# The Role of Attention in Grapheme-Color Synesthesia

A Thesis

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Michael Pitts

# Acknowledgments

I am not precisely sure how I ended up here, but here is indeed where I am.

To the places that I carry inside me: the rolling hills and shaded groves of Marin County, Highland Lake with its denizens enshrined in family legend, Granite Mountain presiding over the Sierra scrubland, the jagged peaks of the Peruvian Andes, and of course the majestic electrophysiology lab at Reed College. Wait, what? After spending more time in the lab than in my own house over the course of the past month, I have developed a special love for the space and those who bring it alive.

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# Abstract

Grapheme-color synesthesia is a unique neurological condition in which affected individuals report experiencing strong and consistent associations between specific colors and graphemes (letters or numbers). The current study used electroencephalography (EEG) neuroimaging techniques to address two primary research questions:

1. Does the brain activity of grapheme-color synesthetes reflect the neural processing of synesthetic color associations and if so, how and when?
2. Are synesthetic color associations processed pre-attentively, or do they require focused attention to be perceived?

To answer these questions, the brain activity of ten grapheme-color synesthetes and ten matched control participants was recorded during exposure to grapheme stimuli in two separate experiments. The first experiment revealed an early event-related potential (ERP) component related to the neural processing of synesthetic color associations. The second experiment revealed behavioral and electrophysiological differences between synesthetes and controls on a visual search task, suggesting that synesthetic color associations are processed pre-attentively or under conditions of minimal attentional allocation.

# Introduction

## *History of Synesthesia*

Imagine, for a moment, a man enjoying a night at the opera house. His ticket cost the same as any other, but he feels privileged, because he is being treated to a private show that his fellow concert-goers cannot hope to experience: a symphony of colors, rising and falling with the swells of the music in a wholly personal display. Now imagine a poet. When asked about a piece of writing, she may explain that she wanted to write a poem that was predominantly blue, or perhaps green. For most this is a stretch of the imagination, but for her it is a visual reality.

The individuals described here are imaginary people with a very real condition. Synesthesia, the crossing of sensory modalities, is a sort of real-life superpower, albeit more subtle than the comic book staples of flight or incredible strength. Synesthesia often entails an abnormal experience of color, such that one might perceive or associate colors with letters, sounds, or even smells. The first medical and scientific record of synesthesia comes from one Georg Tobias Ludwig Sachs (1786-1814), a German man who published a medical dissertation in 1812 on the subject of his brother and sister's albinism (his 'brother', in truth, was himself), which also coincidentally included the first known description of synesthesia (Jewanski, Day, & Ward, 2009). His poetic albeit vague description is as follows:

> There is much which either never comes before the eyes, or which cannot be reckoned with usual sight, that either does not belong to the sense of vision, or which is not perceptible to the senses, which, in the mind of the brother, inspires dark ideas of different colors, so intimate and recurring, that cannot be conceived of, or only scarcely and with difficulty, without a certain attention. I cannot express it better than to say that a colored idea appears to him. For some, however, this seems due more to a certain coincidence than to regulated impressions, whereby the color and the article in which the idea is connected, which affects the mind, seem to stand in harmony. Some ideas convey the colors by themselves, even if the feelings move all in heaven to differ.

He goes on to describe the various stimuli that elicit experiences of color, including letters, numbers, musical notes and timbres, and more complex ideas such as days of the week and time periods in history (Jewanski et al., 2009). The topic of synesthesia did not arise again in the literature until in 1848 French surgeon Edouard Cornaz references Sachs in his doctoral thesis and speculates that synesthesia may be the opposite of color-blindness, dubbing it "hyperchromatopsia" (Jewanski et al., 2009; Jewanski, Simner, Day, & Ward, 2011). However, his theory presumed that synesthesia arises in the eyes rather than the brain; a fundamentally flawed conjecture. Fortunately, some of Cornaz's contemporaries recognized his claim as dubious at best. One anonymous yet perceptive individual wrote in 1852, "This strange phenomenon is likely to be based on a mapping between a sensuous perception and a certain psychological conception" (Jewanski et al., 2011).

Heinrich Kaiser, a German scientist, performed the first consistency test when he recorded a synesthete's color-letter associations in 1872 and again in 1882, finding them to match perfectly (Jewanski et al., 2011). This helped convince scientists that synesthesia was a real perceptual phenomenon, rather than a mere memory association. The topic of synesthesia then experienced a surge of interest, garnering many psychological publications between the years of 1880 and 1930, before dwindling away in the mid-20th century (Ione & Tyler, 2004). During this period many authors felt compelled to exhaustively document and describe any cases of synesthesia they came across in their studies, in the hope of learning more about the unique condition (Alford, 1918; Coriat, 1913; Lay, 1896). No doubt some of the interest during this period was kindled by publicity brought by famous synesthete Wassily Kandinsky, who was most active during these years and publicly attributed his success in the visual art world in part to his condition (Ione & Tyler, 2004). Post-1930 the world became much less interested in synesthesia, but with the advent of modern psychology and neuroscience techniques, interest in synesthesia research is beginning to resurge.

## *The Phenomenon of Synesthesia*

It is currently estimated that synesthetes make up anywhere from 0.05% to 4% of the population, although the precise prevalence rate has proven difficult to pin down

(Baron-Cohen, Burt, Smith-Laittan, Harrison, & Bolton, 1996; Simner et al., 2006), potentially due to differences between studies in recruitment strategies or classification techniques. Synesthesia has been estimated to be more prevalent in females with a ratio of about 6:1 (Baron-Cohen et al., 1996; Rich, Bradshaw, & Mattingley, 2005), but some studies suggest that the ratio is closer to equal (Simner et al., 2006). Because of the apparent sex inequality, some researchers have proposed that synesthesia is genetically biased toward females, while others have argued that the discrepancy is due to self-selection bias in recruitment for research (Simner et al., 2006). Researchers that asked synesthetes to come forward and volunteer independently found themselves with disproportionately female populations, whereas studies with a stricter selection protocol had a more even distribution of males and females. For example, Simner (2006) randomly selected a group of 500 individuals from Edinburgh and Glasgow Universities, gave them a description of many different types of synesthesia, and asked them to indicate whether they possessed or thought they possessed any of them. Individuals who indicated having synesthesia were subsequently tested. Using this method, they found an overall prevalence rate of 4.4%, and a female to male ratio of 1.1:1 (Simner et al., 2006). Possession of the condition is at least partially determined by one's genetic makeup, as studies have found higher rates of synesthesia within families containing at least one other synesthete, as high as 48.6% (Baron-Cohen et al., 1996).

One striking feature of synesthesia is the great multitude of different variations, not all of which are named. Grapheme-color synesthesia, which involves the association of colors with letters or digits, is estimated to be one of the most common forms of synesthesia. Chromesthesia is another well-known form of synesthesia, in which individuals associate colors with different musical notes and timbres. Lexical-gustatory synesthesia is a less common form in which individuals experience various tastes when they hear different words or phonemes. Rare individuals who experience a localized sensation of touch when witnessing another person touched are mirror-touch synesthetes. The plethora of various subtypes of synesthesia reflect the interconnected nature of sensory systems in the brain, and some researchers hypothesize that synesthesia results from abnormal connections between the areas that govern specific sensory modalities. How these connections come about is still a topic of debate, but there is evidence that they are formed during early development (Deroy & Spence, 2013; Spector & Maurer, 2013). Many users of psychedelic substances such as lysergic acid diethylamide (LSD) or psilocybin mushrooms report transient experiences of synesthesia, and there have been reports of users acquiring a permanent condition of synesthesia subsequent to their drug experiences (Brogaard, 2013; Ione & Tyler, 2004). However, most studies restrict their selection of participants to developmental synesthetes; those who report having had synesthesia at least since childhood.

## *Grapheme-Color Synesthesia*

Grapheme-color synesthesia, the focus of this thesis, is thought to be one of the most common forms of synesthesia. Individuals with this variety of synesthesia report associating colors with certain letters and/or digits to a high degree of specificity. For example, the letter ‘C’ may reliably elicit an experience of aquamarine for one person, but deep burgundy for another. In addition, many synesthetes have a letter or group of letters that lack any color association, such that their experience of those letters is identical to that of a non-synesthete. The prevalence rate of grapheme-color synesthesia among 2,847 randomly selected participants was found to be 1.2%, which may be a rough estimate of prevalence in the general population (Carmichael, Down, Shillcock, Eagleman, & Simner, 2015).

Most synesthetes report experiencing consistent color-grapheme associations, but no synesthete is exactly the same. For example, one synesthete in this study reported having more than one color association for a small subset of letters, such that they could change their color based on context. Another reported that several letters in the alphabet elicited colors non-existent on the visible light spectrum (this claim was taken with a grain of salt). In addition, strength and consistency of grapheme-color associations can vary greatly within a synesthete. When it comes to perceived color, some letters may be prone to taking on the hue of their neighbors when appearing in a word together; these letters are referred to as having inconsistent color associations. Letters can also vary in strength of association; some are simply more strongly or brightly colored than others.

To non-synesthetes, it is unclear what it is like to experience a grapheme-color association. Some assume that the experience of synesthesia is like seeing letters printed in color, but most synesthetes would disagree with this assessment. They say instead that letters evoke the idea of color, or that each letter is intimately tied to its associated color in their mind. However, this is not to say that all synesthetes have the same subjective experience of synesthesia. Among the population of grapheme-color synesthetes there are two distinct subtypes: projectors and associators. Projector synesthetes describe their synesthetic perceptions as physical reality, as if the letters on the page are truly printed in vivid color or imbued with a colorful aura. Associator synesthetes describe their associations as more mental than physical; they consistently think of or imagine the color blue when seeing the letter ‘T’ rather than literally seeing it on the page. Projectors are considerably more rare; among the 100 synesthetic subjects of one study, only 11 were judged to be projectors (Dixon, Smilek, & Merikle, 2004). It is unclear why projectors are less common, or why the reported experience of both groups is so different, but it may imply a between-group difference in the neural mechanisms underlying the synesthetic experience.

Little is currently known about the neural basis of grapheme-color synesthesia, but headway is being made through the use of brain imaging techniques. Synesthetes have been shown to possess increased grey matter volume in the fusiform gyrus and parietal cortex, as well as greater activation of V4 when viewing letter stimuli, though the latter result is debated (Hupé, Bordier, & Dojat, 2012; Jäncke, Beeli, Eulig, & Hänggi, 2009; Specht & Laeng, 2011; Weiss & Fink, 2009). In his 2007 review, Hubbard outlines the leading neural models of grapheme-color synesthesia. Cross-activation theory posits that there is an abnormally high level of connectivity between color processing area V4 and the visual word form area (VWFA) in synesthetes, due to a lack of neural pruning in prenatal development (Hubbard, 2007). In other words, genetic factors may result in a failure to sever specific neural connections between these two areas early in development, leading to the presence of grapheme-color synesthesia. An alternative explanation may be that synesthetic associations arise due to disinhibited feedback from sensory information hubs, a theory possibly supported by the fact that synesthesia-like effects can be caused by the ingestion of psychedelic substances (Grossenbacher & Lovelace, 2001). However, the similarity of subjective experience does not necessarily imply that the neural mechanisms are the same. More neuroimaging research is necessary before the substrates of grapheme-color synesthesia are evident, and it is one of the primary goals of the current study to determine the time window in which synesthetic color processing occurs in the brain using electroencephalography (EEG) techniques.

