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Six is Sapphire, but is Sapphire Six?
Bidirectionality and Numerosity in Grapheme-Color Synesthesia

A thesis submitted in partial fulfillment
of the requirements for the degree of

BACHELOR OF ARTS, PSYCHOLOGY, HONORS PROGRAM

by

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May, 2013
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May, 2013
Abstract

In grapheme-color synesthesia, numbers and letters create a color experience that is consistent, automatic, and unique to each synesthete. Recent studies have examined the way viewing graphemes elicits colors as well as the possibility of bidirectional synesthesia, in which viewing colors may elicit graphemes in the minds of synesthetes (Dixon, Smilek, Cudahy, & Merikle, 2000). This thesis addresses the issue of bidirectionality to see if specific colors elicit the information represented by graphemes in a manner that is cognitively accessible to the synesthete observer. Using psychophysics and event related potential (ERP) waveforms, we found bidirectional synesthesia to exist, as evidenced by synesthetes’ ability to accurately complete an arithmetic verification task in which some or all graphemes were replaced with patches of color that matched the synesthetes’ grapheme associations. Synesthete reaction times were just as fast for trials with a color solution as grapheme solution, and were comparable to control participants’ reaction times. The ERP results from showed that the manner in which synesthetes visually process both numbers and colors differs from that of non-synesthetes, with each synesthete showing a wave pattern distinct from controls and from each other. This research adds a crucial piece to the puzzle of how both synesthesia and numerical concepts are processed in the brain, and includes the first study to date that looks at ERP waveforms of synesthetes while performing an arithmetic task requiring bidirectional synesthesia.
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Introduction

Synesthesia is a rare perceptual condition in which one sense is connected to another, allowing synesthetes to experience cross-sensory perceptions. For example, individuals with grapheme-color synesthesia experience achromatic (i.e. gray scale) graphemes as being colored, with each grapheme having its own color. As will be revealed in this thesis, grapheme-color synesthesia is particularly useful for answering questions regarding the way concepts such as numerosity are accessed in the brain. Synesthesia researchers are currently exploring whether synesthetic percepts can be bidirectional, meaning colors associated with concepts can be used to access that concept. For example, a grapheme-color synesthete may report that the number six elicits a percept of sapphire blue; however, what remains unknown is whether the presentation of that shade of blue can then trigger an experience of the number six. An increasingly persuasive body of evidence supports the hypothesis that synesthetic percepts can, in fact, be bidirectional (Cohen Kadosh, Cohen Kadosh, & Henik, 2007; Gevers, Imbo, Cohen Kadosh, Fias, & Hartsuiker, 2010; Meier & Rothen, 2007; Weiss, Kalckert, & Fink, 2009). However, these studies rely upon implicit measures of bidirectional processing, such as priming, and leave unanswered the question of whether a synesthete has full explicit cognitive access to the information elicited by the color. Addressing this unanswered question is a primary goal of this thesis.

One way to study bidirectionality in grapheme-color synesthetes is to look at the way synesthetes process numerosity, or the mental representation of a number concept. The grapheme ‘3,’ for example, is connected to the concept of three items as a group, or the numerosity of ‘three.’ In synesthetes, the color percept is an extra facet attached to a
given grapheme. Just as the grapheme ‘3’ can be represented by different fonts, each allowing cognitive access to its associated numerosity, it is possible that, for a synesthete, such access can be enabled by viewing a color (Cohen Kadosh et al., 2005).

An additional question related to bidirectionality in grapheme-color synesthesia is the issue of serial versus parallel processing. In serial processing, features are accessed one at a time, while parallel processing allows for multiple pathways to work simultaneously in order to access a concept. Because of their color percepts, synesthetes potentially have an extra parallel pathway to access numerosity. For example, just as the grapheme ‘6’ provides instant and automatic access to the numerosity of six, the color that a synesthete associates with the grapheme ‘6’ could also provide instant and automatic access. Another possibility is that any cognitive access to numerosity arising from the color is derived in a serial manner. In this hypothetical situation, a synesthete presented with the color blue may first use his or her memory to deduce that he or she ordinarily associates the grapheme ‘6’ with that shade of blue. Proceeding in a serial manner, the synesthete may then access the numerosity associated with the grapheme.

