor response such as pressing a button (Mulholland, 2012). For example, conscious awareness of the semantic meaning of an audio clip (indicated by neural signatures like P3b and P600/LPC) is preceded by unconscious processing as indicated by ERP components MMN and N400 (Rohaut, B., Naccache, L., 2017). The ERP component N2pc is an attentional marker that happens when the subject shifts attention to a target, and can be used to measure the neural shift in attention that occurs hundreds of milliseconds before the reaction time is recorded.

In the following study, I propose to conduct an EEG study which compares the performance of synesthetes and control subjects in a visual search paradigm, investigating the presence of a 'pop-out' effect for synesthetes when using achromatic graphemes. This study contributes something important to the current body of research because no study on the supposed synesthetic pop-out effect has been conducted with EEG data. Knowing *when,* in the time course of visual processing the attention of the subject shifts to the target, may indicate whether there is evidence for a pop-out effect in synesthetes based on their synesthetic associations. This would contribute to the validity of the theory that synesthetes have differences in functionality in regards to visual processing and feature binding. The results of this study will have implications not only for our understanding of synesthetic processing, but also about how feature binding occurs in general.

HYPOTHESES

If the synesthetic color experience emerges early (before conscious meaning processing of grapheme), then color can be used as an independent search feature and synesthetes will show a faster reaction time, higher accuracy, and an earlier and possibly larger N2pc than control subjects. This would also produce a slope coefficient of synesthetic performance at visual search not significantly different from zero, reflecting a 'pop-out' effect. In contrast, if meaning processing of the grapheme must be completed before synesthetic color is elicited, then the slope coefficient of synesthetic performance at visual search will be significantly different from zero, and will not reflect a 'pop-out' effect. This would likely also produce an N2pc not significantly different between synesthetes and control subjects. Variation on these two main hypotheses would indicate differential effects of synesthesia on behavioral results of reaction time and accuracy, and neural processing as measured by ERP. For example, synesthetes may demonstrate reaction time and accuracy results that indicate an advantage over control subjects, but lack the search slope to indicate a pop-out effect and an N2pc significantly different than that of control subjects. This would not support the existence of a synesthetic pop-out effect but would support a synesthetic advantage in some or several steps of search.

METHODS

PARTICIPANTS

A total of 28 subjects participated in this study, recruited from Reed College and the surrounding colleges in Portland, OR. All subject were 18-30 years old and had normal or corrected vision and no history of brain injury or seizures. Fourteen grapheme-color synesthetes (11 female, mean age: 20) had a matching control subject based on age and assigned sex[11]. All synesthetes were verified by the Eagleman battery (Eagleman et al., 2006) and had grapheme-color congruency test scores less than 1.0 (mean = 0.67). Individual participant age, assigned sex, and synesthetic associations for the specific graphemes used in the study can be found in Appendix 2. Participants were paid $20 for their participation, and funding was provided by the Reed College Psychology Department. The Reed College Institutional Review Board approved all procedures.

STIMULI

All stimuli were generated using a Visual Search paradigm programmed in "Presentation" (Neurobehavioral Systems, San Francisco CA), with continuous fixation dot in the center of the screen. For each synesthete, data collected from the Eagleman et al. (2006) battery was used to select 3 pairs of stimuli from a list generated using pairs commonly used in visual search pop-out paradigms as a starting point (Edquist et al., 2006). Each pair contained two graphemes that elicited different colors for the synesthete, at least 10 Euclidean distance units apart. This was done to ensure that the color elicited

[11] Assigned sex refers to the biological sex category (distinct from gender identity) assigned to the subject at birth by medical professionals.

by the 'distractor' stimuli would be distinct enough from the color elicited by the 'target' stimuli to potentially induce the pop-out effect for synesthetes. To accomplish this, we converted the RGB values corresponding to each synesthete's color associations (as gathered from the Eagleman battery) to CIE xyY and using the Euclidean Distance equation (Laeng, B., 2009).

The graphemes in each pair were also selected to be as similar as possible in shape, to promote a serial search when looking for the target in the absence of physical color. In each presentation of the visual array, one of the stimuli in each pair (target) was presented among a varying number of its paired (distractors). For example, an "L" presented within a random display of various "T"s. The task was to press a button if/when participants found the "odd-one-out", that is, to indicate if one of the stimuli was different from the rest. If no stimulus was detected as different, participants pressed a different button. The stimulus set sizes used were 8, 16, and 36 total objects in the array, with the target appearing on the left and the right side an equal number of times, and all objects randomly distributed across the screen, jittering in location (see Figure 12).

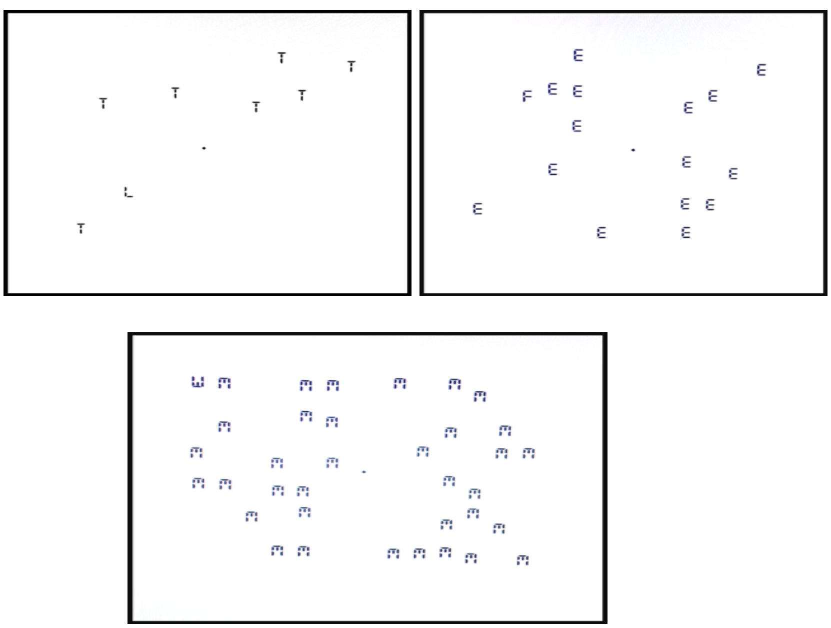


Figure 12. Example displays from the visual search task in which subjects were asked to determine whether a target was present in a display of 8 (top left), 16 (top right), or 36 (bottom) graphemes.

PROCEDURE

Control subjects attended one two-hour session in which they underwent an EEG recording session. Synesthetes also attended one two-hour session, completing the grapheme-color part of the battery beforehand and completing a post-experiment questionnaire afterward, in order to investigate synesthetes' subjective perception of color (if any) during the task, as well as self-reported categorization as projector or associator.

SYNESTHESIA BATTERY

Synesthetes completed the Eagleman et al. (2006) battery, which uses computerized tasks and qualitative questionnaires to determine the consistency and strength of a subject's synesthetic associations.

Before doing the experimental task, both control subjects and synesthetes practiced a version of the visual search task using a pilot version of the program with one of the grapheme pairs used in the experimental portion, as EEG data was recorded. This ensured that subjects were performing the task as instructed and that the EEG data are as clean as possible.

BRAIN RECORDING SESSION

During the EEG recording session, both synesthetes and control subjects completed the same computerized visual search task (see Figure 12 for example display). Before the experiment began, subjects were told that in each trial their task was to find the stimulus that was different from the rest (target present trials), and that there would sometimes be no target present (target absent trials). In each trial, an array of varying set size (8, 16, or 36 total graphemes on screen) appeared randomly distributed across the screen.

Subjects were asked to fixate their eyes on a central fixation dot that was present throughout the experiment, and to respond via a button press to indicate when they located the target or to indicate that the target was absent. After subject response, there was a blank screen (except for the fixation dot) for a jittered time between 800-1200 ms before the next array was presented. Target present trials and target absent trials were presented randomly and with variation, as were trials involving all six graphemes.

Remember that we selected 3 pairs of stimuli (similar in shape, different in synesthetic color) for each synesthete. Participants were presented with 160 trials per pair and per set size, resulting in 1,440 total trials, with 288 target absent trials (20% of all trials). Within those 160 trials, an equal number had the target present on the left and half on the right. For each pair, one of the stimuli played the role of target/distractor an equal number of times (half). Subject-controlled breaks were available to the subject after 40 trials.

EEG RECORDING

In the EEG recording sessions, all participants were fitted with a 64-channel electrode cap (Figure 13). Eye blink artifacts were detected with a VEOG electrode attached to the face below the left eye, and two additional electrodes, each one adjacent to the left and to the right eye for HEOG. Electrodes were also placed behind the ear on the mastoid for reference. Impedance levels were kept below 5kΩ. This was achieved with the use of a saline-based gel and some gentle rubbing of the skin with the wooden end of a Q-tip, in order to abrade away a thin layer of dead skin cells. Immediately after the session was finished, usually within 2.5 hours of participants' arrival, caps were removed and participants were able to wash their hair in the lab.

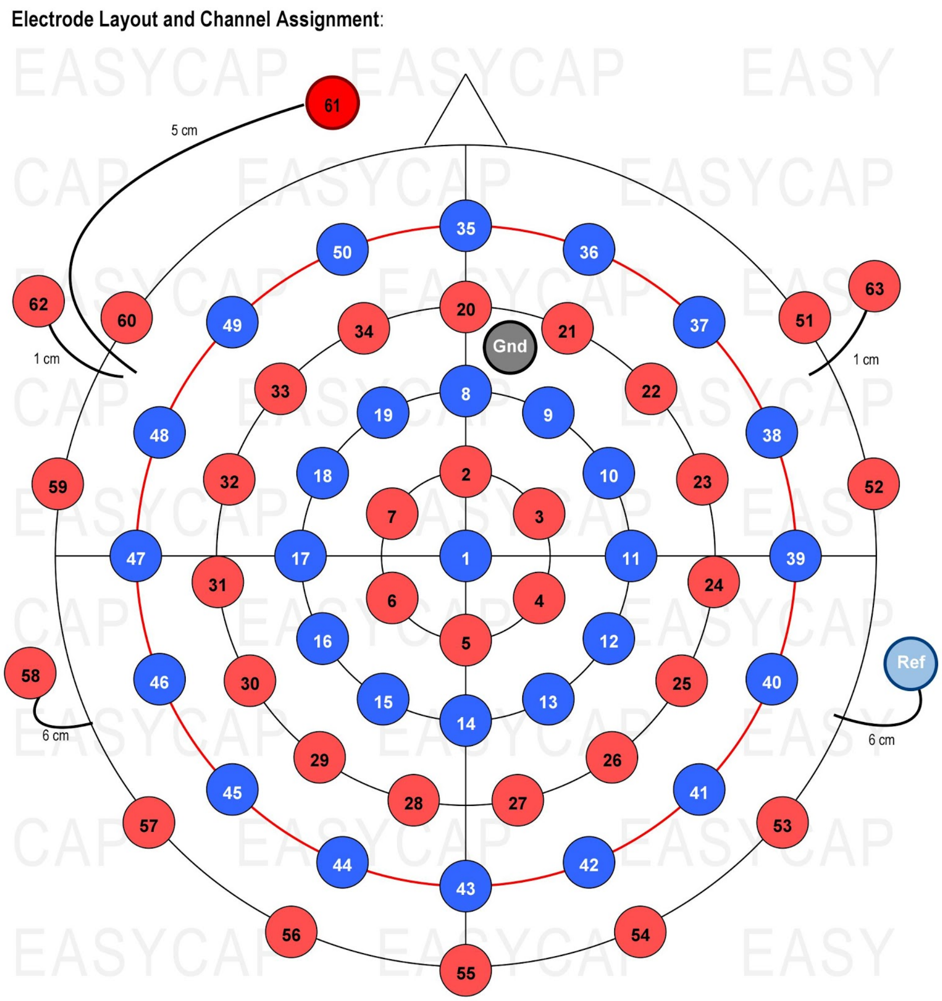


Figure 13. 64-Ch EEG cap, customized for M. Pitts, 2014 (Brain Products, Germany)

DATA ANALYSIS

BEHAVIORAL DATA

Based on our predictions, in regard to reaction times and accuracy, we expect to find a main effect of set size and also a main effect of group, and a possible interaction between group and set size. In addition, reaction times were analyzed by graphing the individual functions obtained between reaction times and number of distractors, resulting in a search slope coefficient, using the equation $t = (b)(s_x)(\sqrt{N-1})/s_{y-x}, df = N-2$ (where b = slope coefficient; s_x= standard error of the regressor or number of distractors; s_{y-x}= standard error of estimate (computed as s_{y-x}= $s_y\sqrt{1-r^2}$ with s_y= standard error of the RTs, and r = Pearson's correlation coefficient) (Howell 1987, Laeng 2009). The resulting individual search slope coefficients were compared against zero. If significantly different from zero, this would suggest that the subject failed to display a pop-out effect. That is, their RTs would show a linear increase with increase in set size. Alternatively, the lack of a significant difference from zero, would suggest a pop-out effect, that is, no linear increase with set size, suggesting a parallel search.

ELECTROPHYSIOLOGICAL DATA

EEG (Electroencephalographic) data were processed using BrainVision Analyzer software (Brain Products, Germany). Trials containing artifacts (blinks, eye movements, facial muscle noise, etc.) were rejected semi-automatically (on average, 38.83%). The final data set included 14 synesthetes and 14 matched control subjects. The latency and amplitude of relevant ERP components (see below) were measured and analyzed via ANOVAs and posthoc t-tests.

RESULTS

BEHAVIORAL RESULTS

REACTION TIMES

Reaction times obtained in correct responses to target-present trials, occurring between 200-2000 ms after stimulus onset, were submitted to a 2x3 mixed ANOVA with Group (synesthete/control) as our between-subject variable, and with Set Size (8/16/36) as our within-subjects variable (See Fig. 14). This analysis revealed that there was no main effect of group, $F(1, 52) = 2.48$, n.s., but there was a significant main effect of set size, $F(2, 52) = 49.42$, $p <0.0$, as well as a set size by group interaction trending towards significance $F(2, 52) = 2.94$, $p < 0.06$. Using Laeng's (2004) equation for determining whether a search slope indicates a "pop-out" effect, the search slopes for both synesthetes and control subjects were analyzed, and both groups were found to have mean slopes significantly different from zero ($p = 0.00$). However, synesthetes 9 and 14, as well as control subjects 4 and 13 demonstrated search slopes less than 1.