### *Electroencephalography and Event-Related Potentials*

EEG is a neuroimaging technique that records minute fluctuations in voltage generated by the brain activity of a live subject. Whenever a neuron in the brain fires, an event called an action potential, a tiny bit of electricity is generated and travels down the axon to the synapse, or the juncture at which information flows from one neuron to the next. If the sum of the signal coming from the pre-synaptic neurons is enough to excite a post-synaptic neuron to reach the depolarization threshold, this neuron will fire as well in an event called a post-synaptic potential (PSP). If a large enough number of similarly-oriented neurons emit PSPs simultaneously, indicating large-scale activation of a localized brain area, they create an electrical dipole that is measurable at the scalp by sensitive electrodes, thereby making EEG research possible (Luck, 2014). The neurons must be oriented in the same direction, or the resulting dipole will be too weak to be detectable; for this reason, EEG is typically recording the responses of pyramidal neurons in the cerebral cortex, which are always oriented perpendicular to the cortical surface and serve as the primary processors of information in the brain (Luck, 2014).

EEG has been used as a research technique in the field of psychology since the early 20th century, because it provides a useful tool for analyzing brain responses to a wide range of stimuli and responses. Event-related potentials (ERPs) refer to the voltage spikes generated by the burst of post-synaptic potentials following the presentation of a stimulus, or leading up to and following a motor response. In most ERP studies researchers present a stimulus many times and average the brain responses; the resulting plot of voltage vs. time is the ERP waveform, with stimulus onset at time zero. Different stimuli generate different patterns of neural activity, which in turn result in unique ERPs, allowing researchers to compare the ERPs generated by different types of stimuli and make conclusions about how the brain processes them. For example, comparing the ERPs generated by letters to those generated by false fonts, pseudo-letter shapes crafted from the same basic stimulus features, reveals a greater negative response to false fonts in the right occipital area of the scalp following about 170 ms after presentation (Appelbaum, Liotti, Perez, Fox, & Woldorff, 2009). Through finding differences like these and building on past research, researchers are able to unpack the brain piece by piece. However, no neuroimaging technique is perfect, and EEG can only access a small portion of the brain's ongoing processes at any given moment.

The primary benefits of the ERP technique are its high temporal resolution and its non-invasive nature. ERPs allow for the precise evaluation of the timing of different neural processes, the only non-invasive technique capable of rendering temporal data on the millisecond scale. The tradeoff is low spatial resolution; it is unfeasible in most cases to trace a neural signal to a particular brain region using EEG data. Imaging techniques with a higher spatial resolution, such as fMRI, can be used in tandem with ERPs to determine approximately when and where a neural signal originates. Invasive techniques such as single-unit recordings are necessary to achieve both high spatial and temporal resolution, but these techniques typically suffer from a lack of spatial coverage and a reason to risk opening up the skull. Single-unit recordings are typically only carried out with patients who are undergoing clinical brain surgery, and as a result only neurons in the relevant brain areas are available for recording.

One of the drawbacks of EEG recording is its low signal to noise ratio on a trial-by-trial basis, resulting in the necessity of many trials as well as a susceptibility to distortion of the data by artifacts. Artifacts are any electrical fluctuations that are not caused by neural activity; the primary sources of noise are muscle contractions, alpha-band oscillations, electricity generated by nearby electronics, and poor connections between the electrodes and the scalp. Muscle artifacts such as head movements, tension in the neck or jaw, and oculomotor artifacts such as blinks and eye movements can easily render EEG data unusable if they are present in large amounts. Alpha-band oscillations, referred to by most researchers simply as 'alpha', are synchronized ~10 Hz oscillations expressed primarily in occipital electrodes when one closes their eyes, or is otherwise feeling sleepy or disengaged. The prevalence of artifacts, along with the fact that neural signals are usually very small fluctuations in voltage (~1-10 μv), necessitates a large number of individual trials in a typical ERP experiment.

## *Experiment One: the Sensory Effect of Color*

Event-related potential (ERP) techniques have been underutilized in the study of synesthesia, and have great potential for revealing some of the neural mechanisms that contribute to synesthetic perception. Chris Graulty, from Reed's own psychology department, provided the first evidence for a sensory effect of color (SEC) in the ERPs of synesthetes exposed to uncolored letter stimuli. A positivity of roughly 1.2 μv was observed for letter stimuli when compared to false fonts in the time window of 170-230 ms following stimulus presentation and expressed near the top of the head in electrodes FC3, FCz, FC4, C3, Cz, and C4 (Graulty, 2015). Since all stimuli were physically uncolored, and synesthetes had color associations with letters but not false fonts, this difference was concluded to be related to the synesthetes' grapheme-color associations. Furthermore, the ERPs of control participants displayed no difference in the same time window, strengthening this argument. However, this evidence was collected in the context of an experiment designed to test the necessity of awareness for synesthetic perception, and thus was not optimized for analyzing brain activity related to color. The rapid presentation of stimuli in this paradigm (a new stimulus was shown every 100ms) creates difficulty in drawing conclusions about brain activity generated roughly 200 ms after stimulus presentation, at which point a new stimulus would already be present on the screen. At this point, early processing of the next stimulus would have begun, influencing the ERPs evoked by the previous stimulus.

The primary goal of experiment one was to test for the presence of the SEC in the ERPs of synesthetes presented with letter and false font stimuli in an unhurried and isolated manner. To isolate the SEC, brain responses to letter stimuli with synesthetic color associations were compared to stimuli from three other categories, in both synesthetes and matched control participants. The first stimulus category (to be abbreviated as syn-colored) was made up of physically uncolored letters which strongly and consistently elicit perceptions of color for each synesthete. The second category (phys-colored) was composed of the same letters, but each was physically colored according to each synesthete's specific color associations. The third category (syn-uncolored) contained physically uncolored letters that were known to not elicit any color experience for synesthete subjects and the fourth category contained physically uncolored false fonts, which also did not elicit color associations in synesthetes.

The primary comparison of interest regarding the SEC was between the syn-colored and syn-uncolored categories. For control participants, this is merely a comparison of the ERPs generated by letters to the ERPs generated by a different set of letters. These ERPs should be identical in most respects, perhaps with minor differences related to letter form. Since synesthetes perceive the first category as colored and the second category as uncolored, any systematic difference in the ERPs is necessarily color-related. If this theoretical difference was present in the ERPs of synesthetes but not those of controls, this hypothesis would be confirmed.

The other comparisons are as follows: comparing the syn-colored and false font categories should yield an SEC in synesthetes but not in controls, because synesthetes do not have color associations with false fonts. This comparison also makes the distinction between letter and non-letters, allowing for the assessment of any ERP differences related to letter form. Comparing the syn-uncolored and false font categories should reveal no color-related ERP differences, since there is no experience of color for either group when presented with these stimuli. Instead, the only differences should be those related to the letter/false font distinction. The final comparison, syn-uncolored vs. phys-colored, has multiple possibilities when considering the SEC. If the brain activity generated by viewing physical color is identical to that generated by a synesthetic color association, then one would expect to see an SEC for both groups with no between-group differences. It seems unlikely that this would be the case, given that the neural processes related to perceiving physical color and those that give rise to synesthetic perceptions are likely different. Since letters in the phys-colored category elicit color associations for synesthetes in addition to being physically colored, it is possible that these two distinct experiences of color would each elicit a unique color-related ERP component in synesthetes, resulting in a dissociation between a physical-SEC and a synesthetic-SEC. To sum up, the stimulus categories and key comparisons are as follows:

**Stimulus Categories:**

1. Synesthetically-colored letters (syn-colored, phys-uncolored)
2. Physically-colored letters (syn-colored, phys-colored)
3. Synesthetically-uncolored letters (syn-uncolored, phys-uncolored)
4. False fonts (syn-uncolored, phys-uncolored)

**Key Comparisons and Predictions for the SEC:**

| **SEC** | in synesthetes? | in controls? |
|---|---|---|
| syn-colored vs. syn-uncolored | **Y** | **N** |
| syn-uncolored vs. phys-colored | **Y** | **Y** |
| syn-colored vs. false fonts | **Y** | **N** |
| syn-uncolored vs. false fonts | **N** | **N** |

## *Attention and Synesthesia*

The necessity of attention and awareness in synesthetic perception is an unresolved debate, with diverging bodies of evidence pointing to opposite conclusions. Some researchers believe that focused, top-down attention is necessary for synesthetic perception. This would support a feedback theory of synesthesia, in which letter and color percepts are combined after the visual system has fully processed the letter stimulus. The opposing camp argues that synesthetic associations are processed pre-attentively, which would support a bottom-up or feedforward, stimulus-driven model of synesthesia. When speaking about attentional processes the phrase ‘top-down’ refers to attention that is consciously driven; when one makes the decision to focus on a stimulus, they are orienting their attention in a top-down manner. On the other hand, bottom-up orienting refers to when one’s attention is forcibly captured by an external stimulus, such as a loud noise or a bright flash. When it comes to synesthesia, the question is whether one needs to consciously focus (top-down orienting) on an eliciting stimulus to experience the grapheme-color association, or whether the association can draw attention (bottom-up orienting) to said stimulus.

A number of case studies of grapheme-color synesthetes have concluded that synesthetic color associations are processed pre-attentively, and can subsequently guide the focus of attention (Palmeri, Blake, Marois, Flanery, & Whetsell, 2002; Smilek, Dixon, & Merikle, 2003). This evidence comes primarily from visual search paradigms in which the synesthetic subject was able to consistently locate the target more quickly than control subjects on the basis of its elicited color perception. Visual search arrays used in these studies consist of a unique target grapheme amongst a group of distractor graphemes and participants are given the simple task of finding the target, indicating via manual response when they find it. The primary hypothesis is that synesthetes will find the target faster because the stimuli are imbued with color, effectively turning a serial search into a pop-out. In a serial search, the target has no physical stimulus features that stand out, necessitating a strategy of focusing on each object in turn to classify it as target or distractor. In a pop-out search, the target stimulus is immediately distinguishable from the distractors, no matter the number of items in the search array.

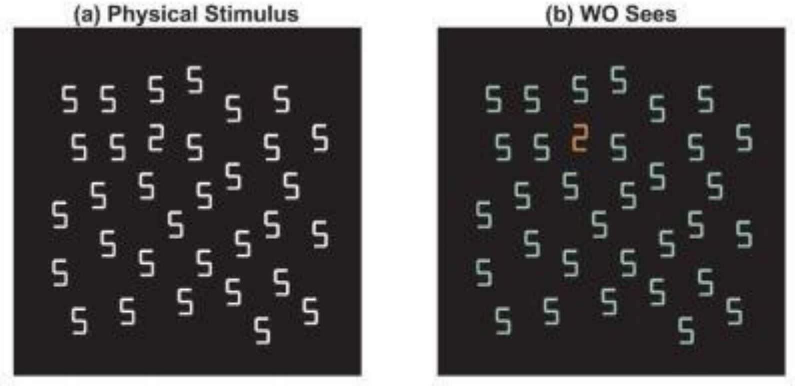

Figure 1: Serial vs. pop-out search

Figure 1 is a representation from Palmeri et al. (2002) of what the same search array might look like for a synesthete (right) and for a non-synesthete (left). In an array of similar looking characters like these, non-synesthetes would be forced to resort to a serial search strategy, while synesthetes may be able to use the additional stimulus feature of color to find the target (a red 2 amongst blue 5's) much more quickly. This hypothesis is predicated on the theory that synesthetic perception is a bottom-up process, independent of top-down factors such as conscious attention. In case studies such as Palmeri et al. (2002) and Smilek et al. (2003), this is exactly the conclusion. Palmeri et al. (2002) found a difference between the search slopes of a synesthete and controls (see figure 2).