While preliminary research shows colors can be used implicitly to access the concept of a grapheme (Dixon, Smilek, Wagar, Cudahy, & Merikle, 2002; Gevers et al., 2010), no previous research explores the brainwaves of synesthetes while performing arithmetic problems, let alone those explicitly comprised of colors rather than graphemes. Using psychophysics and EEG as measures, this thesis explores how synesthetes and non-synesthetes differ in their processing of numerosity, and how synesthetes process graphemes and colors to access numerosity. We, therefore, use two experiments to answer our research questions; Experiment 1 uses psychophysics, while Experiment 2
uses EEG/ERP in addition to psychophysics. To summarize, our two questions are: A) can synesthetes use their color associations to cognitively access numerosity, and, if so, B) do synesthetes use their color associations to access numerosity in a serial or parallel manner? To answer the first question, we look at accuracy results in Experiments 1 and 2. To answer the second question, we look at reaction time results in Experiments 1 and 2, and ERP waveform results in Experiment 2. As no prior ERP data of synesthetes solving math equations have been collected, these findings provide a significant contribution to the field, and may help researchers better understand both grapheme-color synesthesia and numerical processing in the brain.
Literature Review

Synesthesia History and Prevalence

Synesthesia was first documented as a legitimate neurological phenomenon in 1710 when ophthalmologist Thomas Woolhouse reported that a man who had become blind experienced color perceptions associated with sounds (as cited in Cytowic, 1989). Subsequent research helped bring synesthesia into the awareness of the scientific community and gave it operational definitions that aided in more systematic study of the phenomenon (Cytowic, 1989). Cytowic defined synesthetic percepts as involuntary and automatic, somehow spatially located, consistent, memorable, and containing emotional affect (Cytowic, 1989). This set of definitions has been adapted and debated as research expands the understanding of the variations of synesthesia. However, synesthesia is generally accepted to be consistent, involuntary, and automatic, meaning that synesthetes cannot be without their percepts, and these percepts stay stable over days, weeks, and years of retesting (Ward, 2013).

One hypothesis regarding the cause of synesthesia suggests everyone is synesthetic as an infant, but for the majority of people these extra connections are removed during the natural neural pruning process that occurs around toddler age (Wagner & Dobkins, 2011). The evidence presented in favor of this hypothesis is that infants have increased functional connectivity compared to adults, as demonstrated by synesthetic-like associations that have been found in infants and toddlers. For example, infants tend to spend more time gazing at certain associated pairs, such as triangles on a red background, than other pairs, indicating preference (Wagner & Dobkins, 2011). These synesthetic-like associations decrease with development, lending support to the
idea that pruning removes synesthetic connections in normal populations as people age, and synesthetes’ brains simply do not prune away the connections. However, other researchers believe that this effect in infants is qualitatively different from the effect found in synesthetes and that much of the evidence for synesthetic-like associations in infants has also been found in non-synesthete adults (Goller, Otten, & Ward, 2009).

The timing and level of sophistication of synesthesia is considered contentious. One commonly held view is that synesthesia occurs very quickly in neural sensory processing streams due to hyperconnectivity, or “crossactivation”, between areas of the brain that represent different sensory modalities, such as color and graphemes (Hubbard & Ramachandran, 2005; Rouw & Scholte, 2007). In particular, Hubbard and Ramachandran (2005) provide evidence for increased interconnectivity between the visual word form area and the color processing region, which lie adjacent to each other in the brain. This crossactivation would explain grapheme-color synesthesia, although other forms of synesthesia are better explained by more long-range theories that trace the source to disinhibited feedback between various brain areas and a hypothetical multisensory nexus (Grossenbacher & Lovelace, 2001; Hubbard & Ramachandran, 2005). In this system, cross-sensory activation may potentially occur in everyone but be inhibited in non-synesthetes so that they do not have synesthetic experiences; in other words, the potential may be there for everyone, but only synesthetes actualize that potential due to this multisensory nexus allowing the signals to go through to perception (Grossenbacher & Lovelace, 2001).