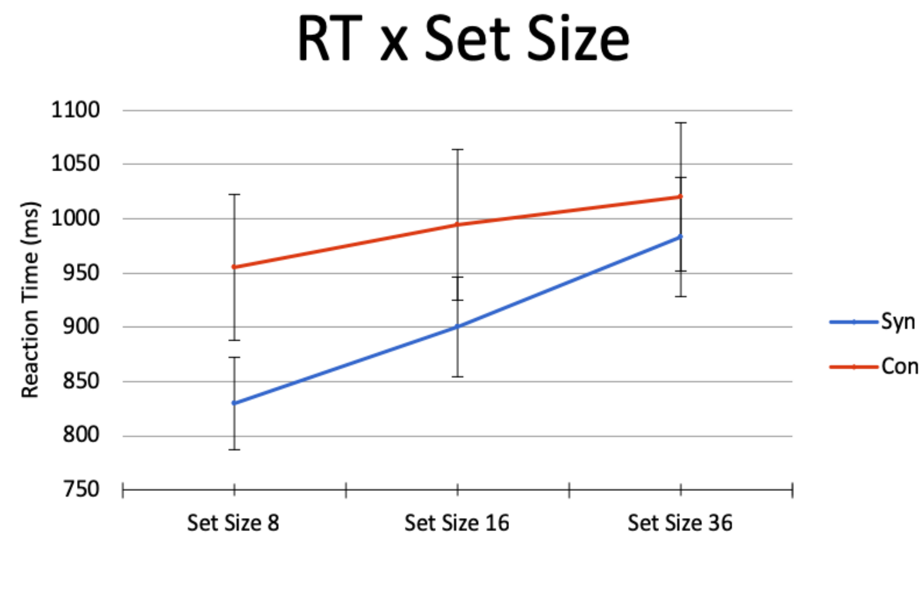


Figure 14. Reaction times for each set size for synesthetes (blue) and control subjects (red), showing a significant difference between groups at set size 8.

ACCURACY

A similar analysis with proportion of correct responses (accuracy, See Fig. 15), revealed a trend towards a main effect of group, $F(1, 52) = 2.97$, $p = 0.09$), but a significant main effect of set size, $F(2, 52) = 214.64$, $p = 0.00$), and no significant interaction, $F(2, 44) = 0.59$, n.s.

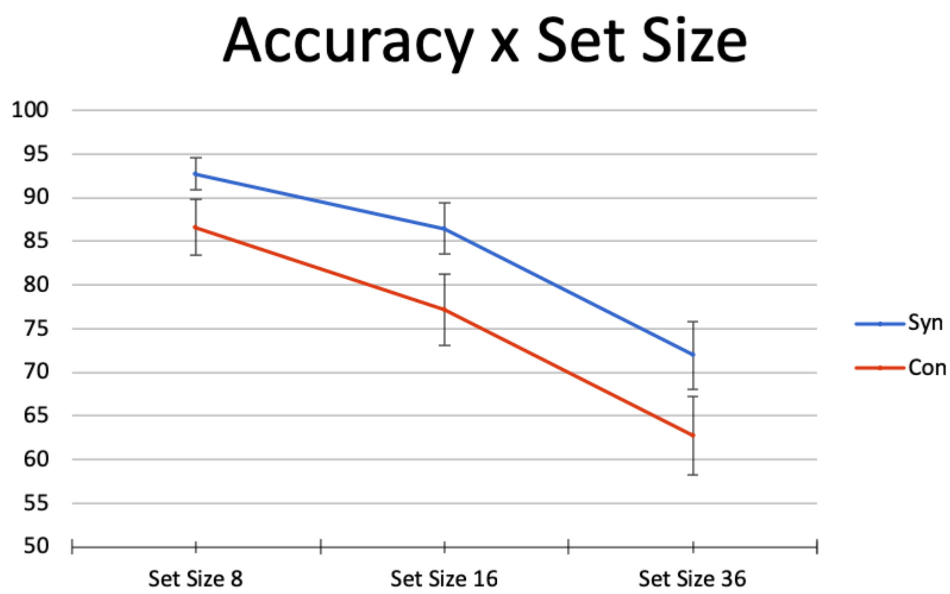


Figure 15. Proportion of correct responses for each set size for both synesthete (blue) and control subjects (red). The difference between groups was significant at each set size.

SEARCH SLOPES

In addition to the synesthetic advantage found in both reaction times and accuracy data, we explored the individual search slopes in each group. These can be seen in Figure 16 for synesthetes, and in Figure 17 for controls. It is evident a large variation in search slopes within each group of participants. However, it is also apparent that there is greater variability in the control group (see Table 1). It is also clear that one control participant (con02, average RT across set sizes= 587 ms) and one synesthete (syn10, average RT across set sizes=559 ms) were particularly fast.

Table 1: Standard Deviations for Reaction Time

	Set Size 8	Set Size 16	Set Size 36
Synesthetes	143.6129512	154.6440582	190.7135898
Control Subjects	231.9126864	240.1942489	236.2220504

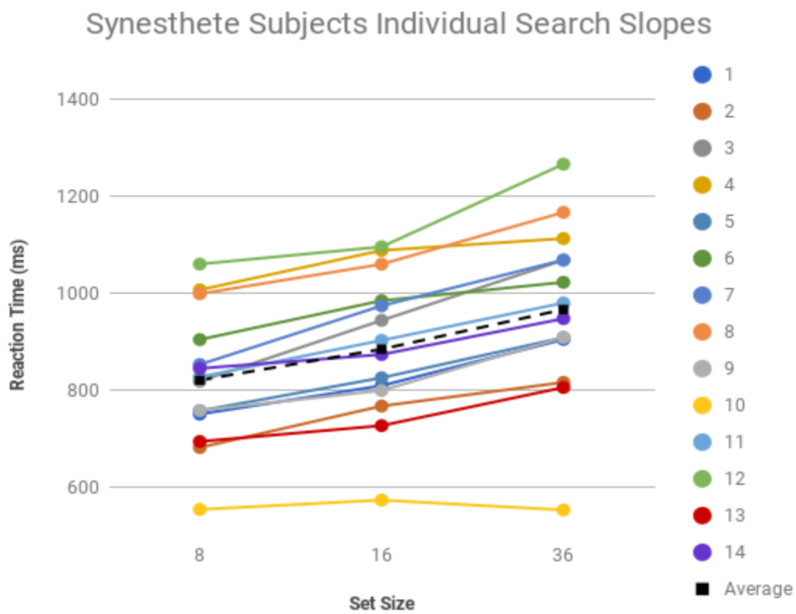


Figure 16. Individual search slopes for synesthetic subjects.

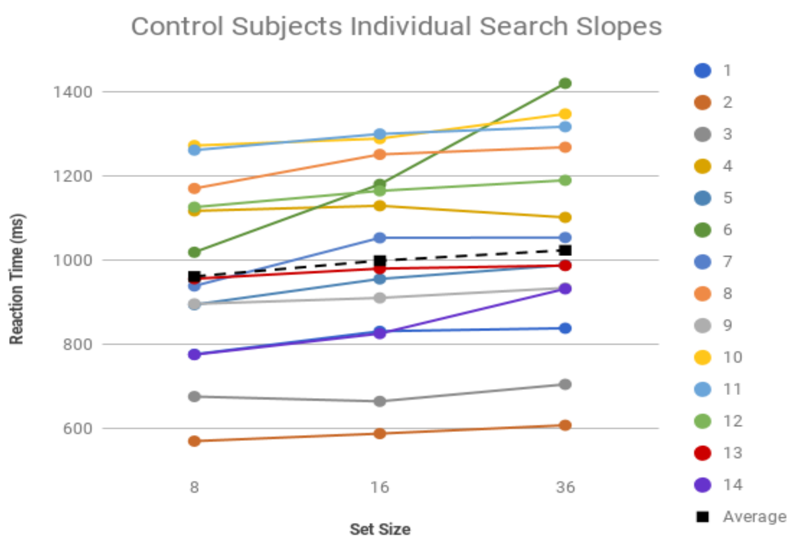


Figure 17. Individual search slopes for control subjects.

Paired accuracy data by set size and individual pair search slope graphs can be found in Appendix 3.

EEG RESULTS

ERPs were time-locked to stimulus onset. Analysis (of pooled contra/ipsi electrodes 28/27, 29/26, 30/25, 44/42, 45/41, 46/40) showed no presence of the N2pc ERP component in either controls or synesthetes in any set size, as shown in the ERP averaged across set size (Figures 18, 19).

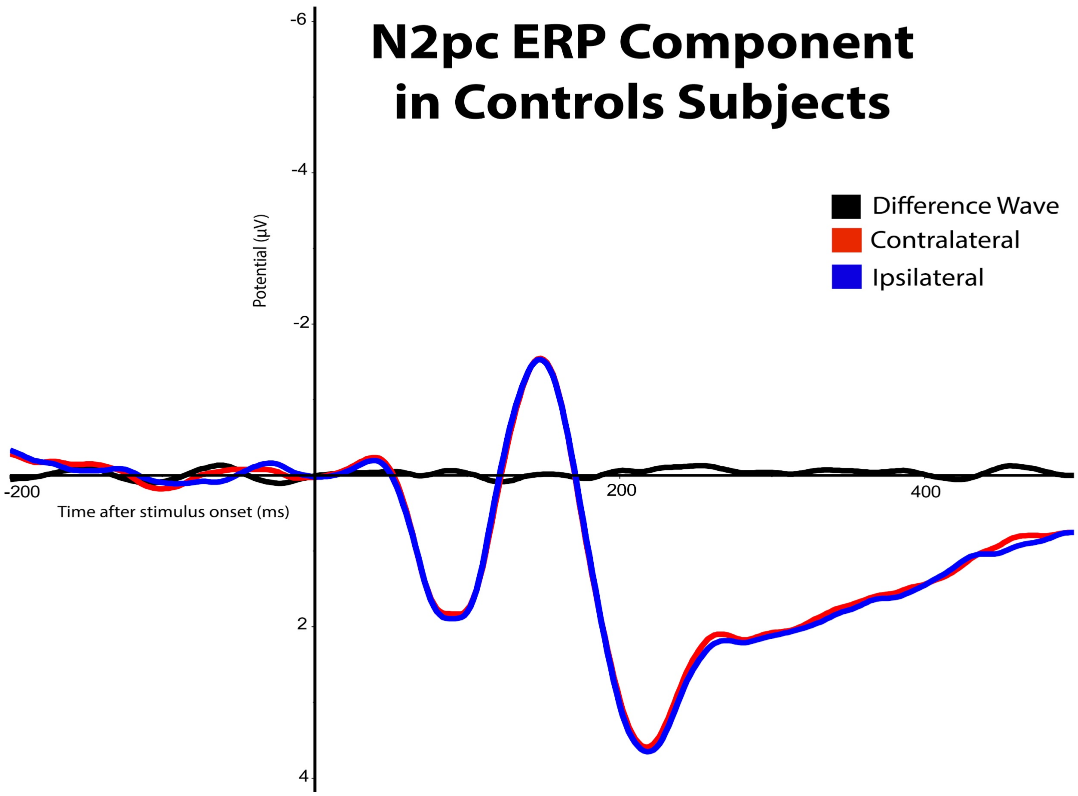


Figure 18. N2pc ERP, with electrodes contralateral to the target and ipsilateral to the target overlapped, of control subjects, demonstrating the lack of N2pc.

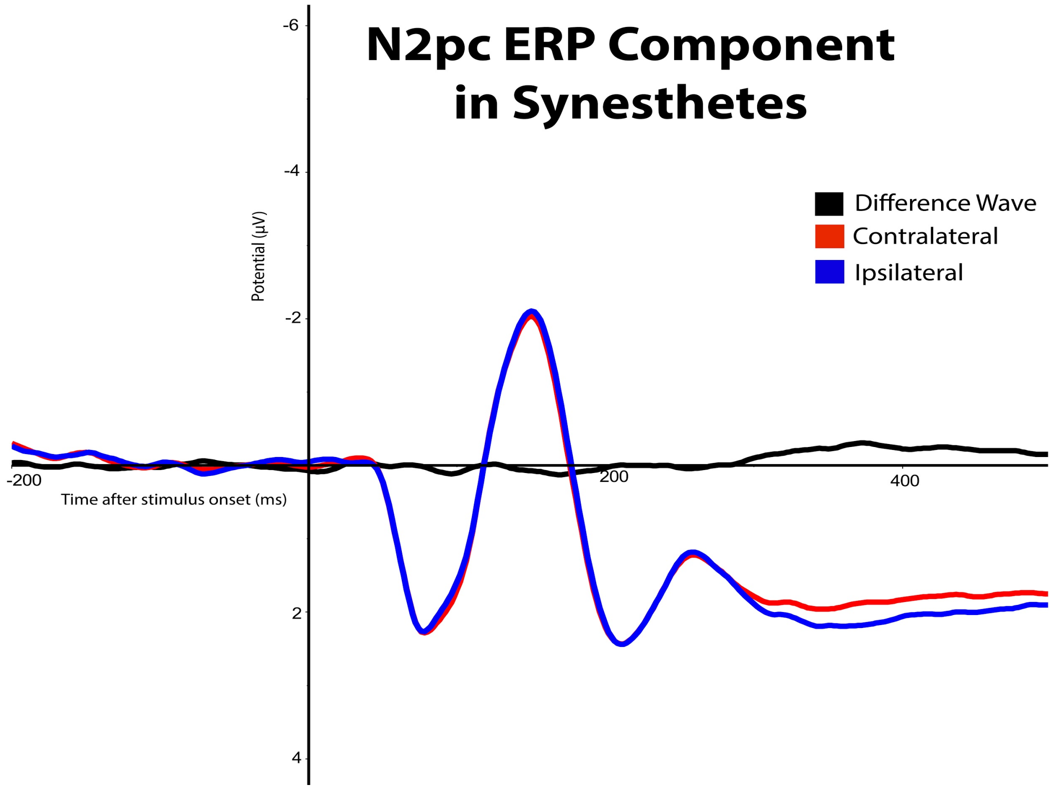


Figure 19. N2pc ERP, with electrodes contralateral to the target and ipsilateral to the target overlapped, of synesthetes, demonstrating the lack of N2pc.

Upon failing to find any N2pc component in the data, we turned to analysis of early ERP components, where other researchers (Schiltz, 1999; Sagiv, 2006) have found group differences between synesthetes and control subjects. Though this analysis cannot answer the original hypothesis about when the attention of synesthetes was placed on the target, analysis of early ERP components supplements analysis of behavioral data and can indicate the use of attention differentially by synesthetes and controls.