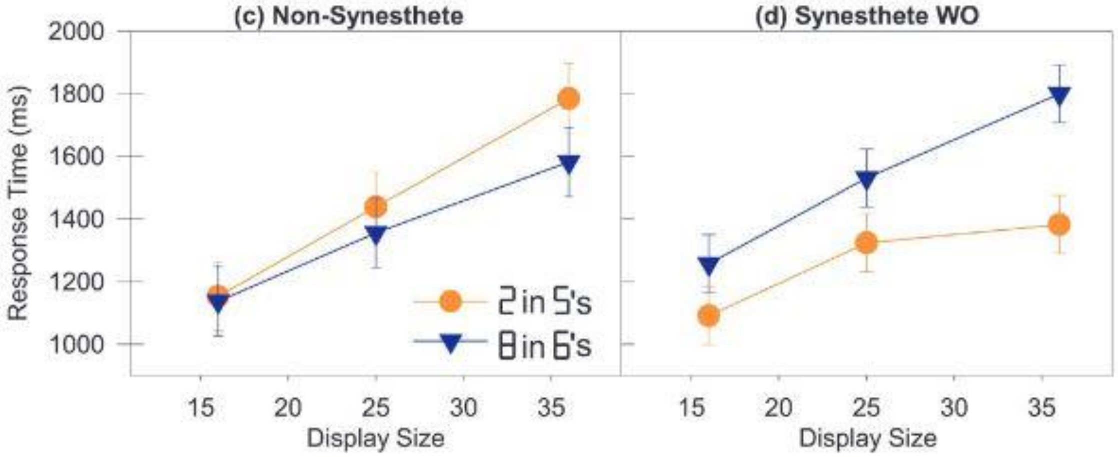

Figure 2: Palmeri et al. (2002) results

In visual search paradigms, the search slope shows how reaction time changes as a function of set size. A linearly increasing search slope indicates that reaction time increases at a constant rate when more items are added to the search array, a sure sign of serial search. In contrast, a flat search slope indicates a perfectly pop-out search because the target is immediately obvious regardless of the number of distractors, resulting in roughly the same reaction time across different set sizes. It is important to note when considering figure 2 that the digits 2 and 5 are different colors (orange and blue, as shown in figure 1) for synesthete WO, while 6 and 8 are the same (both blue). Both search slopes increase linearly for control subjects, indicating a serial search. Unsurprisingly, WO’s synesthesia conferred no benefit when searching for an 8 among 6’s, because the array appeared uniformly-colored. However, searching for an orange digit amongst blue digits produced a search slope that is not entirely flat, but not linear either. This within-subject comparison clearly indicates that WO’s synesthesia played a role in visual search performance, while the between-subject comparison verifies that this difference was not due to simple stimulus features. Smilek et al. (2003) carried out a similar procedure with a synesthete “J” and seven controls, albeit with a methodological twist. They used the digits 2 and 5 as targets, and the characters 0, (, and # as distractors, which did not elicit synesthetic photisms for J. They varied the number of distractors between six, twelve, and eighteen, and each display was a balanced mix of each distractor character. The key manipulation for this study was background color, which was varied to be either congruent or incongruent with J's synesthetic color association with the target. The subsequent search slopes for J and controls, shown in figure 3, look very similar to the results of Palmeri et al., in that control performance in congruent and incongruent conditions is virtually identical, while J's performance was markedly better in the incongruent condition. In addition, J's responses were generally faster than those of controls, but this result is not addressed in the paper and it is unclear whether J's synesthesia is a factor. One of the benefits of case studies is that the stimuli can easily be tailored individually for the synesthete subject. However, it is difficult to make sweeping statements about the nature of synesthesia as a whole based on the results of one or two synesthetes.

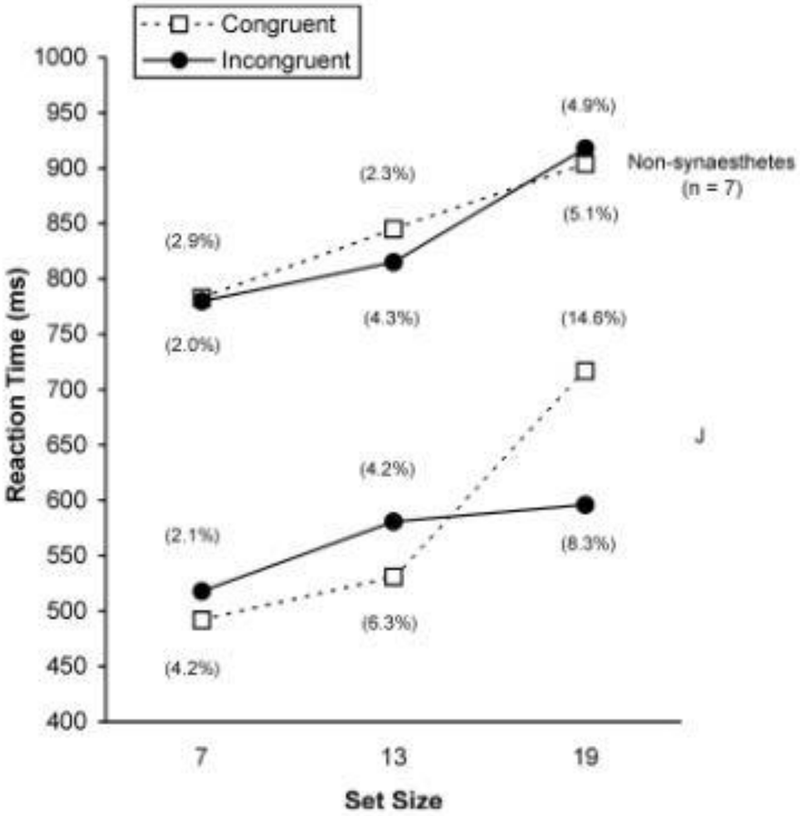

Figure 3: Smilek et al. (2003) results

Group experiments with synesthetes have attempted to address the problems inherent in a case study approach, but in doing so have come to the opposite conclusion:

that is, synesthesia appears to confer no significant advantage on visual search performance, implying that synesthetic perception requires attention. In other words, they argue that synesthetic perception is a top-down process, requiring feedback from higher-order perceptual areas to ‘edit’ the incoming sensory information and add the experience of color. Several studies used variations of a visual search task with a group of synesthetes and matched controls, and each found no difference between groups in reaction times or accuracy (Brogaard, Marlow, & Rice, 2015; Edquist, Rich, Brinkman, & Mattingley, 2006; Rothen & Meier, 2009). These results imply that synesthetes, like controls, must employ a serial search strategy to find the target, and only once it is found does it elicit an experience of color. Rothen & Meier report that three of thirteen synesthetes outperformed controls on the visual search task, which was not enough to influence the average but when taken individually their results are comparable to those of previous case studies. They offer the tentative explanation that some synesthetes have an advantage in visual search and others do not. If this is true, it may be the case that particular synesthetes attracted the attention of researchers and subsequently became the focus of case studies, causing a selection bias.

Graulty (2015) utilized electroencephalography (EEG) and an attentional blink paradigm to approach the question from a different perspective. In this task, participants were given two target stimuli to identify amidst a rapid stream (~100 ms each) of distractors. The attentional blink is a brief window of time, roughly 200-500 ms following presentation of a target stimulus, during which stimuli are not consciously perceived. As a result, if one of the targets is presented in this window, participants will not be able to report seeing it. Graulty presented letter and false font stimuli to synesthetes in this paradigm and discovered a systematic difference between the event-related potentials (ERPs) generated by each stimulus category in synesthetes that was not found in control subjects. He concluded that this ERP component was the sensory effect of color (SEC), generated by the synesthetes’ grapheme-color associations. Notably, the SEC was absent in ERPs generated by stimuli presented during the attentional blink. Graulty subsequently concluded that for a grapheme-color association to be perceived, the synesthete must first focus on the stimulus. This result reinforces the conclusion of previous group studies that synesthetic associations are generated late in sensory processing and require focused attention.

There exists a middle road between the two extremes of the aforementioned conclusions: one case study found that a synesthete was faster at locating a target than controls, but only when the target was relatively close to the location of initial fixation (Laeng, Svartdal, & Oelmann, 2004). Given the conflicting nature of the existing literature, it seems that convincing evidence has yet to be put forth for either side, especially since there are difficulties in the methodology of both sides. Drawing conclusions from a case study is an inherently risky prospect, considering the sample size of one. There may also have been a selection bias toward projector synesthetes with strong associations, as they could have attracted the attention of researchers. On the other hand, group studies suffer from the frustrating challenge of creating a task that is equivalent for every member of a group of synesthetes, considering the diversity between subjects in the color and strength of associations.

## *Experiment Two: Visual Search and the N2pc*

The second experiment in this thesis is an attempt to answer the question regarding the necessity of attention for synesthetic perception, this time utilizing ERP techniques to gain a new perspective. The N2pc is an ERP component elicited by the attentional selection of a target amongst distractors, and serves as a useful non-behavioral index of the latency to locate a target in a visual search array. The name refers to the fact that it is a negativity observed at about 200 ms at the posterior of the head and contralateral to the target. When the target appears in the right visual field, the N2pc is a small negative deflection in voltage appearing on the left side of the back of the head, visible when comparing data from electrodes contralateral (opposite side) and ipsilateral (same side) to the visual hemi-field in which the target appears (Luck, 2014). To date, no study has examined the N2pc component of synesthetic participants in a visual search task. Experiment two utilizes a special visual search paradigm for ERP studies, in which items are laid out in a circle equidistant from the point of fixation. Each visual search array is composed of a unique target amongst a group of heterogeneous distractors. If synesthetic perception is pre-attentive, then synesthetic participants may display some combination of faster reaction times, a shorter latency N2pc, or a higher-amplitude N2pc. If attention is required for synesthetic perception, then the N2pc components and behavioral indices of synesthetes and controls will be identical. Given the mixed nature of previous results, it is difficult to predict which of these outcomes will be observed. Based on the outcome of most group studies, a likely hypothesis is that no differences will be observed between groups. However, this may simply be due to a failure of previous studies to effectively tailor their stimuli to each synesthete, thus muddying the results. In the present study, steps were taken to individually tailor the stimuli to each synesthete and their matched control.

# Methods

## *Participants*

Participating in this study were 11 grapheme-color synesthetes (eight female) and 11 matched control subjects. All subjects were aged 18-25 (M = 20) and all were undergraduates or recent graduates from Reed College in Portland, Oregon. Control subjects were matched to each synesthete based on age and biological sex. One synesthete was excluded due to an insufficient number of trials remaining after artifact rejection in both experiments, leaving a participant pool of 10 synesthetes and 10 controls. Furthermore, two synesthetes were excluded from analysis in experiment one because they reported experiencing color associations with the false font stimuli, and one synesthete was excluded from analysis in experiment two due to excessive eye movement artifacts. After all exclusions, eight pairs were useable for analysis in experiment one, and nine pairs in experiment two. All participants completed the Eagleman synesthesia battery to verify synesthetic status before participation. All synesthetic participants met requirements for grapheme-color synesthesia, and all control participants did not. Based on the test results, 10 synesthetes were determined to be associators, and one was a projector. Prior to participation all subjects gave informed consent, and were paid a total of $30 for their participation. This project was approved by the Reed College Institutional Review Board (IRB).