The debate regarding the source of synesthesia is further complicated by the fact that not all synesthetic percepts are the same in intensity or quality. Smilek, Dixon,
Cudahy and Merikle (2002) have broken down the types of synesthetes into two categories: associators and projectors. Associators have associations for graphemes or other stimuli that appear to them in the ‘mind’s eye,’ while projectors state they experience their synesthetic percepts as real and physically present in the world. Hubbard, Arman, Ramachandran, and Boynton (2005) have linked the associator and projector types to higher and lower processing levels in the brain, respectively. In this model, associator synesthetes’ percepts are linked to concepts, while projector synesthetes’ experiences rely on the percept of physical stimuli (Hubbard et al., 2005). Different levels of processing could have different neurological sources, allowing for the possibility of interconnectivity and feedback disinhibition as sources for different types of synesthesia.

Differences in brain connectivity or feedback may be due in part to genetics, and synesthesia does in fact appear to have a genetic basis (Brang, Kanai, Ramachandran, & Coulson, 2011; Brang & Ramachandran, 2011; Hubbard & Ramachandran, 2005). Research on the genetics of synesthesia has shown that synesthesia is unlikely to be a solely X-linked dominant gene or set of genes, as it can skip generations and does not necessarily appear in both members of monozygotic twin sets. A recent study attempting to trace the genetic roots of grapheme-color synesthesia found a connection to a specific gene in two of five families analyzed, indicating that grapheme-color synesthesia is most likely heterogeneous (Tomson et al., 2011). This study also provided support for the crossactivation idea, but emphasized that normal brains use crossactivation as well; the difference lies in the amount of crossactivation, which can be passed down in families.

Studies of families also help researchers understand the prevalence and gender
ratios for synesthesia. Accounts of synesthesia prevalence vary based on researcher, with estimates ranging from 1 in 25,000 to 1 in 20 (Hubbard & Ramachandran, 2005). The current general estimate for grapheme-color synesthesia, one of the more common types, is 1.4% (Ward, 2013). Initially synesthesia was thought to be more prevalent in females, but this view may have been due to an underreporting bias in earlier studies, as more comprehensive surveys have found equal numbers of synesthetes between genders (Hubbard & Ramachandran, 2005; Ward, 2013). Still, some researchers who study genetics of synesthesia insist the female bias does exist, as families in which synesthesia is prevalent have equal gender ratios but a larger percentage of female synesthetes (Tomson et al., 2011). The development of neuroscience and genetic methods has added to the understanding of synesthesia, but there is still much to learn regarding how synesthetic percepts occur. One thing that remains unclear is the extent to which synesthesia, and grapheme-color synesthesia in particular, is bidirectional.

**Bidirectionality in Synesthesia**

Bidirectionality in grapheme-color synesthesia has been researched from several angles, although the paradigms often use implicit manipulations to indicate bidirectionality (Cohen Kadosh et al., 2005; Gertner, Henik, & Kadosh, 2009). In a study by Cohen Kadosh et al. (2005), researchers used a color congruity paradigm to discover if colors could interfere with synesthetes’ ability to name which number was numerically larger. Grapheme numbers were displayed either in their correct colors or in colors associated with other numbers. The researchers found that synesthetes performed faster when numbers were presented in colors further apart on the number line. For example, if the numbers 4 and 5 were displayed in the colors of 2 and 7, the synesthetes were faster
at stating that 5 is bigger than 4, indicating that the visual experience of a color can influence behavior regarding numbers, even though neither 2 nor 7 were physically present (Cohen Kadosh et al., 2005).

In a follow-up study, numbers were displayed either in congruent colors or in crossed colors, so that, for example, 3 was presented in the color of 4 and vice versa (Cohen Kadosh & Henik, 2006). The synesthete participant experienced interference when colors were incongruent, but the interference decreased the further apart the numbers were on the number line, so that her reaction times were faster if 2 and 7 were displayed in crossed colors than if 3 and 4 were in crossed colors. A similar study using number-form synesthesia, which is when the synesthete ‘sees’ numbers arranged in a particular and consistent order, found the same effect of interference when numbers were presented in a location incongruent to the synesthetes’ personal representation (Gertner et al., 2009).