Early ERP differences were found between synesthetes and controls in the N1 component (Figure 20) (pooled electrodes 26, 27, 40, 42, 44, 46, 53, 54, 56, 57), and amplitude decreased with set size in both synesthetes, (set size 8: 2.54µV, set size 16: 2.53µV, set size 36: 1.91µV) (Figure 21), and control subjects (set size 8: 1.73µV, set size 16: 1.31µV, set size 36: 0.94µV) (Figure 22). An analysis of the amplitude of the N1 of synesthetes (M=2.24µV, SD=1.36µV) and controls (M=1.47µV, SD=1.56µV) with a two-sample t test showed a significantly larger amplitude for synesthetes ($p < 0.01$).

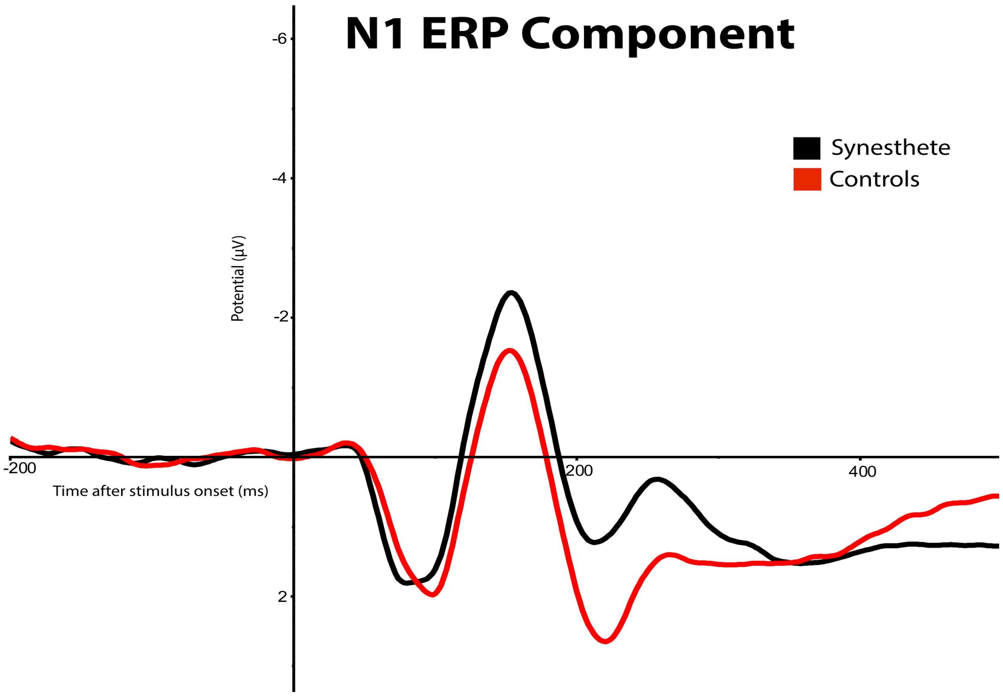


Figure 20. N1 ERP, showing greater amplitude for synesthetes than control subjects.

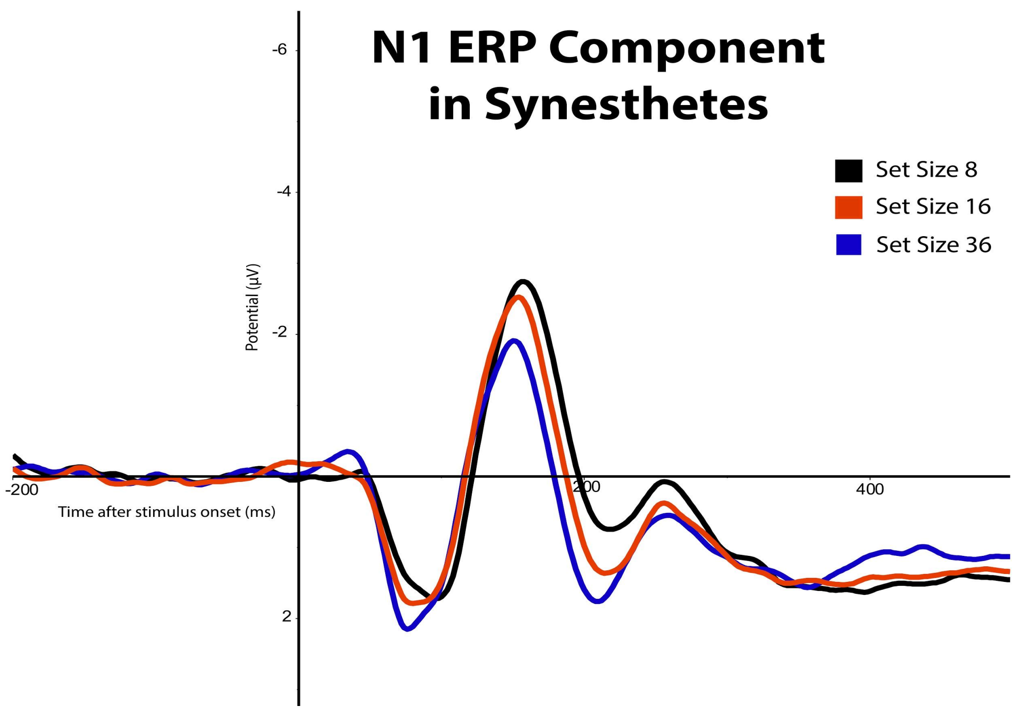


Figure 21. N1 ERP in synesthetes, showing decreasing amplitude with increasing set size.

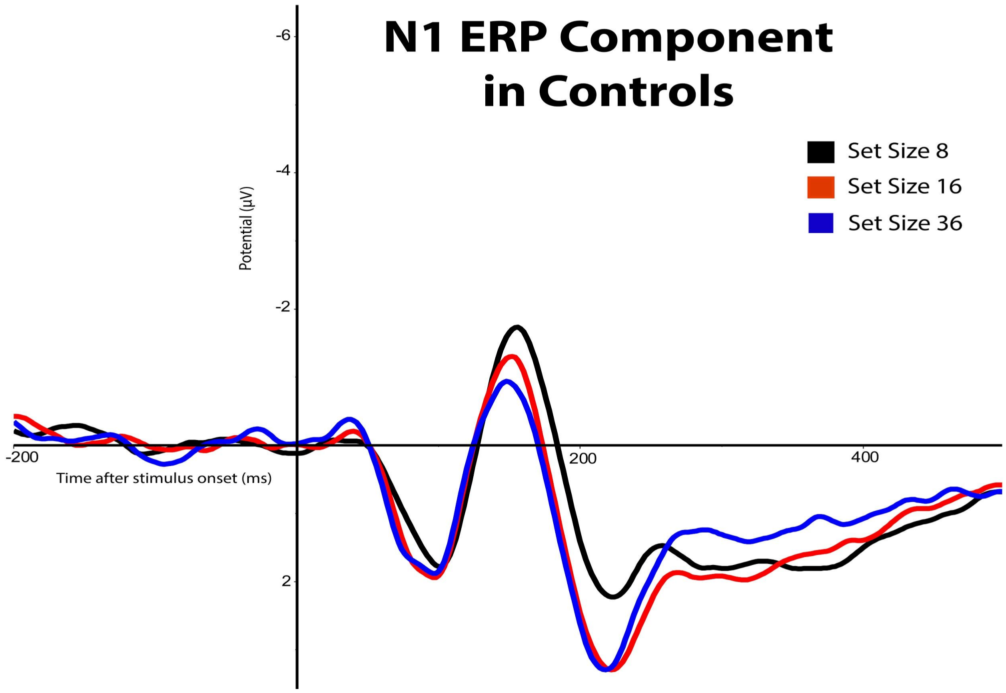


Figure 22. N1 ERP in control subjects, showing decreasing amplitude with increasing set size.

Early ERP differences were also found between synesthetes and controls in the P2 component (Figure 23) (pooled electrodes 2, 3, 8, 9, 10, 17, 18, 19, 21, 22, 33, 34), and amplitude differed with set size in both synesthetes (set size 8: 8.84μV, set size 16: 10.12μV, set size 36: 9.68μV) (Figure 24) and control subjects (set size 8: 6.57μV, set size 16: 7.11μV, set size 36: 6.81μV) (Figure 25).

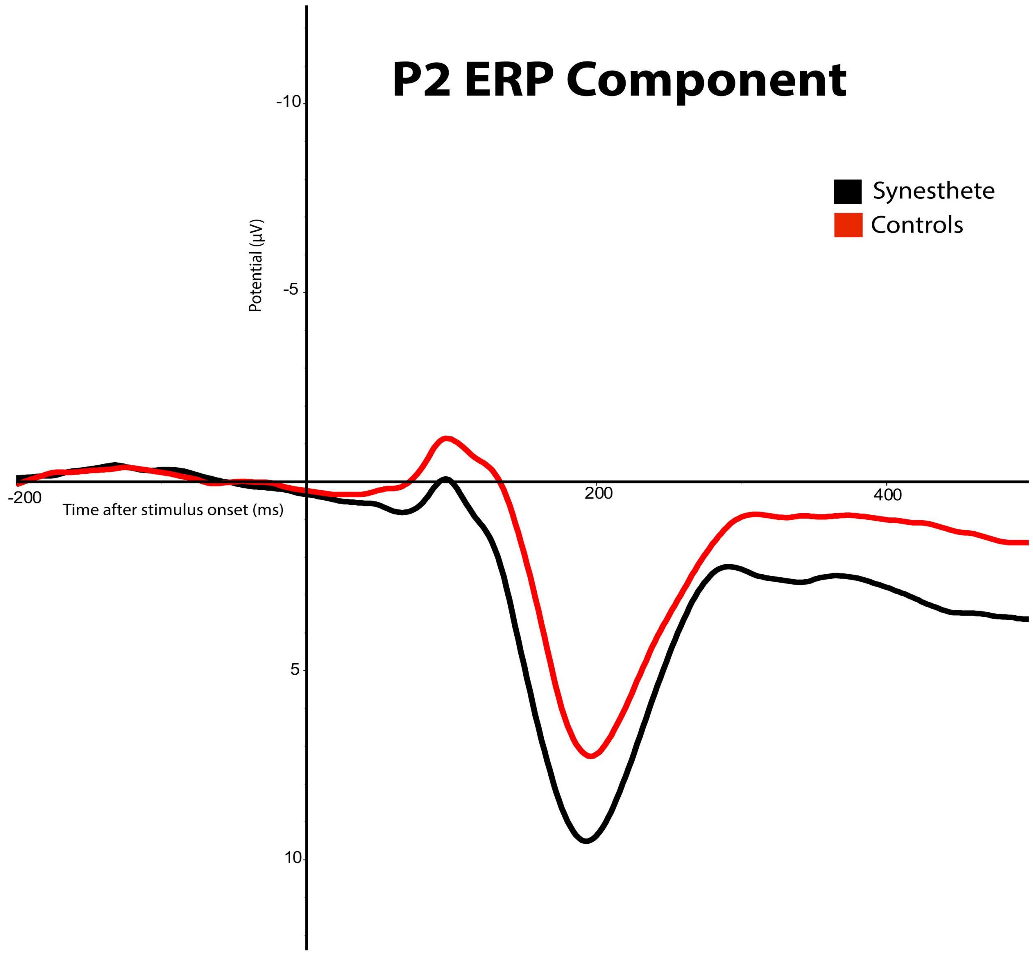


Figure 23. P2 ERP, showing greater amplitude for synesthetes than control subjects.

Analysis of the amplitude of the P2 of synesthetes (M=9.51μV) and controls (M=7.27μV) with a 2x3 mixed ANOVA showed no main effect of group, $F(1, 52)=1.04$, n.s., but did show a main effect for set size, $F(2, 52) = 7.36$, $p < 0.00$, as well as a significant interaction between group and set size, $F(2, 52) = 4.04$, $p < 0.02$. A post-hoc pairwise comparison showed that the effect of set size was significant between groups at all three set sizes, all $p < 0.00$.

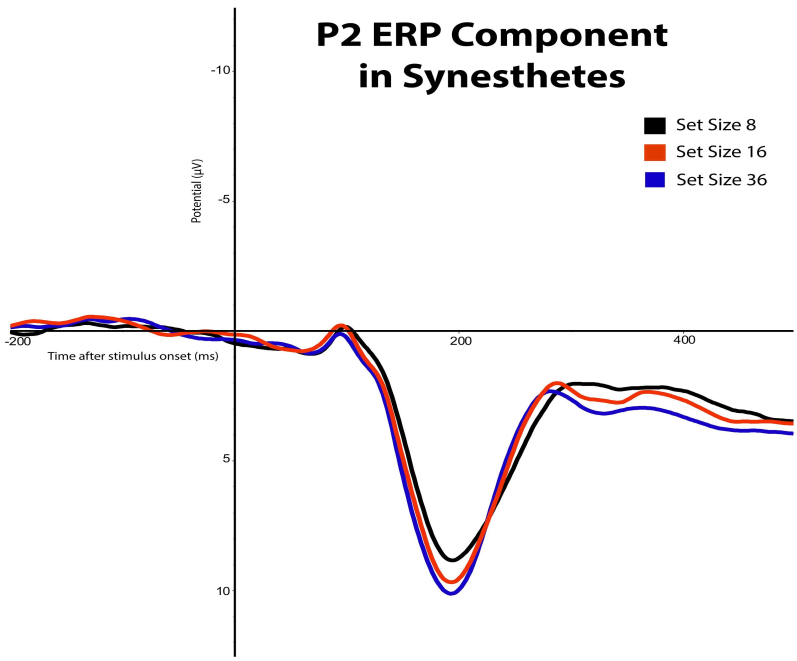


Figure 24. P2 ERP in synesthetes, showing increasing amplitude with increasing set size.