### *Stimuli*

The stimuli were black letters, colored letters, and black false fonts. During experiment one, letters were presented in 250pt Myriad Pro font at the center of fixation. False fonts were created from 250pt Myriad Pro font letters by scrambling the letter components. Four stimuli were chosen for each stimulus category in experiment one (syn-colored, syn-uncolored, phys-colored, and false fonts), forming a set of 16 stimuli presented to each synesthete and matched control in experiment one. Figure 4 shows an example stimulus set used in this experiment.

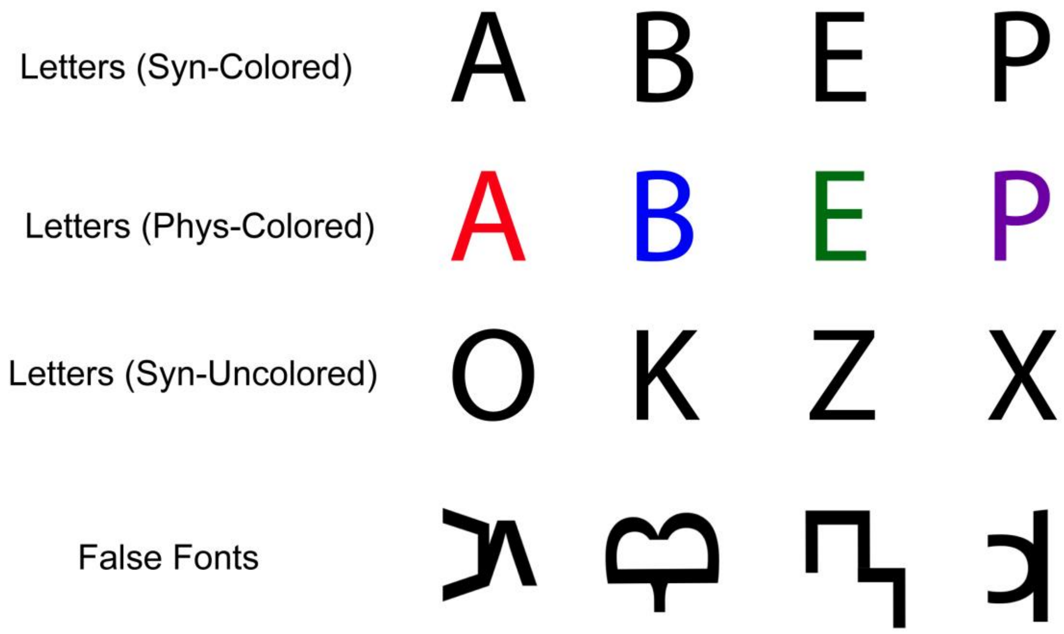

Figure 4: Experiment One Stimulus Categories

In experiment two, each visual search array was composed of eight letters arranged in two symmetrical arcs around a fixation cross at the center of the screen, with none of the letters appearing on either the vertical or horizontal midline. Figure 5 is an example of a visual search array used in this study (left), along with a representation of how the search array might appear to a synesthete (right; note that in this experiment none of the letters were ever physically colored). The array on the right is not meant to be an accurate reproduction of the synesthetic experience; it merely suggests how the task might change with the added dimension of color. In this particular example, the target letter was 'R', which the synesthete strongly associated with the color red. In theory, the color red becomes an additional stimulus feature to use in visual search, making the task easier for the synesthete.

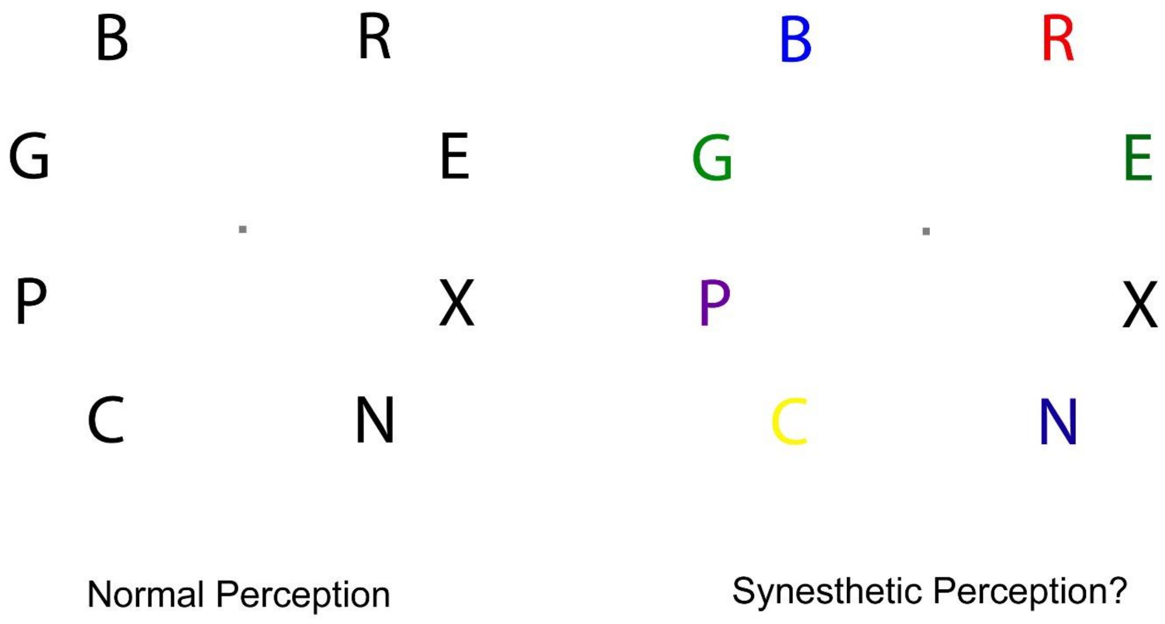

Figure 5: Search Array

The arrays were arranged in a manner such that each stimulus was equidistant from the fixation point, so that no stimulus position was more visually accessible than any other. Nine letters were chosen for each synesthete based on color and strength of association as well as similarity of form, eight of which were subsequently used to create each search array. Two letters were chosen as targets such that both elicited photisms within the same color category, which was always either red, green, or blue for consistency and to ensure . Seven distractor letters were chosen to be in different color categories than targets. For example, targets might be selected for a given synesthete because they both elicit the color red, and seven distractors would be chosen such that none of them also elicit an experience of red. Each search array was composed of one of the two targets along with the seven heterogeneous distractors. The identity of the target and the positions of the target and distractors were randomized from trial to trial, such that over the course of the experiment each target appeared an equal number of times and had an equal chance of appearing in all eight positions.

All stimuli were created and presented using Presentation software with the exception of the false font stimuli, which were created in Adobe Illustrator. Specific letters and false fonts were changed accordingly with each individual synesthete's strength of association, and shades for the colored letters were selected to match each synesthete's perception. Control participants were exposed to the same stimuli as matched synesthetic participants.

## *Procedure:*

### **Session One:**

This study was composed of two separate sessions, the first of which required participants to complete the Eagleman synesthesia battery as well as a color-matching task to gather detailed information about each synesthete's color associations. At the beginning of the first session, participants signed an IRB-approved consent form and had their heads measured in advance for EEG recording in the second session. The Eagleman synesthesia battery is an online test that requires participants to match each letter of the English alphabet as well as the digits 0-9 to their specific color association a total of three times in a randomized order.

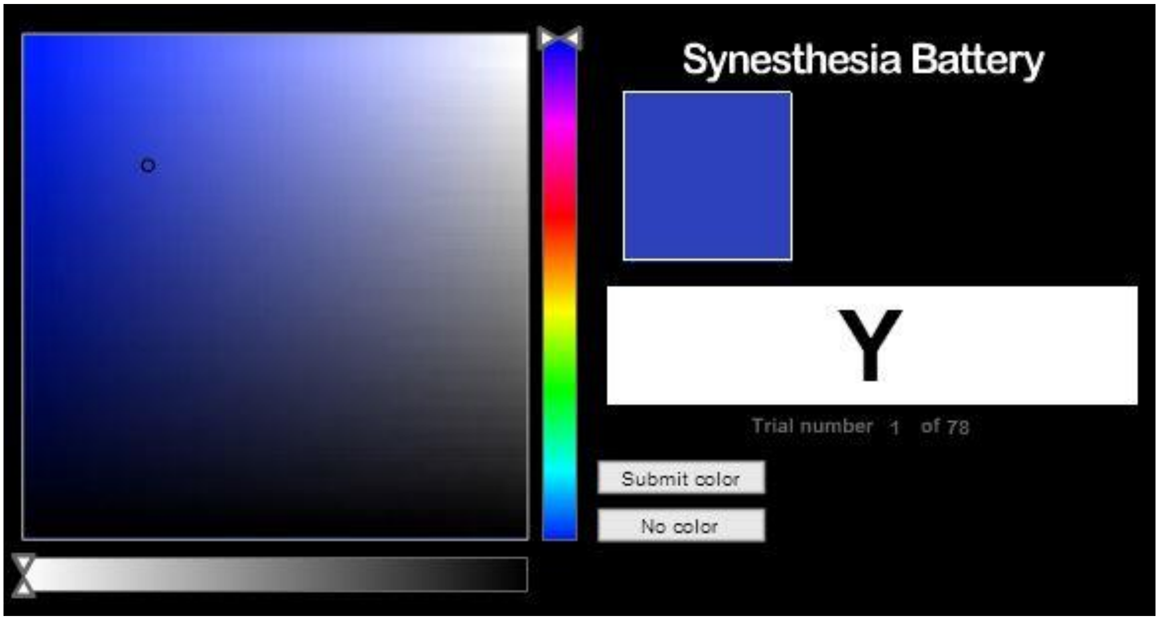

Figure 6: Grapheme Color Picker

Figure 6 shows an example trial from the grapheme color picker task in the Eagleman synesthesia battery, in which synesthetic participants can adjust the hue and luminance of a two-dimensional color space to match their color associations. Upon completion of this task participants are given a score that corresponds to the consistency of their color selections, where scores of 1.0 or below are indicative of synesthesia. Figure 7 is an example of performance by a synesthete (right) and a non-synesthete (left), where shorter bars indicate higher consistency of color selection.