Research on synesthetes and arithmetic also tends to involve interference or facilitation tasks in which number graphemes are displayed in either congruent or incongruent colors (Dixon et al., 2002; Gevers et al., 2010; Ghirardelli, Mills, Zilioli, Bailey, & Kretschmar, 2010; Daniel Smilek, Cudahy, & Merikle, 2000). Gevers et al. (2010) used a multiplication verification task in which the solution was presented as a grapheme over a block of color that was either congruent with the solution, congruent with other close but incorrect solutions, or white, which was not associated with any number grapheme for the study’s synesthete participant. The white background and those with colors that were congruent with the true answer facilitated the synesthete’s performance, while incongruent colors interfered (Gevers et al., 2010). The synesthete
performed best when numbers were displayed in congruent colors, whereas control participants performed best on trials where all numbers were displayed in black, showing that congruent color can facilitate performance for synesthetes but interfere with performance for non-synesthetes (Ghirardelli et al., 2010).

These studies do show bidirectionality in arithmetic, but do not use the synesthetic percept to replace a grapheme. There are very few studies in which synesthetes complete a task where graphemes are completely replaced with a color. Researchers in Germany used such a paradigm for letters and word fragments, in which the first letter of a word was replaced with a block of color in order to prime synesthetes to complete the word as either a common or uncommon German word (Weiss et al., 2009). The researchers chose each fragment so that it could be completed in only two ways, one of which was a high-frequency word and the other low-frequency, such as the fragment ‘atze,’ which could be completed as either the high frequency word ‘katze’ (cat) or the low-frequency word ‘tatze’ (paw). They then displayed a block of color that matched the low-frequency word for the synesthete participants. Synesthetes completed the fragment with the low-frequency word at a significantly higher rate than control participants when the color of the patch matched their percept of the low-frequency word’s first letter (Weiss et al., 2009). Dixon et al. (2000) used a Stroop task in which the solution of an arithmetic equation was a block of color that was either congruent or incongruent with the actual answer to the equation. The task was then not to solve the equation but to name the color displayed. The synesthete in this study was significantly slower at naming colors that were incongruent with the correct solution of the equation, indicating that synesthetic percepts are automatic, involuntary, and at least implicitly
One way to investigate bidirectionality is to look at the way synesthetes access numerosity. In order to understand this process, however, we must also compare it to existing research on arithmetic in both synesthetes and non-synesthetes.

**Numerosity and Arithmetic**

Research on individual differences in arithmetic ability shows that people high in arithmetic ability are more likely to retrieve solutions to equations from memory, while people who are less skilled with arithmetic solve the equations directly (Nunez-Pena, Suarez-Pellicioni, Gracia-Bafalluy, & Tubau, 2010). Synesthetes report either weaker or stronger math abilities than non-synesthetes, indicating that synesthesia can either facilitate or interfere with numerical processing (Ward, 2013). In this thesis, comparisons between synesthete and non-synesthete groups are complicated by individual differences in arithmetic ability; if synesthete participants are different in their ability they may be using a different strategy to solve the problems, which can impact ERP wave timing. We partially controlled for this possibility with reaction time comparisons between the synesthete and control groups.

A recent study by (Jasinski & Coch, 2012) is particularly relevant to this thesis, as the researchers used a similar arithmetic verification task and recorded EEG activity in order to compare waveforms on true and false trials. The researchers found that there were distinct differences in the timing and magnitude of waveforms, with a negative peak averaging around 280 milliseconds after onset that was larger for false solutions, a positive peak around 300 milliseconds larger for true solutions, and a late positive component to the waveform more sensitive to false solutions (Jasinski & Coch, 2012). As
this study so closely parallels Experiment 2 of this thesis, it is important for comparison; we expected control participants’ waveforms to exhibit these three components and planned to compare the waveforms of synesthete participants when viewing either graphemes or color patches. The purpose of this comparison is to help us answer another key question regarding serial and parallel processing.