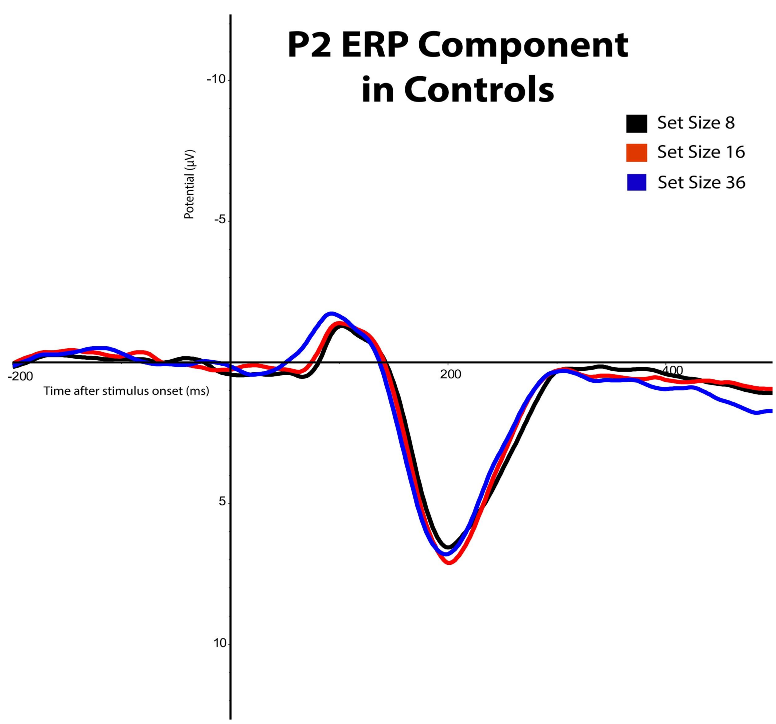


Figure 25. P2 ERP in control subjects, showing no significant difference in amplitude with increasing set size.

A difference in latency of the onset of the P3 ERP component was also seen between synesthetes (296 ms) (Figure 26) and controls (260 ms) (Figure 27) (pooled electrodes 4, 5, 12, 13, 15, 16, 27, 28), with controls showing an earlier differentiation between the ERP of target absent (red) and target present trials (black).

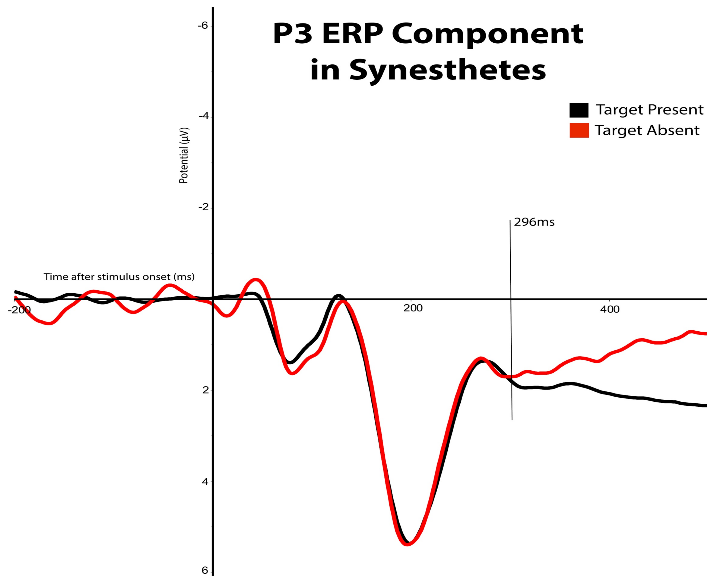


Figure 26. P3 ERP, showing an onset of differences at 296ms in synesthetes.

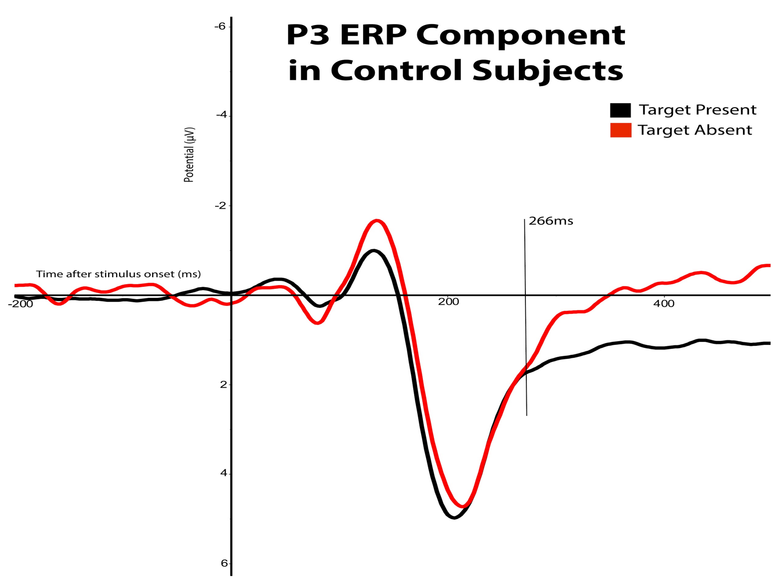


Figure 27. P3 ERP, showing an onset of differences at 266ms in control subjects

PHENOMENOLOGICAL SURVEY RESULTS

In a post-experiment qualitative survey sent to synesthetic participants, questions about their synesthetic associations and phenomenological experience during the study were investigated. First, synesthetes were asked to self-categorize their synesthesia as ‘projected’ or ‘associated’: “For your synesthesia, do the letter/number color associations happen in your mind's eye, or are the colors projected out on the physical letter in some way?”

Of the eleven synesthetes who responded to the survey, all eleven rated themselves as associators, with one synesthete saying “for me, I'd say that when I see a three (for example) I just feel very certain that it should be green, and when I visualize it in my head it is always green. The number 3 on a piece of paper doesn't literally look green, but I feel like 3=green. It's sort of a super strong mental association, rather than something that impacts my actual vision”, consistent with previous categorizations of associator synesthetes.

Next, the synesthetes were asked, in each set size, whether they perceived any color during the experiment. If they did, they were asked to describe whether it was helpful to them in completing the task. Nine out of eleven synesthetes reported perceiving color in the set size 8 condition, and five claimed it helped them complete the task. Two other synesthetes remarked that the color was not particularly helpful, as the task was not difficult. In the set size 16 condition, seven of the eleven synesthetes reported seeing color and all claimed it helped their performance, with one synesthete reporting “At this point [the color associations] started to become more helpful, although not directly. It was more like I felt that one was different for some reason rather than seeing it”. In the largest set size (36 stimuli on screen), ten of the eleven reported color perception and eight claimed it helped their performance. Several synesthetes notes that the color was most helpful in this set size, saying that “that the color associations were the most helpful when there were a lot of letters”, and “when the symbol which was different was located near the edges of the cluster”.

Finally, synesthetes were asked whether each grapheme in a given pair evoked distinctly different colors, and all eleven synesthetic respondents confirmed they did.

DISCUSSION

DISCUSSION OF BEHAVIORAL RESULTS

Synesthetes and controls completed a task in which they were asked to determine whether a visual search display contained a target among distractors (the "odd one out") or not (a homogeneous display with no single stimulus different from the rest). Three pairs of graphemes were individually chosen for each participant pair, based on the specific synesthetic associations, of that particular synesthete. We made sure that the two graphemes in each pair were physically similar in shape, but they also elicited a distinctly different synesthetic color. These grapheme pairs were displayed in three different set sizes (8, 16, 36), with a number of target-absent trials in each set. All these different types of trials (target-present, target-absent; 8, 16, 36 set size) were presented randomly, with reaction time and accuracy measured in each trial and for each subject.

On average, as a group neither synesthetes nor controls display a search slope indicating a "pop-out" effect, with both mean slopes significantly different from zero (5.2 and 2.1 respectively). However, the synesthetes did demonstrate significantly faster reaction times at set size 8, and a trend at set size 16. Given the low accuracy average for synesthetes (72%) and control subjects (63%) in the largest set size, compared to set size 16 (86% and 77% respectively) and set size 8 (93% and 87% respectively), it is possible that a significant difference in reaction time in the largest set size was not seen due to a ceiling effect, in which reaction times were at maximum length due to the display timing out. Individual pair search slopes (Appendix 3) show 8 out of 13 synesthetes outperforming their matched control in the smallest set size. Synesthetes also demonstrated lower variability in their reaction time performance (range in set 8=520ms, controls=690 ms) Table 1). Synesthetes also demonstrated significantly higher accuracy across all set sizes, indicating that the advantage seen in reaction time was not due to a speed-accuracy trade-off.

These results support previous research indicating a synesthetic advantage in visual search (Ward, 2010; Hubbard, 2005), as well as the lack of a synesthetic pop-out effect (Edquist, 2006; Laeng, 2004). This advantage may occur at any of the many steps involved in a visual serial search. For example, synesthetes' perceived color may allow them to move from stimulus to stimulus faster than control subjects, without sacrificing accuracy. Synesthetes may also indeed be attending to the target faster due to color perception or some other mechanism. However, the lack of sensitivity of the visual search paradigm used to the N2pc component makes answering that question not possible. Therefore, the analysis of the early ERP components N1, P2, and P3 can be used to supplement behavioral analysis.

DISCUSSION OF ERP RESULTS

As mentioned in the results section, the lack of an N2pc effect in either group, is a puzzling result. Discounting any processing differences that may have caused the lack of a N2pc component in synesthetes, its absence in the control subjects, especially in set size 8, suggests that some aspect of the visual search paradigm we used, failed to elicit this component. Among other factors, this could be the location and arrangement of our stimuli. It is possible that the randomized location and jittering of the stimuli created a display that was not structured enough to strongly differentiate target location clearly on the left or right side of the display. For example, in some trials, the targets were much closer to the midline, while in others, they appeared on the perimeter of the display. It is also possible that the blank area left in the midline of the display was not large enough to differentiate the two fields of vision, creating a weak differentiation of targets on the left and right. Other explanations are certainly possible (e.g. the distance from the screen may have been too short), and further experimentation and modification of this paradigm is necessary to determine the source of this result. In short, our paradigm seems to have been insensitive to elicit an N2pc and therefore, its value as a reflection of allocation of attention was impossible.

However, the larger amplitude of the N1 component seen in synesthetes could indicate several things. Larger amplitude N1 has been used as a signifier of a participant's attention being correctly allocated, as the amplitude increases when the attention is focused on the area that the relevant information is presented, as opposed to distributed across the visual field or focused in an area without relevant information (Luck, S., Hillyard, S., Mouloua, M., Woldorff, M., Clark, V., Hawkins, H., 1994). This may indicate that synesthetes are more likely to allocate their attention correctly to the target, due to their use of their synesthetic color, in addition to the form of the letter in the serial search task. The amplitude of the N1 component decreased for both synesthetes and control subjects as the set size increased, likely due to the fact that increasing the number of stimuli in the display made it less likely that attention was focused in the relevant area. There was also an increased amplitude for the P2 component seen in synesthetes as compared to control subjects. The P2 component has been demonstrated to be larger in amplitude when a search is more efficient (Phillips, S., Takeda, Y., 2009), and so this result may support the idea that synesthetes are carrying out a more efficient serial search process for some reason. Analysis of the P3 component (which is derived from comparing the ERP in the target present condition to the target absent condition) showed that controls demonstrated an earlier P3 component. This also was a surprising result, as the P3 component is elicited by the use of attention in a task and a shift in attention (Polich, J., 2003), such as to a target stimulus. This result is surprising because synesthetes showed faster reaction times than control subjects, possibly indicating a significant post-attentional advantage.

DISCUSSION OF PHENOMENOLOGICAL SURVEY RESULTS

The results of the survey administered post-experiment indicated that not only did synesthetes perceive color (according to self-report) during the study, but it may have assisted them in completing the visual search task. Although the significantly higher accuracy of the synesthetes supports this theory, the lack of consistent advantage in reaction times does not. If, as they reported, the synesthetic color associations became more and more helpful as the set size increased, then the difference between the reaction time of synesthetes and control subjects would have increased or stayed the same. Instead, the difference decreased, indicating that the phenomenological data is not communicating the full story.

FURTHER DIRECTIONS

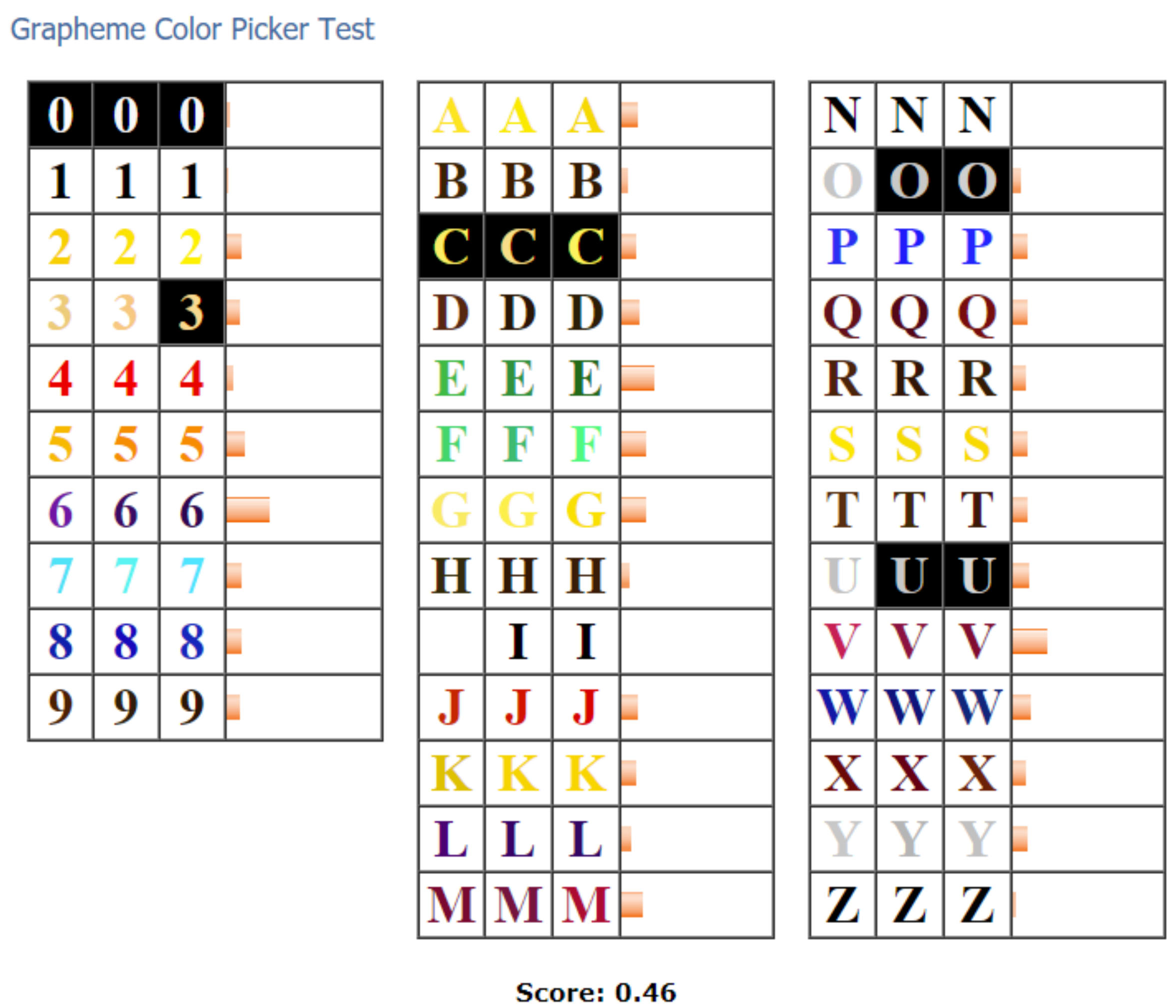
The results of this thesis produce many more questions than answers, and further investigation on many fronts is required to fully understand the its results. The lack of N2pc is the most obvious and baffling result, with manipulation of the visual search paradigm necessary in order to determine the cause. Use of set stimulus locations, extending of the blank area on the midline, and less jittering of stimuli, may all be ways to modify the paradigm to make it more likely to elicit an N2pc. Use of larger grapheme stimuli, as well as less stimuli in the largest set size may also improve clarity of results. Additionally, further analysis of the literature on early ERP differences between synesthetes and controls across various studies (not just visual search), is necessary in order to further interpret the complex results of the N1, P2, and P3 analysis.