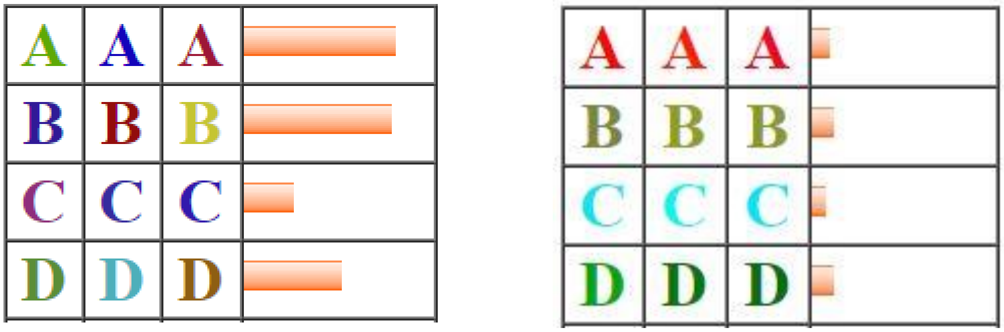

Figure 7: Eagleman Synesthesia Battery Results

The second part of the test is a speed-congruency test, in which colored letters appear on the screen for one second each, and participants are required to indicate whether the color of the letter matches their association for that letter. Synesthetes typically display an accuracy of 85% or higher for this task, whereas non-synesthetes score closer to 50%. Although not directly related to synesthesia, the creators of the synesthesia battery included the vividness of visual imagery quotient (VVIQ) test to assess the correlation (or lack thereof) between synesthesia and vividness of visual imagery. The VVIQ comprises a series of questions asking participants to visualize or imagine a scene, and rate the vividness of different aspects on a five-point scale.

The last portion of the Eagleman synesthesia battery is a projector-associator test, which is intended to classify synesthetes as either associators or projectors. Participants respond to various statements relating to their subjective synesthetic experience on a five-point Likert scale (for example, participants can indicate whether they agree or disagree with a statement such as ‘I see my synesthetic associations as physical color on the page’). Based on the responses this test returns a numerical score, where a negative score indicates an associator and a positive score indicates a projector.

After completing the Eagleman synesthesia battery, participants were asked to complete an online questionnaire designed to collect more detailed data about each participant’s associations. The survey presented each letter of the English alphabet one by one, as well as two different false fonts corresponding to each letter, and required participants to select their color associations for each letter in a full-range digital color palette as well as indicate their strength and consistency of association on a three point scale. This task was designed to allow the experimenter to most effectively choose the letters for use in session two. Two versions of each false font were designed, so in case a synesthete indicated that one elicited a color association a second was available as back-up. This test was useful because there is no way to indicate either the strength or consistency of association in the synesthesia battery, which was key for individually selecting stimuli for each participant. Stimuli were chosen to maximize overall strength and consistency of association.

### Session Two:

When participants arrived for session two they were fitted with a 64-electrode EEG cap and seated in a sound-attenuated booth at an approximate distance of 70cm from a computer monitor. They completed two tasks run in the same order for each participant. The first task was a one-back task, in which participants viewed a semi-random stream of letters and false fonts and were required to press a target button whenever the same stimulus appeared twice in a row. Stimuli were presented at the center of a white background for 500 ms each, with an inter-stimulus interval (ISI) that varied randomly between 400-600 ms. Participants were instructed to fixate on a small cross in the center of the screen for the duration of this procedure. Each of the 16 stimuli in experiment one were presented an equal number of times, and each block contained one one-back trial for each stimulus. In addition, stimuli in the syn-colored and phys-colored categories were not allowed to follow one another (e.g. red 'A' following uncolored 'A'), in order to avoid confusion about the task. Each block contained 128 trials, 16 of which were one-backs (12.5%), and participants each completed a total of six blocks with a short break programmed at the end of each block. The first block served as practice and neither responses nor EEG data were recorded. Trials on which the participant responded were rejected, leaving five blocks and a maximum of 560 trials useable for data analysis, 140 trials per condition.

Upon completion of the one-back task participants were given a longer break before completing the visual search task. On each trial in this task, participants located and reported the identity of the target letter by pressing one of two buttons with their right index or middle finger, each of which corresponded to one of the two targets. The search array remained on the screen for 3000ms or until a response was made, and blank ISIs varied from 800-1200ms. There were a total of six blocks of 96 trials each, with a short break half-way through and at the end of each block. The first half-block served as practice, leaving 528 trials useable for data analysis. All trials on which the participant made an incorrect response (indicated the wrong target) were excluded from analysis, which was typically 2-5% of trials.

After completing the visual search task, participants were disconnected from the EEG recording system and paid for their participation.

### *EEG Recording*

EEG data was collected from 64 electrode sites on the scalp, distributed equidistantly on the scalp in a custom electrode cap (EASYCAP). Figure 8 displays an overhead view of the electrode distribution, with the front of the head facing up.

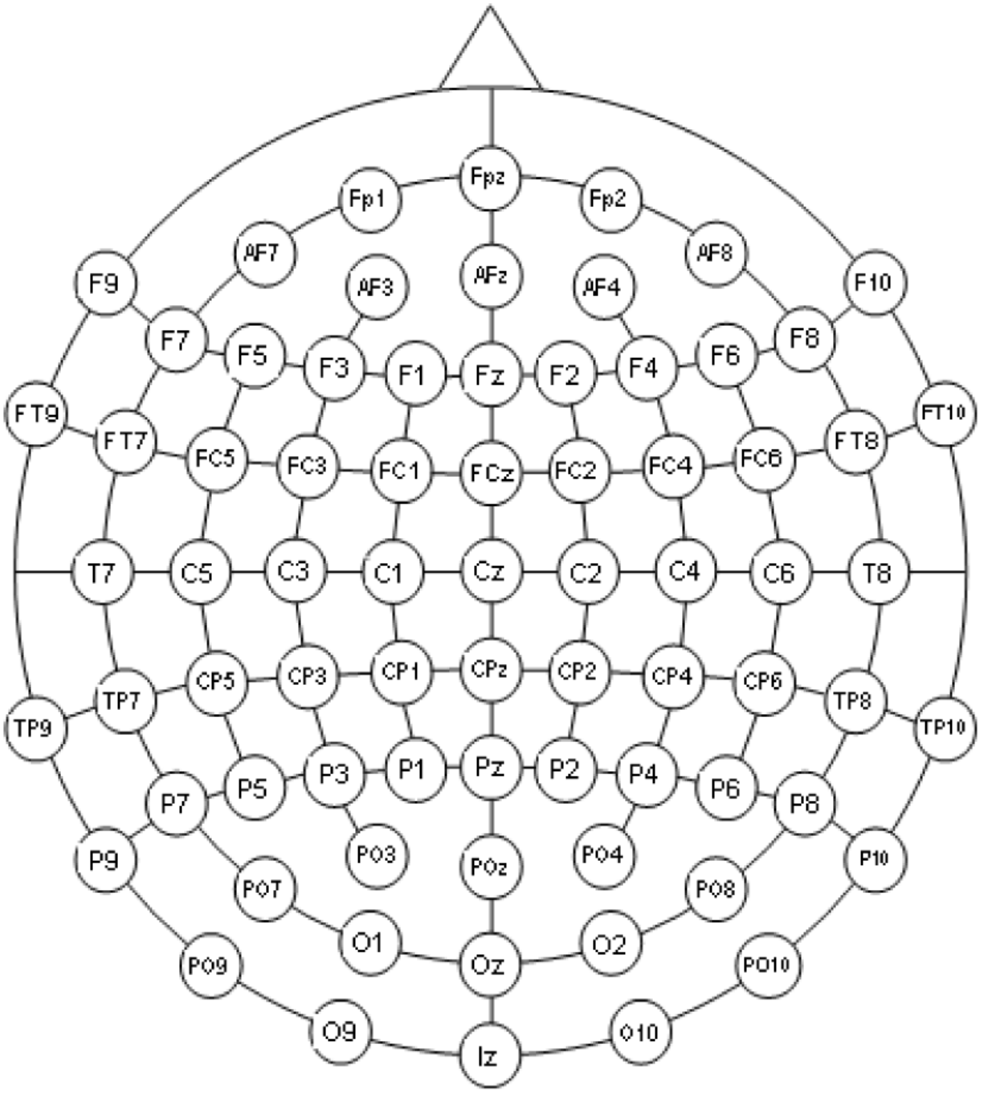

Figure 8: Electrode Distribution Map

The actiCAP electrode system, manufactured by Brainproducts, recorded continuous voltage data from all 64 electrode sites throughout the experiment. Electrode impedances were kept below 50 kΩ at all times through the use of a high-viscosity electrolyte gel (SUPERVISC), which forms a conductive bridge between the electrodes and the scalp. A blunt-tip needle was used to apply the gel individually to each electrode, as well as slightly abrade the scalp and brush any hair out of the way. Signals gathered by the electrodes were routed through a set of amplifiers (BrainVision Professional BrainAmp) and digitized at a rate of 500 Hz before being saved to the recording computer. Data was recorded using BrainVision Recorder software, which was monitored by the experimenter outside the recording booth. Participants completed the experiment in a dimly-lit, sound-attenuated booth (Industrial Acoustics Company, Inc.) to minimize contact with external stimuli. Oculomotor artifacts were detected with an electrode placed under the left eye (for blinks) and electrodes lateral to each eye (for eye movements). Participants made responses using a Cedrus RB-830 button pad.

### *Data Analysis*

EEG data was analyzed using the BrainVision Analyzer software. Electrode channels were referenced to FCz during recording, and re-referenced to the average of the right and left mastoids, located behind each ear, before analysis. Artifact rejection was completed semi-automatically and voltage thresholds were set on a participant-by-participant basis for each type of artifact (blinks, eye movements, and miscellaneous noise). Any trials in which voltage fluctuations exceeded the threshold were flagged and discarded.

Of all valid trials, an average of 11.8% had to be discarded in experiment one, and 19.6% in experiment two due to the presence of eye blink, eye movement, or muscle artifacts.

# Results

## *Eagleman Synesthesia Battery*

All synesthetes completed the online Eagleman synesthesia battery and reached criteria for possession of grapheme-color synesthesia except for one special case, which is described below. All matched control participants subsequently completed the battery to verify their statuses as non-synesthetes. The mean synesthetic score on the grapheme color picker task was 0.62, and the mean non-synesthetic score was 2.50. Mean accuracy on the speed-congruency test was 91.88% for synesthetes, and 56.17% for controls. Mean reaction time on the speed-congruency test was 1.49 seconds for synesthetes and 1.43 for non-synesthetes. Mean score on the VVIQ test for synesthetes was 3.80 and 3.24 for controls. It is important to note that one synesthetic participant received a score of 1.1 on the grapheme color picker task, which ranks as non-synesthetic according to the battery. This participant reported that a select few graphemes held multiple color associations (for example, the letter 'M' could appear either purple or green), leading to a lower consistency of performance at the task. However, this participant scored above the accuracy threshold of 85% on the speed-congruency task, and was counted as a synesthete for the purpose of the study. The experimenter was careful to avoid using stimuli for which this participant had inconsistent color associations.

## *Experiment One*

EEG data from eight synesthetes and eight matched controls were analyzed for experiment one. ERPs were time-locked to stimulus onset, and trials on which the participant responded at all (correctly or incorrectly) were discarded, to avoid influences due to motor responses as well as task-relevance of the one-back stimuli.

To test for ERP differences related to the neural processing of synesthetic color perception, amplitude data from electrodes Iz, Oz, O1, O2, and POz were first averaged across the time interval of 110-150 ms. The time window was selected based on a grand average of all 16 participants across all four stimulus categories, and the electrodes were selected based on a difference map (similar to those pictured in figure 10) of the chosen time interval, hence time-window and electrode selection were orthogonal to the effects of interest. Data were submitted to a 2x4 mixed-model ANOVA comparing group (synesthetes vs. controls) and stimulus category (syn-colored, phys-colored, syn-uncolored, false fonts), which found no significant main effect of group ( $F(1,14) = 2.22$, $p = 0.16$ ) or stimulus ( $F(3,42) = 1.54$, $p = 0.22$ ), and no significant interaction ( $F(3,42) = 1.00$, $p = 0.40$ ). However, both main effects are trending toward significance, which could be reached with more participants.

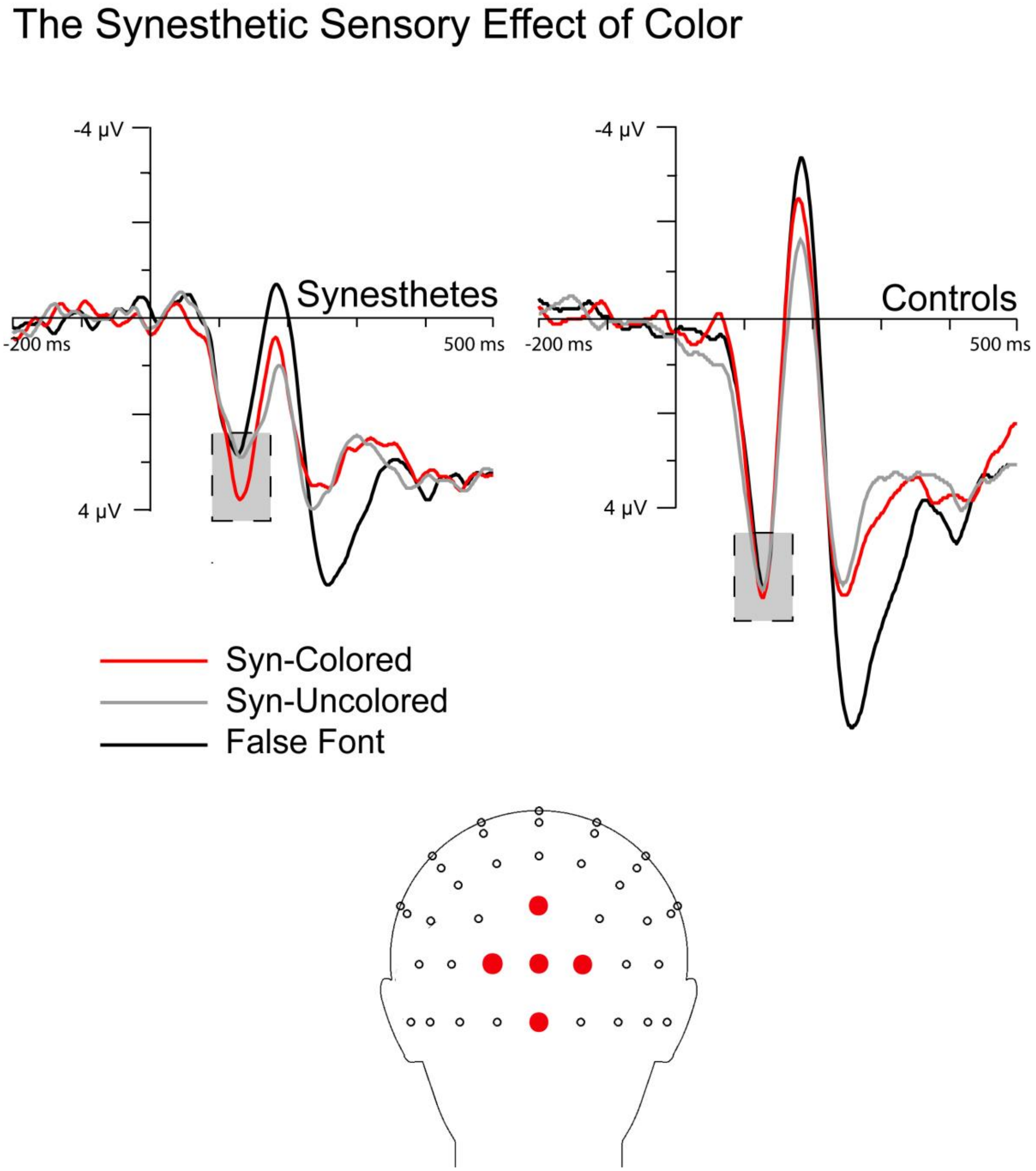

Figure 9: The Synesthetic Sensory Effect of Color (SSEC)

The effect of interest is highlighted in both groups by the solid grey box. Note that in the ERPs of synesthetes, there is a positive deflection for syn-colored stimuli that is absent for both other stimulus categories, which do not elicit any color-grapheme associations. In the ERPs of controls the difference collapses, suggesting that this positivity is related to the neural processing of grapheme-color associations in synesthetes.

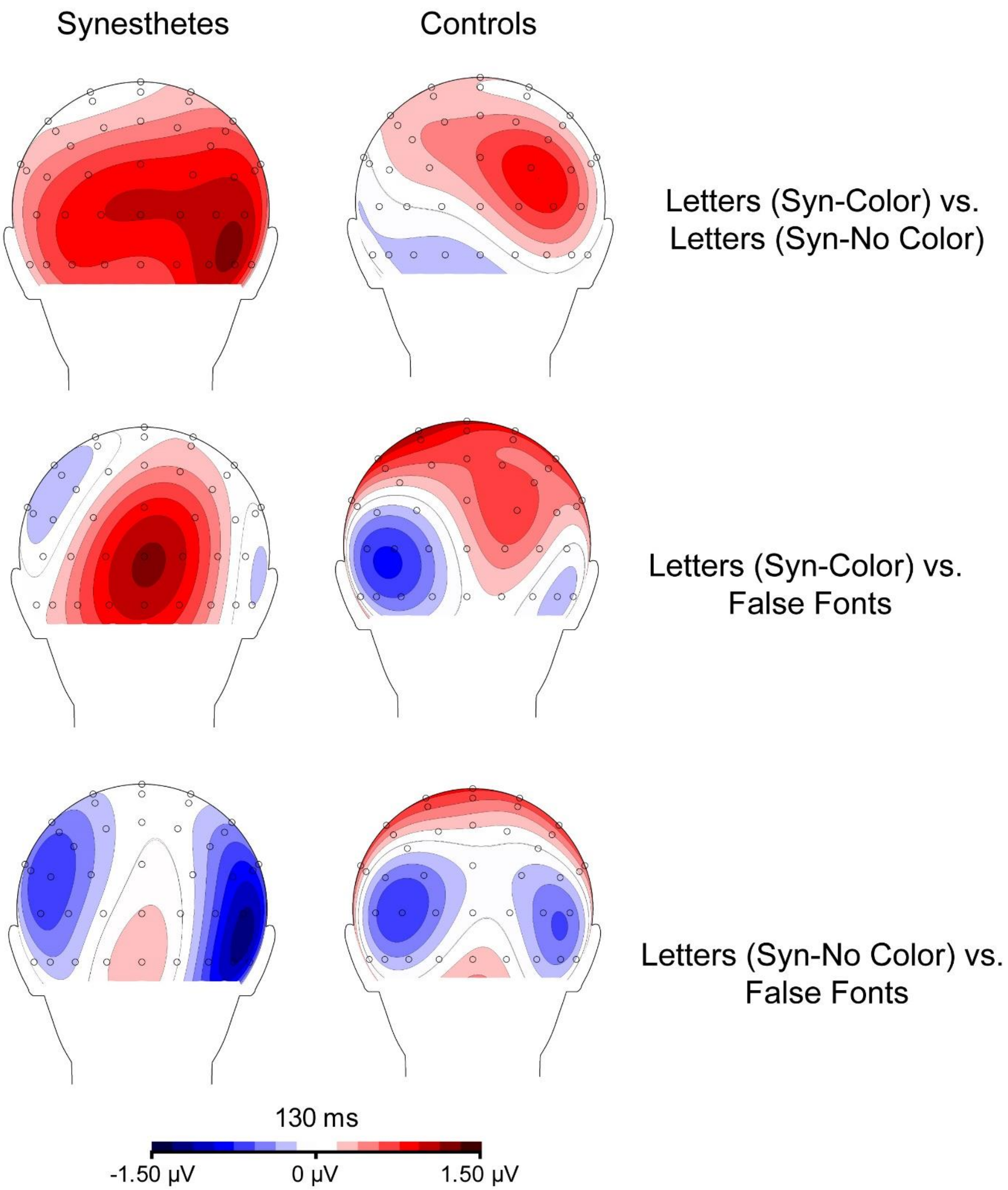

Figure 10: SSEC Difference Maps

These difference maps (the ERPs in one category subtracted from the ERPs in another) show three unique stimulus category comparisons in synesthetes and controls at 130 ms post-stimulus presentation. Each map represents the back of the head, and small circles represent electrodes on the scalp, affording a localized view of all ERP differences.

Figures 9 and 10 display the ERP results from experiment one. As shown in figure 9, a small positivity of about 1 μv was observed in the time window of 110-150 ms in synesthetes' ERPs generated by stimuli in the syn-colored category when compared to the syn-uncolored and false font categories. This positivity was entirely absent in the ERPs of control participants. The displayed ERPs are pooled averages of the data collected from electrodes IZ, OZ, O1, O2, and POZ, as shown by the highlighted dots on the scalp map. Figure 10 shows the individual comparisons of each condition pair as difference maps for synesthetes and controls taken at 130 ms. The positivity is clearly visible in red at the center of the occipital view in synesthetes in the syn-colored vs. false font comparison, and to a lesser extent in the syn-colored vs. syn-uncolored comparison. It is unclear why there is a right posterior positivity in this comparison for both synesthetes and controls, but it may be related to shape differences between the letters in each category and would likely disappear with a larger sample size.

The N170 false font negativity was exhibited in the time window of 170-210 ms for both groups when comparing letters to false fonts. The difference maps in figure 10 clearly show the beginning of this effect, in the form of a negativity appearing on both sides of the back of the head in comparisons involving false fonts. The difference is shown more clearly in figure 11, which displays a grand average ERP of all participants taken from the average of electrodes PO7 and PO8. The false font effect is clearly visible as a greater negative deflection in the ERPs generated by false fonts when compared to the ERPs generated by letters in the time window of 170-210. When submitted to a 2x4 mixed-model ANOVA comparing N170 amplitude in group (synesthetes vs. controls) and stimulus category (syn-colored, phys-colored, syn-uncolored, false fonts), a significant main effect of stimulus category was found ( $F(3,42) = 19.47$, $p < 0.01$ ), with no significant main effect of group ( $F(1,14) = 0.69$, $p = 0.42$). Subsequent paired t-tests found significant amplitude differences between the ERPs generated by stimuli in the false font ($M = -3.83$ μv, $SD = 4.13$) and syn-colored ($M = -1.15$ μv, $SD = 3.52$) categories ( $t(15) = -6.68$, $p < 0.01$ ), the false font and phys-colored ($M = -1.20$ μv, $SD = 3.31$) categories ( $t(15) = -4.54$, $p < 0.01$ ), and the false font and syn-uncolored ($M = -0.52$ μv, $SD = 3.24$) categories ( $t(15) = -7.27$, $p < 0.01$ ), thereby showing that in the time window of 170-210 ms the amplitude of the ERPs generated by false font stimuli was significantly different than the amplitude of those generated by letter stimuli, confirming the results of Appelbaum et al. (2009).