Finally, the vast majority of the synesthetes used in this study (at least 11 out of 14) reported experiencing synesthetic color in a manner consistent with their categorization as associator synesthetes. Replication of this study (with a modified visual search paradigm that successfully elicits the N2pc ERP component), with projector synesthetes, is necessary in order to effectively investigate the results of previous studies that claimed the existence of a synesthetic pop-out effect. While it is unlikely that the absence of the pop-out effect (which would be demonstrated by a flat search slope) is solely due to the lack of projector synesthetes, it is worth examining whether differences between these groups may underlie our findings.

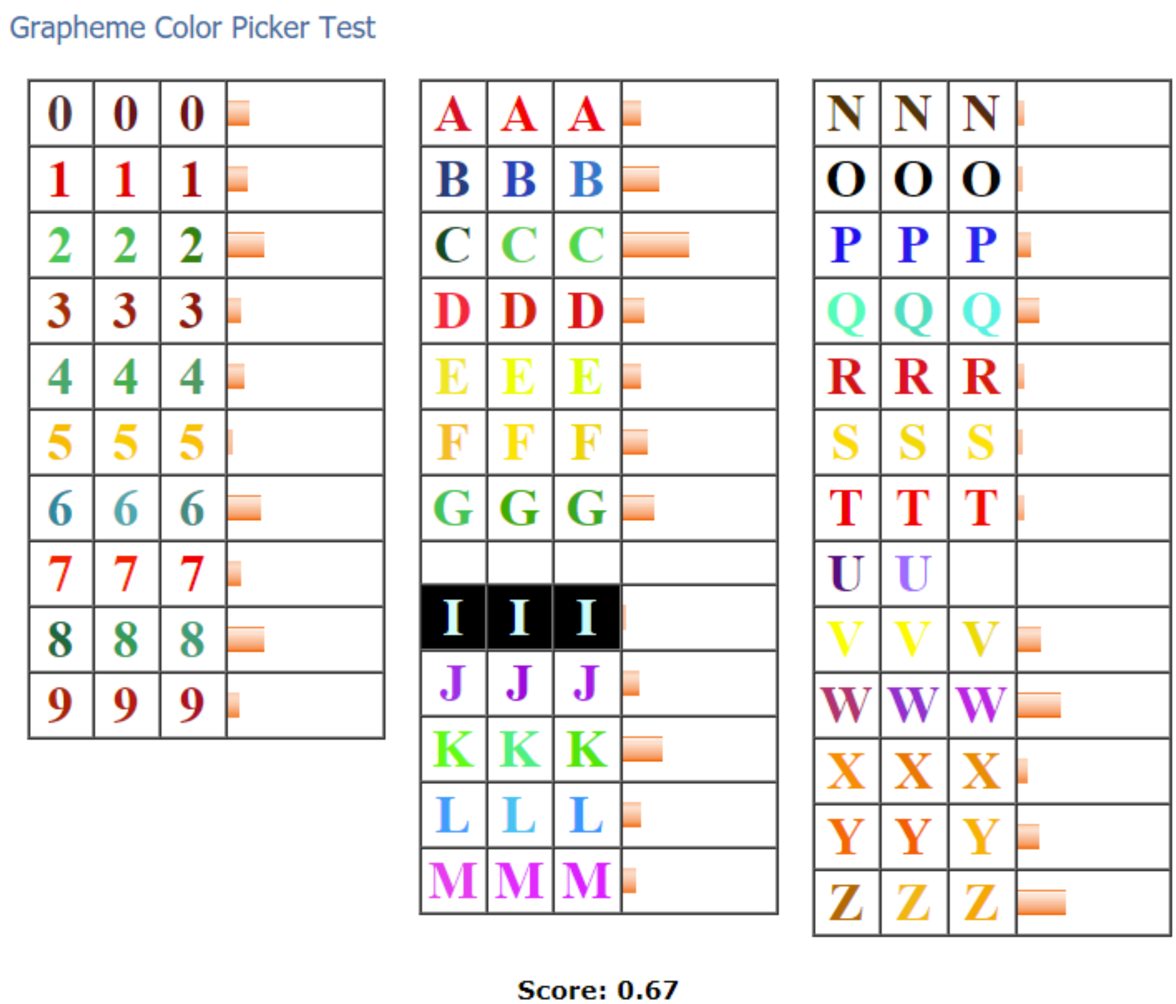
In conclusion, this study confirms the existence of early ERP differences between synesthetes and control subjects, as well as significant behavioral differences indicating faster reaction times and greater accuracy in this visual search paradigm. Further research is necessary in order to elucidate and contextualize these results further, as perceptual research on synesthesia continues to provoke new and interesting questions.