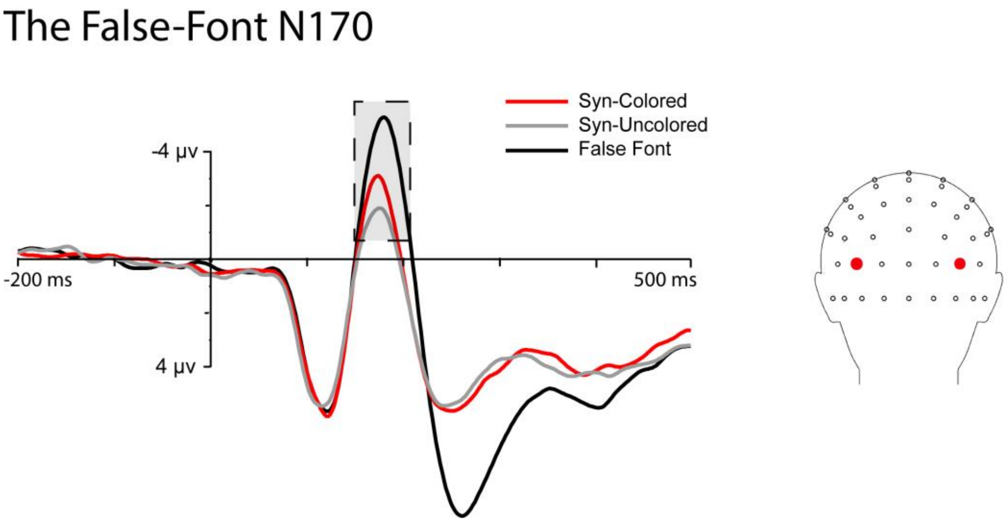

Figure 11: False Font N170

This figure shows the grand average ERPs of all 16 participants, with the N170 effect highlighted by the grey box. This effect manifests as a greater negative deflection in the ERPs evoked by false font stimuli starting at about 170 ms.

## *Experiment Two*

EEG and behavioral data from nine synesthetes and nine controls were analyzed for experiment two. ERPs were time-locked to stimulus onset, and trials in which the participant made an incorrect response (by way of indicating the wrong target) or failed to respond were discarded.

Contrary to the results of previous group studies, the reaction times of synesthetes (M = 597.18, SD = 158.67) were found to be significantly faster than controls (M = 812.18, SD = 82.53) when submitted to an independent-means t-test ( $t(16) = -3.61$, $p < 0.01$ ). Synesthetes (M = 96.7%, SD = 0.05) and controls (M = 98.3%, SD = 0.01) were equally accurate at reporting target identity. Individual and group reaction time data are shown in figure 12.

Figure 13 displays the key results regarding the N2pc. The displayed waveforms were pooled averages based on data collected from electrodes P3, P4, P5, P6, P7, P8, PO3, PO4, PO7, and PO8, with locations highlighted on the accompanying scalp map. The difference waves in figure 12 directly compare the N2pc components of synesthetes (red) and controls (black). Each difference wave is a representation of the contralateral waveform minus the ipsilateral waveform for each group. When superimposed, it is apparent that the N2pc component in synesthetes has both a slightly greater amplitude as well as a shorter latency than that of controls.

Both groups displayed a significant N2pc component in the typical 200-300 ms time window when submitted to single-sample t-tests (Synesthetes: $t(9) = -3.59$, $p < 0.01$, Controls: $t(9) = -3.55$, $p < 0.01$). When submitted to a one-way ANOVA, no significant differences in N2pc amplitude were found between synesthetes ($M = -1.04$ μv, $SD = 0.59$) and controls ($M = -0.69$, $SD = 0.42$) ( $F(1,16) = 1.05$, $p = 0.32$ ). In order to test for differences in N2pc latency the data were submitted to a 50% peak latency measure. The time at which the N2pc amplitude reached half its peak value was compared between synesthetes ($M = 247.33$ ms, $SD = 31.48$) and controls ($M = 250.22$ ms, $SD = 20.94$) in an independent means t-test, and no significant difference was found ( $t(16) = -0.23$, $p = 0.82$ ). Given the small effect size and the low number of participants, this result is unsurprising. With a larger participant pool, it is possible that differences in N2pc amplitude and latency could reach significance.

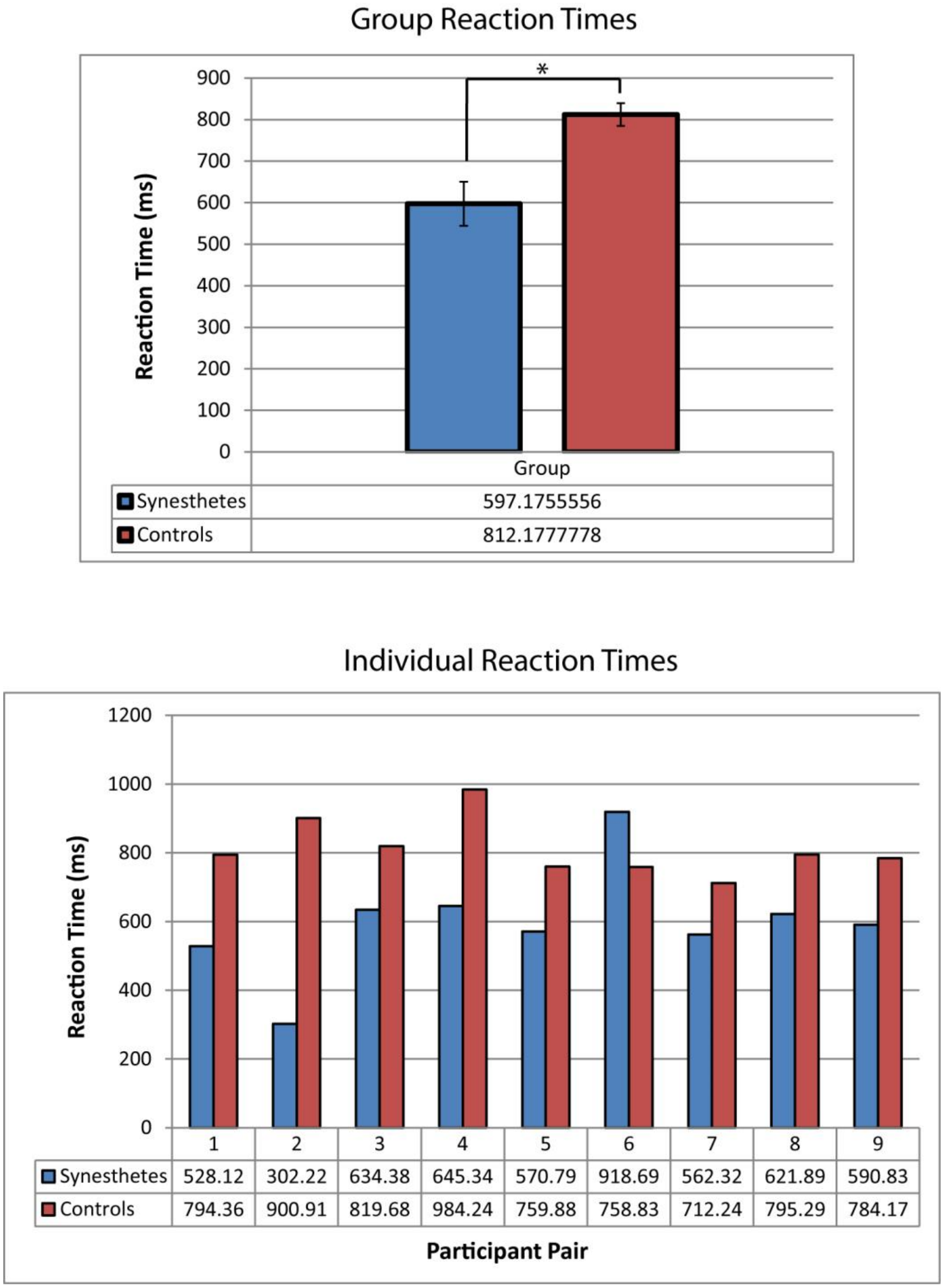

Figure 12: Experiment 2 Behavioral Results

Bar graphs displaying average reaction time data between groups (top) and between individuals (bottom), clearly illustrating the advantage held by synesthetes in the visual search paradigm used in this study.

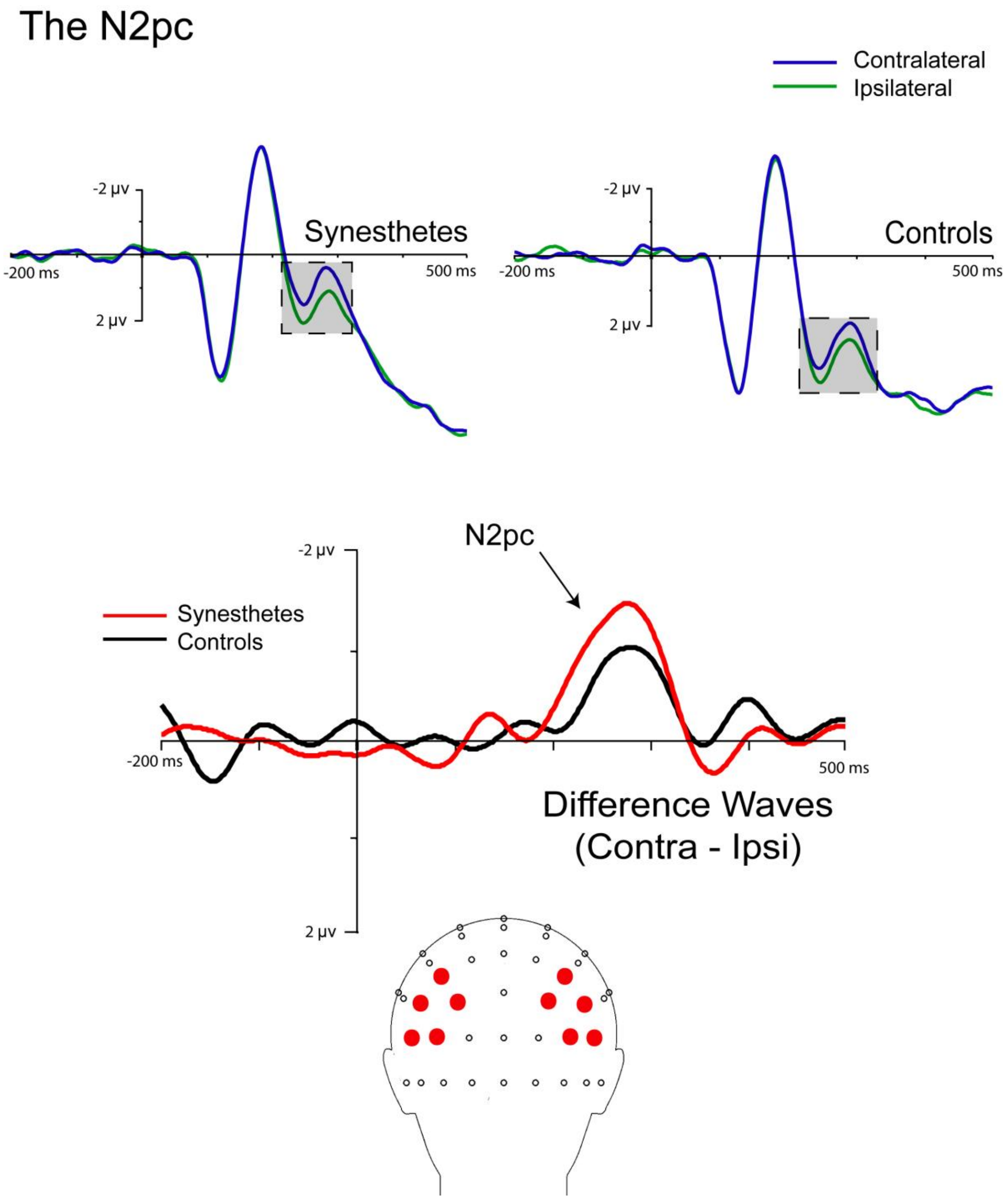

Figure 13: The N2pc

The top plots display contralateral and ipsilateral ERPs for synesthetes and controls, with the N2pc component highlighted. The bottom plot displays difference waves (contralateral minus ipsilateral) for both groups, directly comparing the N2pc components of each group.

# Discussion

## *The Synesthetic Sensory Effect of Color*

Experiment one established the presence of a unique color-related component in the ERPs of synesthetes presented with uncolored graphemes for which color associations existed, thereby providing new objective confirmation of the synesthetic experience. This component, observed at the back of the head in the time window of 110-150 ms, was visible in synesthetes when comparing ERPs generated by letters with synesthetic associations (syn-colored) to false fonts and letters without associations (syn-uncolored). Furthermore, the component was not observed in control participants; the ERPs generated by all three conditions were identical in the time window of 110-150 ms. These results confirm that this ERP component must be related to the neural processing of synesthetic color associations.

It is important to note that this component, to be referred to now as the synesthetic sensory effect of color (SSEC), exhibits a different scalp distribution and timing than that observed by Graulty (2015), which was a positivity in the time window of 150-250 ms expressed at the top of the head in electrodes FC3, FC4, FCz, C3, C4, and Cz. This color-related effect disappeared when the inducing stimulus fell within the attentional blink, demonstrating that awareness of a stimulus is necessary to perceive synesthetic color. It is unclear why the timing and scalp distribution of these effects differ when both appear to be directly related to the processing of synesthetic color associations, but it is possible that this difference is task-related. Given the rapid presentation of stimuli in Graulty (2015), the observed SEC may have been influenced by the processing of subsequently presented stimuli.

The discovery of an SSEC occurring at ~110 ms and localized at the back of the head above the visual cortex lines up well with theories that support the early processing of synesthetic associations. The early nature of this effect leaves little time for much feedback processing or cross-talk between brain areas, lending support to the notion that synesthesia is largely a feedforward, stimulus-driven phenomenon. At the very least, there must be some level of communication between the visual word-form area (VWFA), color area V4, and primary visual cortex V1 to drive the phenomenon of grapheme-color synesthesia, but the results of this experiment suggest there is not time for much more than that.

There were several difficulties in designing experiment one that should be considered in future studies on grapheme-color synesthesia. One potential confound was the fact that some synesthetic participants had fewer than four letters in the alphabet for which they experienced no color associations, making selection of stimuli for the syn-uncolored category difficult. If there were fewer than four unassociated letters for a given synesthete, a compromise was reached by first selecting letters which elicited perceptions of black, white, or grey. If more were necessary, letters with the lowest possible strength and consistency scores were selected to complete the set of four. As a result, stimuli in the syn-uncolored category were not perfectly controlled. However, a quick glance at figure 9 appears to show no difference between the syn-uncolored and false font conditions in the key time window of 110-150 ms for synesthetic color processing, so it seems unlikely that the results were significantly affected.

Another consideration is the fact that oftentimes the same letters were selected for the syn-uncolored category between participants, introducing a potential confound due to the disproportionate use of some letters. In addition, the letters ‘O’ and ‘I’ were sometimes selected, which share close similarities in form to the numbers ‘0’ and ‘1’. When this was the case, the experimenter was careful to ensure that these numbers shared similar color associations with the letters ‘O’ and ‘I’, so there was no possible conflict in color perception given the somewhat bi-stable nature of these stimuli. However, differences in ERPs related to number perception could possibly have affected the results of experiment one, if the letters ‘O’ and ‘I’ were perceived by some participants as numbers rather than letters. The small positivity apparent on the right posterior of the scalp in the syn-colored vs. syn-uncolored comparison for both groups in figure 10 may be related to numeral processing, or perhaps related to the fact that certain letters had a higher weighting in the averages than others because they were used more often.

The inclusion of false fonts in this study may have inadvertently revealed something about how synesthetic associations develop. Graulty (2015) reported that one synesthetic participant was excluded from data analysis because they developed a color association with one or more false fonts over the course of the experiment. None of the participants in the current study reported a similar experience, but two synesthetes were excluded from data analysis in experiment one because there was an insufficient total number (<4) of useable false fonts. That is, when completing the questionnaire in session one, two synesthetic participants reported experiencing strong and consistent color associations for almost every false font stimulus, despite the fact that they had never been exposed to them before. Most other synesthete participants reported having associations with a small number of the false font stimuli, usually because they resembled an elicitor, but none to the extent of these two. This implies that synesthetic associations can easily influence or 'bleed' into each other, perhaps to a greater extent in some synesthetes. It also might imply that synesthetic associations are based more in the form of the elicitor than any semantic content, although some synesthetes report experiencing color associations with words that denote concepts, termed "ideasthesia" or even "higher synesthesia" by some researchers (Mroczko-Wąsowicz & Nikolić, 2014). One participant in this study reported experiencing this type of synesthesia, in addition to simple grapheme-color synesthesia.

### *The N2pc*

Experiment two revealed important differences in the N2pc components of synesthetes and controls, confirming that the brains of synesthetes were able to locate the target more efficiently in visual search. While visual search studies with synesthetes have been done before, the N2pc provides a useful tool for investigating the relationship between attention and synesthesia. This was the first synesthesia study to use ERP techniques in conjunction with a visual search paradigm, and thus offers a novel perspective on the issue. The discovered differences in latency and amplitude of the N2pc suggest a guiding of attention toward the target in synesthetic participants, which supports the claim that synesthetic perceptions occur pre-attentively. In addition, the finding of a significant difference between the reaction times of synesthetes and controls provides behavioral evidence of their improved performance. This result is particularly interesting, given that most studies using visual search paradigms do not find any reaction time differences between groups. This suggests that previous studies were not well optimized for detecting differences between synesthetes and controls, and individual tailoring of the stimuli for each synesthete-control pair may have contributed to this result.

Also contributing to this finding might be differences in the visual search task itself. In most other studies, stimuli are presented in an intermixed array rather than in a bilateral arc formation. Typical visual search tasks use only one target and present a number of trials in which the target is absent, requiring participants to press one button to indicate its presence (once they find it) and another its absence (once they searched the entire array and did not find it). In this study a target was always present, and participants were required to locate and identify it before indicating its identity with a button press. Both paradigms use a binary response scheme, but the responses are indicating very different things (presence or absence of target vs. identity of target). In addition, participants in this study were not allowed to move their eyes to focus directly on the visual search elements. Instead, they were told to use their peripheral vision and covertly focus attention on the stimuli, resulting in a much different search strategy than in traditional visual search studies. It could be argued that participants were deploying a broadened attention strategy, in which they spread their attention across the array to locate the target. If this were the case, then it could be concluded that synesthetic associations are not necessarily processed pre-attentively, but are at least capable of being perceived under conditions with minimal attention allocated to the inducing stimulus.

## *The False Font N170*

The presence of a significant false font-related negativity in the ERPs of both synesthetes and controls conforms to the results Appelbaum et al. (2009) and others. While not directly relevant to the questions posed in the current study, it is nevertheless productive to corroborate the findings of previous research.

It is worth discussing the implications of the fact that the false font effect occurs later in time than the SSEC observed in this study. This appears contradictory, because the brain must have differentiated between letters and false fonts early enough to imbue the letters with color (~110 ms), but the signature false font-related difference is observed later (~170 ms). If the SSEC indeed indexes a generated synesthetic color, this implies that the N170 is not in fact a neural correlate of the earliest differentiation between letters and false fonts, but rather a downstream effect. If the N170 instead represents the neural correlate of the conscious distinction between letters and false fonts (i.e. the moment at which the perceiver is consciously aware of the difference), this would strongly support a pre-attentive or even pre-conscious theory of synesthesia, because the synesthete's brain is selectively imbuing letters with color (but not false fonts) before the synesthete is even aware of the difference between the two. This would also provoke a search later in time for a neural correlate of the conscious experience of synesthetic color. The present study was specifically aimed at searching for the earliest differences between the various stimulus categories and did not manipulate awareness at all, however, a future study might target the pre-conscious vs. conscious neural correlates of synesthetic color perception more directly.

## *Projectors and Associators*

The distinction between projector and associator synesthetes is an important one when it comes to the role of attention in synesthetic perception, and is hardly discussed in the current body of research. First established in 2004, this categorization scheme has proven useful and relevant to the subjective experience of synesthetes in both groups (Dixon et al., 2004). Projectors report that they experience synesthetic associations externally in space, as if the text on a page is literally and physically colored according to their associations. Associators report that they experience their associations internally, such that they imagine the color or see it in their mind's eye when exposed to the eliciting stimulus.

Dixon et al. (2004) ran five projectors and seven associators through a synesthetic Stroop task in which subjects were presented with a grapheme and asked to name either its physical color or the associated color. Each trial was either congruent or incongruent, meaning that the grapheme was physically colored to match the synesthete's association or physically colored to contrast with it. Researchers measured response times and found significant differences between conditions (color-naming vs. photism-naming) and group (projectors vs. associators), as well as a significant interaction. The key conclusion of this study is that projector and associator synesthetes perform very differently on a task related to synesthesia, calling into question the results of any previous studies that failed to make the distinction. It is possible that researchers have been drawing conclusions about two fundamentally different groups under the misconception that they are one and the same. For example, previous case studies may have used exclusively projector synesthetes, and they do in fact have an advantage in visual search as a result of pre-attentive processing of color associations. Since projectors are much less common, group studies are more likely to use a subject pool comprised predominantly of associators. If associators require focused attention on a stimulus to experience the synesthetic association, this could contribute to their null findings when comparing synesthetes and controls on a visual search task. However, this hypothesis is called into question by the results of the current study, since there were nine associator synesthetes and only one projector.

Future studies should compare three groups: projectors, associators, and non-synesthetes. While both are classified under the term grapheme-color synesthesia, the subjective rift between the experiences of projectors and associators may imply fundamental differences in their neural bases, and necessitate the distinction to be made in future studies.

## *Conclusions*

In conclusion, this thesis study made significant steps toward a more complete understanding of the neural basis of grapheme-color synesthesia. More participants must be run through both experiments before the relevant ERP results have enough power to be fully tested for significance, but the finding of significantly different reaction times between synesthetes and controls in experiment two is important and highly pertinent to the ongoing debate regarding the role of attention in synesthesia.

To summarize, experiment one found evidence for an ERP component, the SSEC, which corresponds to the neural processing of grapheme-color associations in synesthetes. The early nature of this component suggests that these associations are largely stimulus-driven and feedforward in nature. Experiment two found that synesthetes are consistently faster than controls at locating a target letter amongst distractor letters, which also supports an early, bottom-up theory of synesthesia. It is currently unclear whether the N2pc components of synesthetes and controls differed in a consistent manner, but the current set of 8 subjects suggested possible latency and amplitude differences. This issue may be elucidated with more participants.

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