APPENDIX 1: Eagleman Battery Results

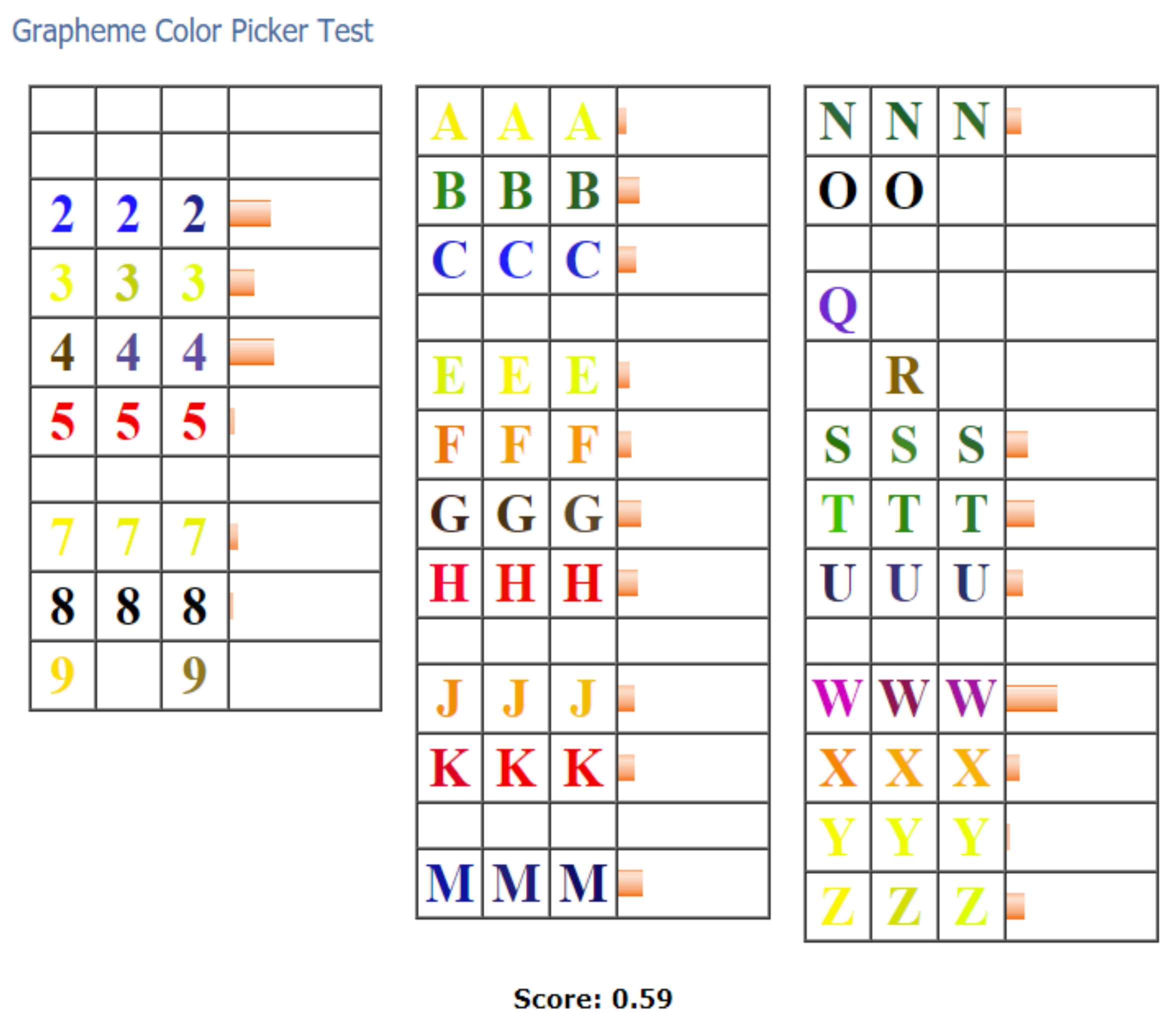
Synesthete 01



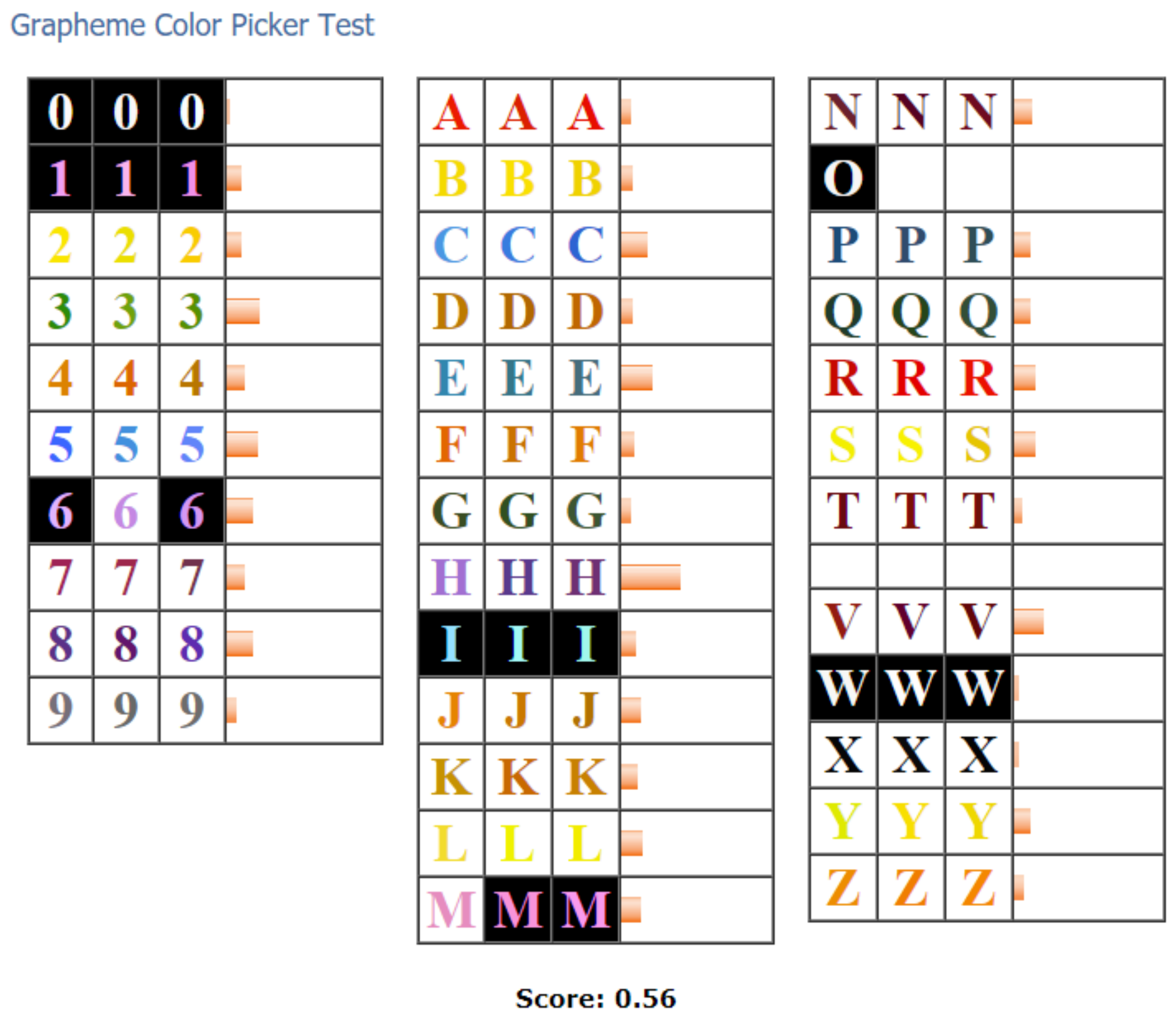
Synesthete 02



Synesthete 03

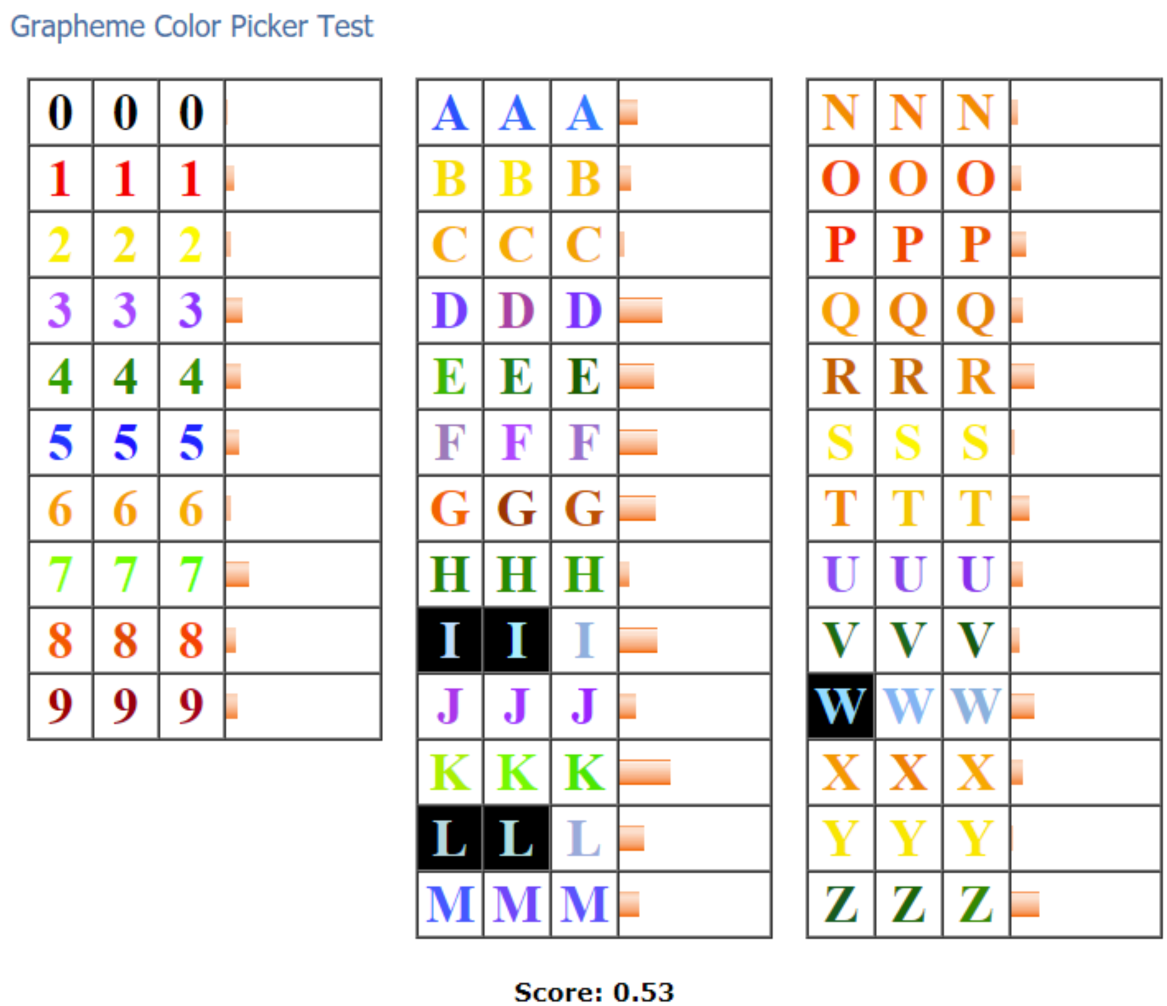


Synesthete 04

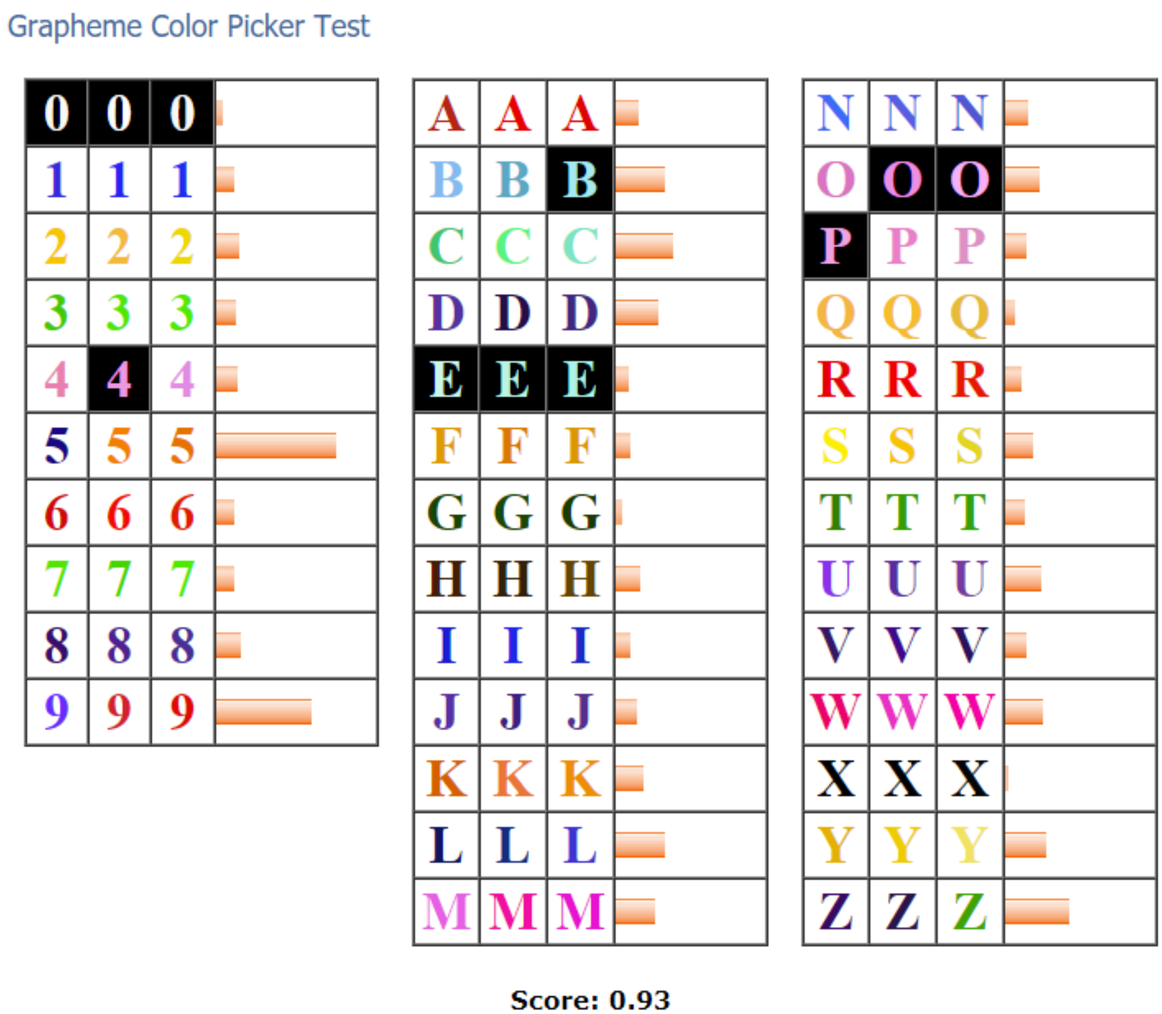


Synesthete 05

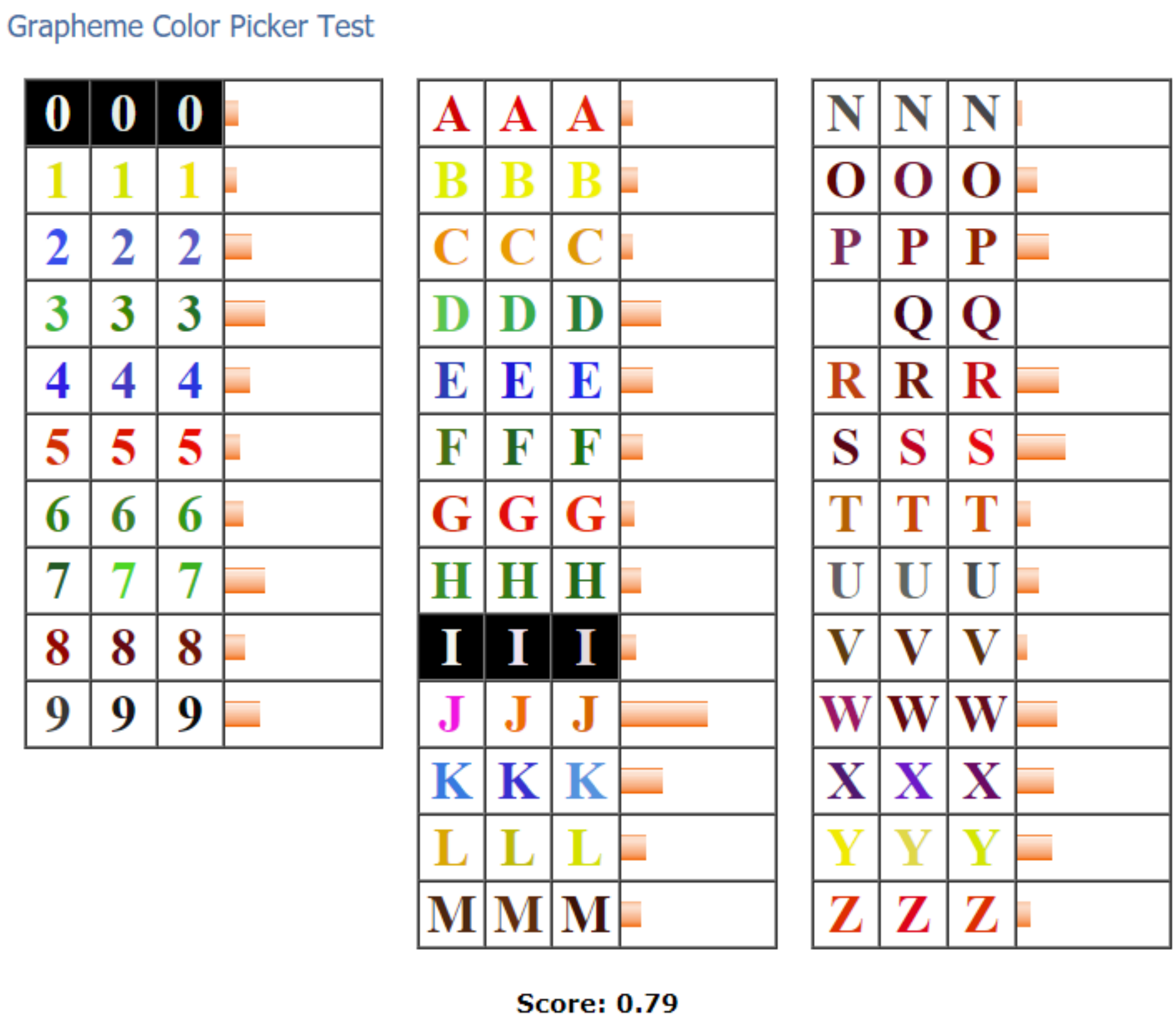
Synesthete 06



Synesthete 07



Synesthete 08



Synesthete 09

Grapheme Color Picker Test

0	0	0	
1	1	1	
2	2	2	
3	3	3	
4	4	4	
5	5	5	
6	6	6	
7	7	7	
8	8	8	
9	9	9	

A	A	A	
B	B	B	
C	C	C	
D	D	D	
E	E	E	
F	F	F	
G	G	G	
H	H	H	
I	I	I	
J	J	J	
K	K	K	
L	L	L	
M	M	M	

N	N	N	
O	O	O	
P	P	P	
Q	Q	Q	
R	R	R	
S	S	S	
T	T	T	
U	U	U	
V	V	V	
W	W	W	
X	X	X	
Y	Y	Y	
Z	Z	Z	

Score: 0.57

Synesthete 10

Grapheme Color Picker Test

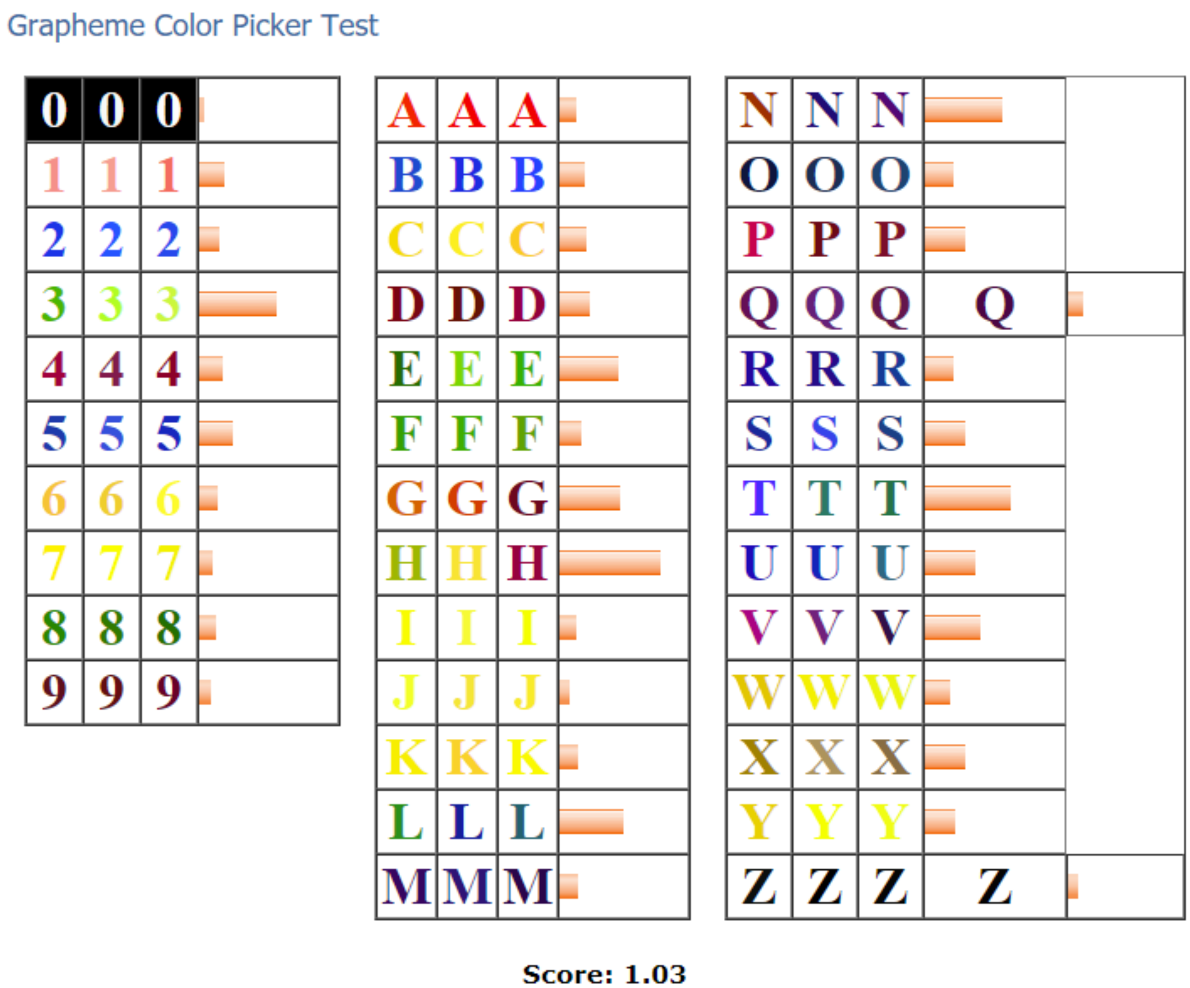
1	1	1	
2	2	2	
3	3	3	
4	4	4	
5	5	5	
6	6	6	
7	7	7	
8	8	8	
9	9	9	

A	A	A	
B	B	B	
C	C	C	
D	D	D	
E	E	E	
F	F	F	
G	G	G	
H	H	H	
J	J		
K	K	K	
L	L	L	
M	M	M	

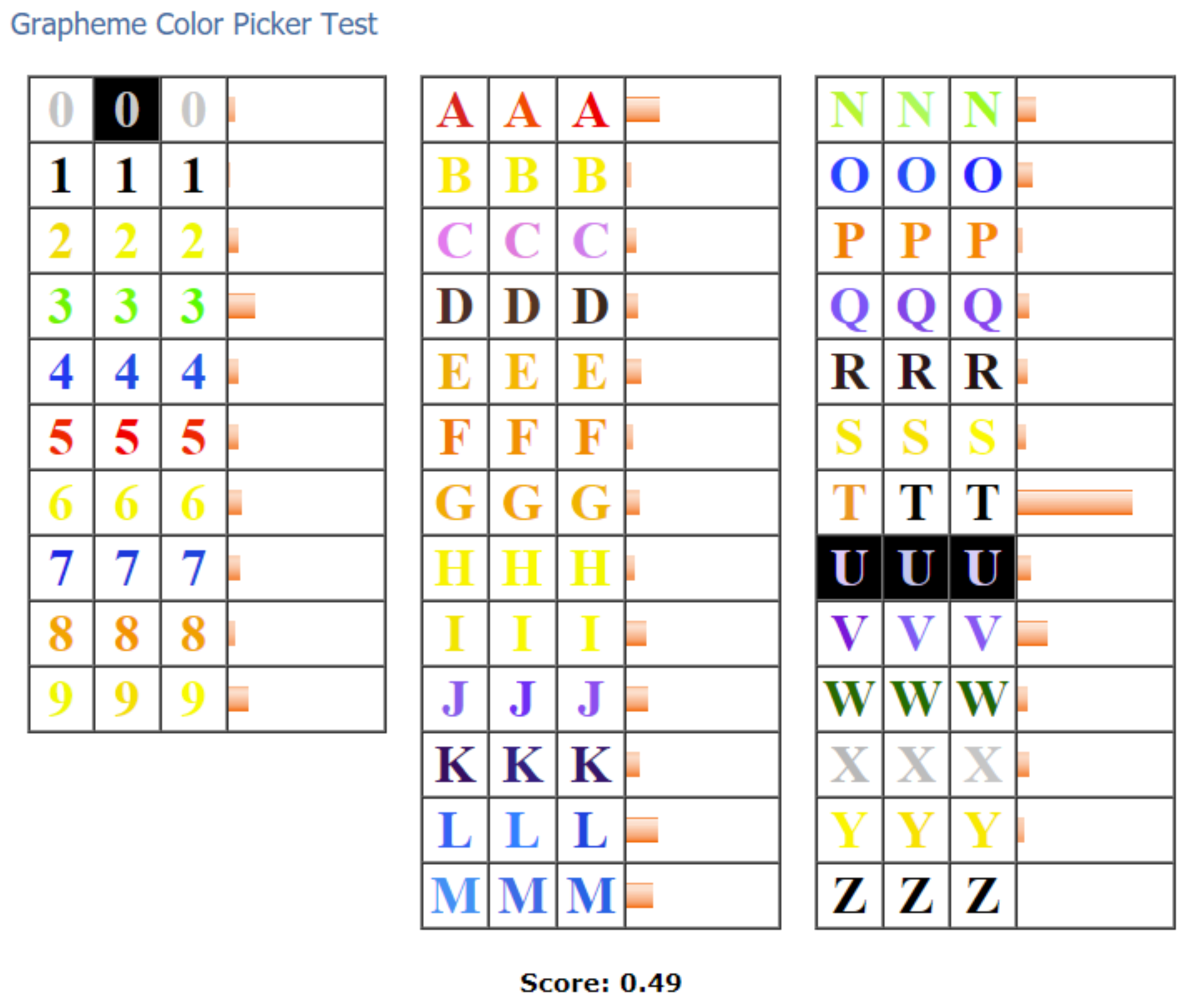
O	O	O	
Q	Q	Q	
R	R	R	
S	S	S	
T	T	T	
U	U	U	
V	V	V	
W	W	W	
Y	Y		
Z	Z	Z	

Score: 0.66

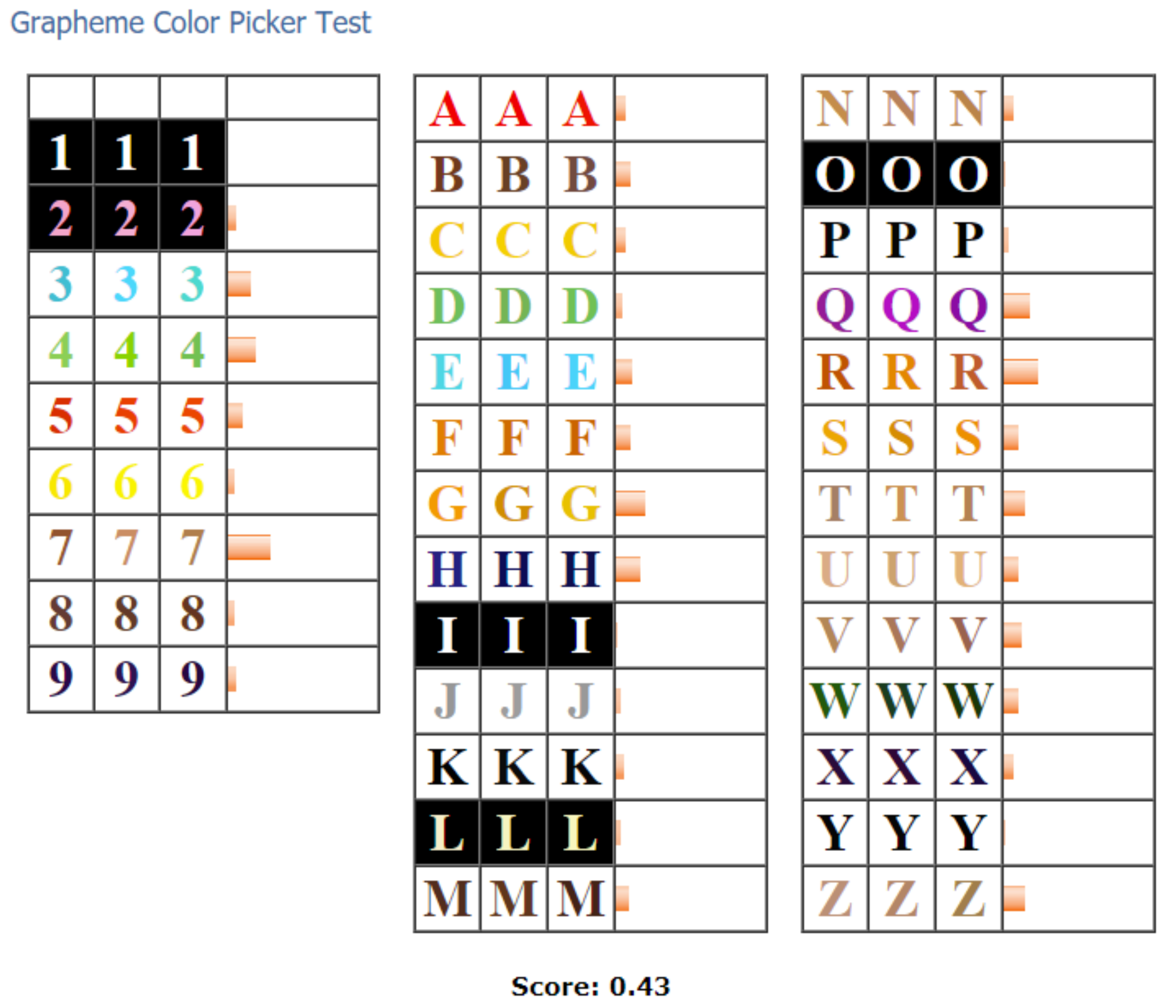
Synesthete 11



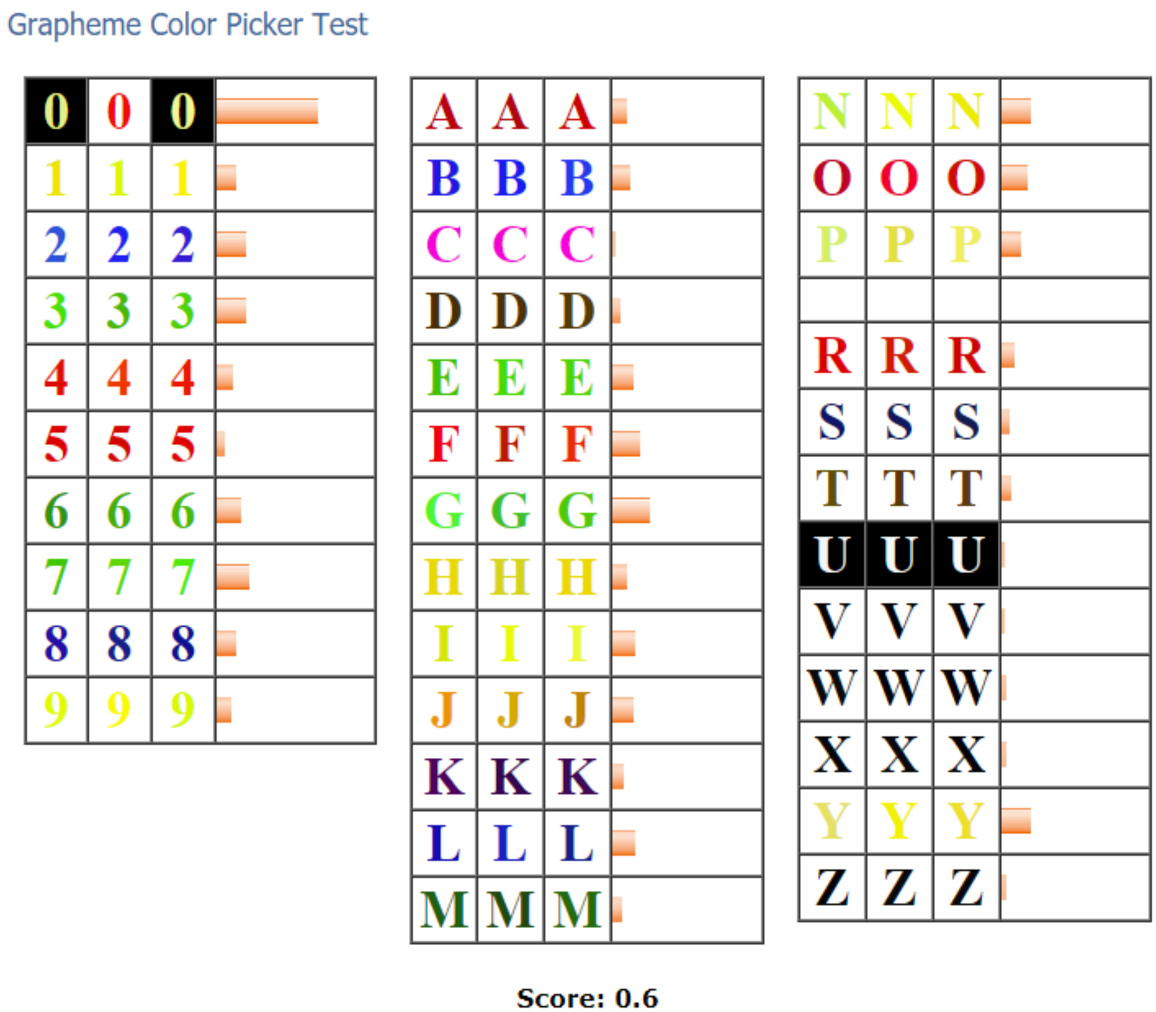
Synesthete 12



Synesthete 13



Synesthete 14



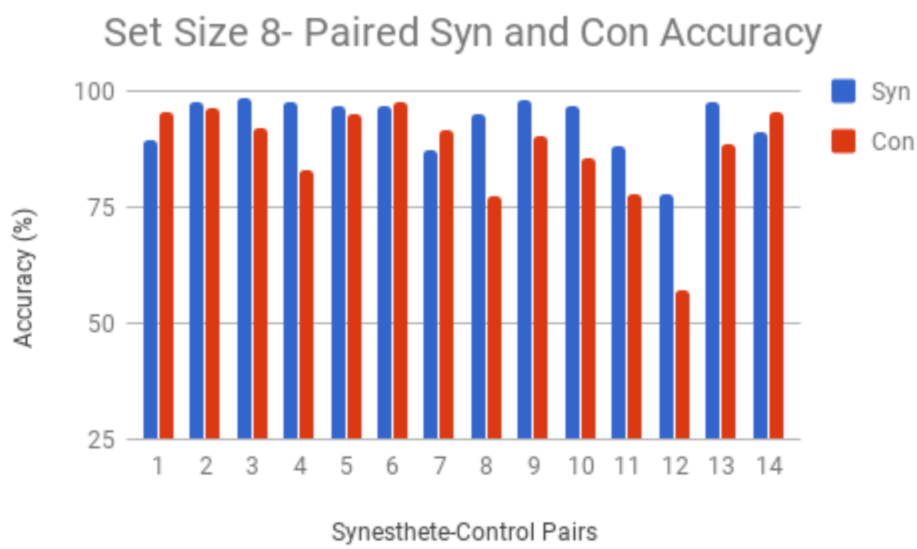
APPENDIX 2: Grapheme Pairs

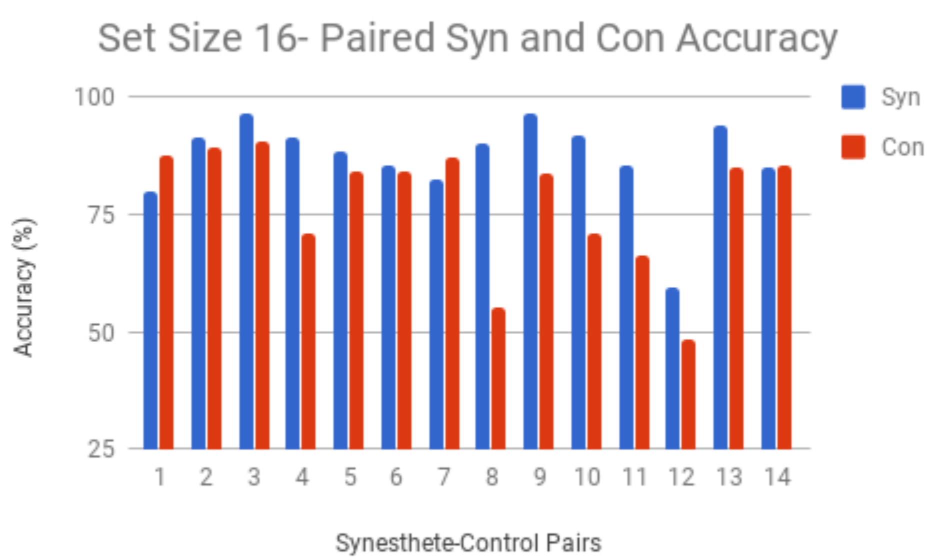
	Pair # 1	Pair #2	Pair # 3
Pair 01 (21F)	2 5	J 7	W M
Pair 02 (21M)	6 9	2 5	J 7
Pair 03 (20M)	J 7	W M	J 7
Pair 04 (19F)	2 5	3 E	F E
Pair 05 (18F)	2 5	3 8	6 9
Pair 06 (19F)	6 9	2 5	J 7
Pair 07 (22F)	L T	F E	A P
Pair 08 (22M)	2 5	Y 4	3 E

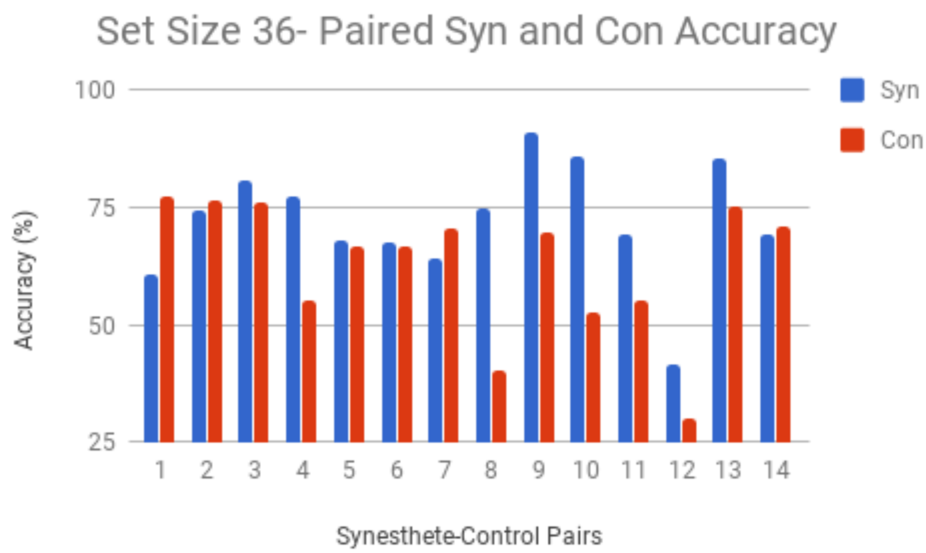
Pair 09 (21F)	J 7	L T	W M
Pair 10 (19F)	2 5	L T	3 E
Pair 11 (19F)	W M	6 9	Y 4
Pair 12 (21F)	2 5	P 9	Y 4
Pair 13 (19F)	2 5	J 7	W M
Pair 14 (21F)	F E	W M	L T

APPENDIX 3: More Results

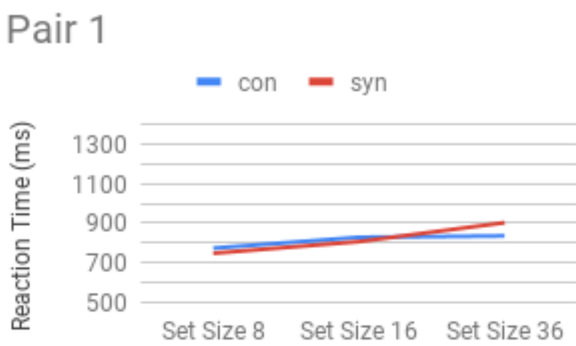
Paired Accuracy by Set Size Data

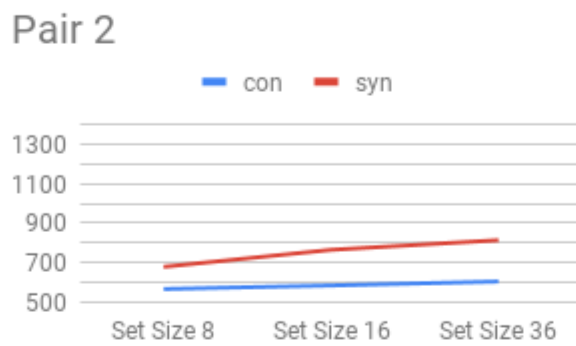


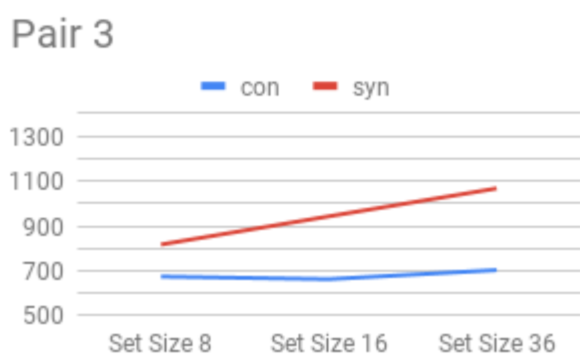


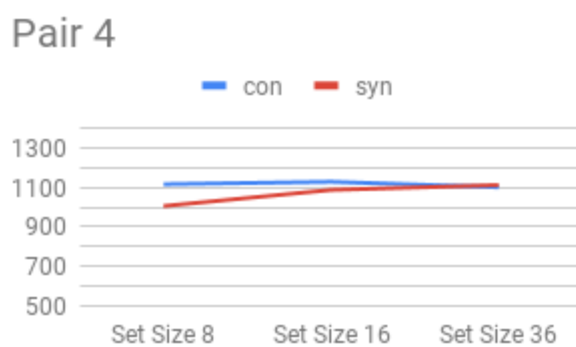

Set Size 36- Paired Syn and Con Accuracy
Syn
Con
Accuracy (%)
100
75
50
25
1
2
3
4
5
6
7
8
9
10
11
12
13
14
Synesthete-Control Pairs

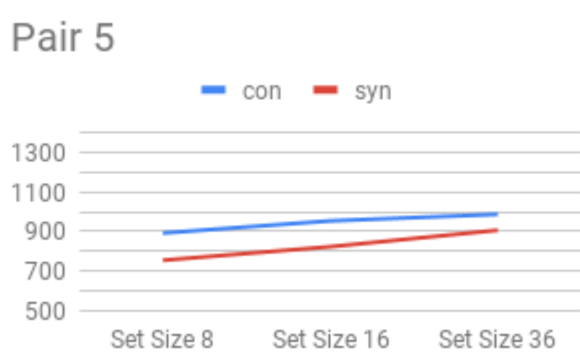
Paired Search Slope Graphs

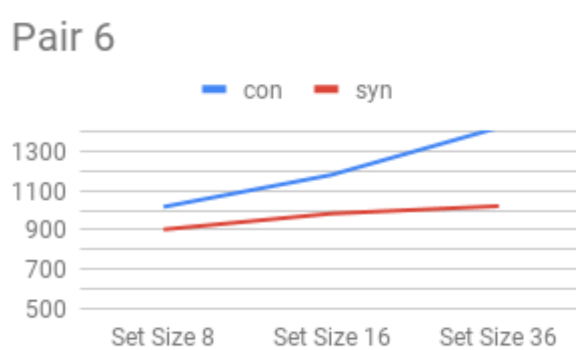


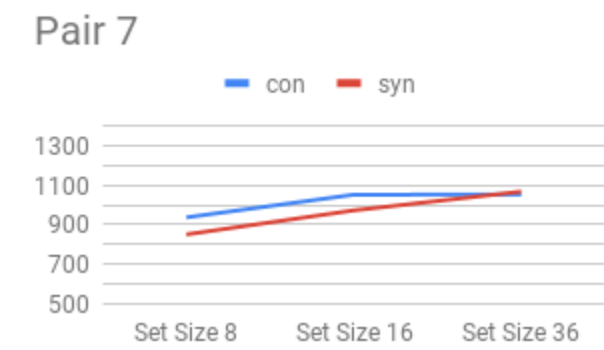


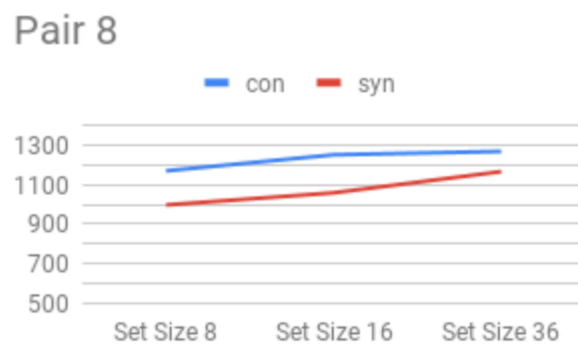


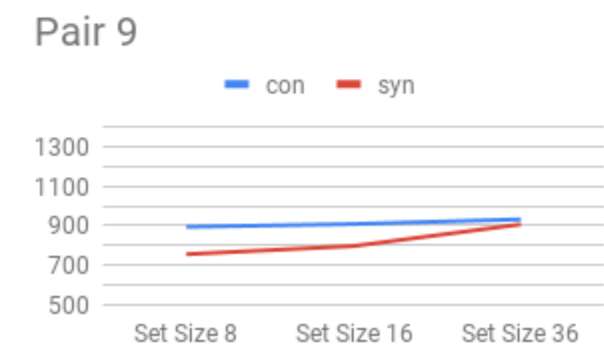







Pair 7
con
syn
1300
1100
900
700
500
Set Size 8
Set Size 16
Set Size 36


Pair 8
con
syn
1300
1100
900
700
500
Set Size 8
Set Size 16
Set Size 36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syn
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1100
900
700
500
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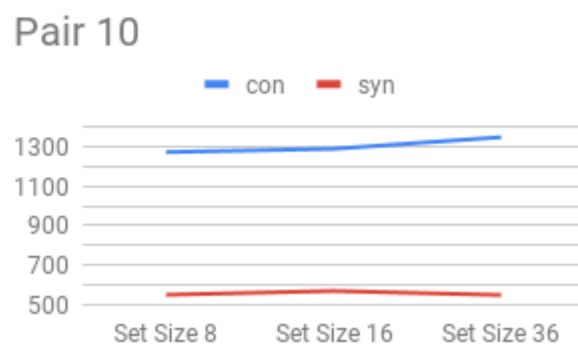
Set Size 36


Pair 10
con
syn
1300
1100
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700
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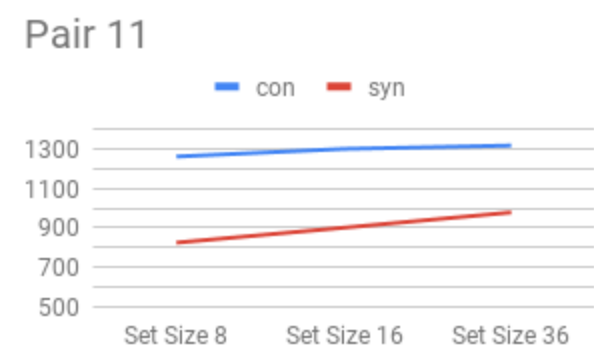
Set Size 8
Set Size 16
Set Size 36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syn
1300
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Set Size 8
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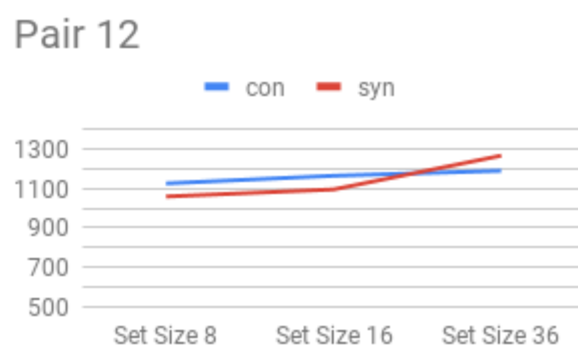
Set Size 36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syn
1300
1100
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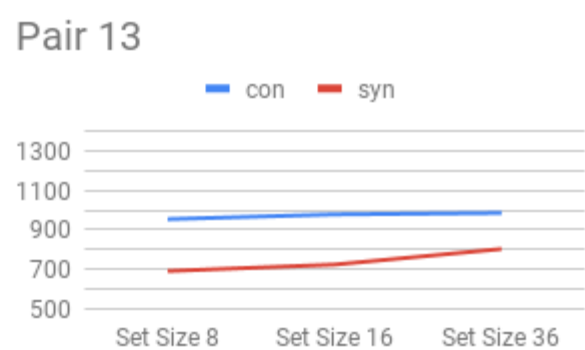
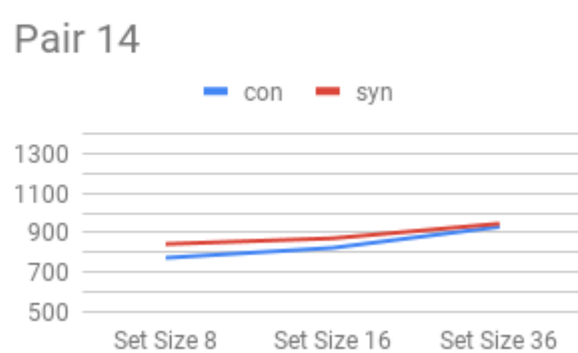
700
500
Set Size 8
Set Size 16
Set Size 36


Pair 13
con
syn
1300
1100
900
700
500
Set Size 8
Set Size 16
Set Size 36


Pair 14
con
syn
1300
1100
900
700
500
Set Size 8
Set Size 16
Set Size 36

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