**Serial and Parallel Processing**

Researchers posit that individuals access numerical information in either a serial or parallel manner (Townsend & Fifić, 2004). Parallel processing is more efficient, as multiple pathways increase the likelihood that the concept will be accessed more quickly than in serial processing. Current research shows that both methods can be used in arithmetic to access numerosity (Stanislas Dehaene, Molko, Cohen, & Wilson, 2004). In addition to numerical cognition, the visual system itself uses a massively parallel process in order to synthesize the many elements of visual perception at the same, or nearly the same, time (Van Opstal, de Lange, & Dehaene, 2011). This processing can occur non-consciously, and can be seen in averaging mathematic tasks, while more exact mathematics tends to function in a more serial manner (Van Opstal et al., 2011). However, as mentioned in the discussion of numerosity, it is very difficult to generalize which process is being used, as it can vary between individuals and equation types, and the individual’s expertise with an equation can also affect whether serial or parallel processing is being used to access numerosity and solve the equation (Nunez-Pena et al., 2010). For example, an individual may be very familiar with the equation, “2+2=4,” but may need to serially solve the equation, “9-5=4.” Recording precise latencies, or the timing of the response, can help researchers recognize parallel versus serial processing, as
parallel processing will occur in the brain earlier than serial processing.

With regards to synesthesia, if graphemes and colors are interchangeable, then synesthetes may use parallel processing in the brain to access numerosity. However, slower color speeds would indicate serial processing, in which information travels from color to grapheme to numerosity. As previously mentioned, synesthetes self-report being either better or worse at math than control participants, which could indicate differences within the synesthete population regarding serial and parallel processing (Ward, 2013). It is possible, therefore, that some synesthetes may use serial processing while others use parallel processing; such differences would be evident in the timing of their response to color patches as opposed to black graphemes. Reaction time data can help as answer this question, while ERP (event related potential) research provides an optimal method to discover these timing differences due to its latency sensitivity. Therefore, reviewing previous studies that use ERP to look at the timing of synesthetic percepts can show precisely how researched have used ERP to answer questions regarding synesthesia.

**Existing ERP Research**

Few studies exploring the possible bidirectional nature of grapheme-color synesthesia use ERP or other neurological measures, and thus few studies are available to use as comparisons for this thesis. One clever study used generally accepted color descriptions, such as blue skies or lakes, and on some trials replaced the color word with either patches of color or numbers, forming sentences such as, “The lake was the most beautiful hue of 7” (Brang, Edwards, Ramachandran, & Coulson, 2008). These patches or numbers were either congruent or incongruent with synesthetes’ color associations (Brang et al., 2008). The researchers found that numbers congruent with the correct color
descriptor created a smaller negative peak around 400 milliseconds, referred to as the N400. This congruent versus incongruent response mirrored the response of non-synesthetes on the word and color patch trials; however, non-synesthetes did not have the characteristic smaller N400 response to graphemes. These results provide strong support for bidirectionality in the synesthetic experience, as synesthetes responded with congruent-incongruent effects for Brang et al. (2008). Most relevant to the subject of this thesis were the findings that the congruity response for presented graphemes in synesthetes occurred earlier than the same response for blocks of color. Additionally, the congruent-incongruent difference was seen beginning at 100 milliseconds after presentation of stimuli, supporting the idea of parallel processing and that synesthesia stems from neural interconnectivity (Brang et al., 2008).

In a similar follow-up study, synesthetes and non-synesthetes who had learned synesthetic associations viewed sentences with either congruent or incongruent color descriptions (Brang et al., 2011). This paradigm was used to discover if synesthetic percepts are conceptual and learned or more fundamental to perception (Brang et al., 2011). Specifically, the researchers wanted to explore the ERP components discovered in the previous study in order to parse out which components were due to the subjective experience of viewing colored graphemes and which showed knowledge of the relationship between graphemes and colors. The research found evidence for both forms of processing, indicating that both early/lower and later/higher level processing contribute to the synesthetic experience (Brang et al., 2011). Most importantly, the synesthetes’ waveforms had an earlier onset of a negative response at 100 milliseconds (N100) than the waveforms of non-synesthetes who were told to explicitly visualize the
learned color-grapheme associations. This finding supports the idea that the connection between color and grapheme occurs very early in visual processing (Brang et al., 2011).

Research on vision in synesthetes explicitly shows these differences in early sensory processing (Barnett et al., 2008). In a recent ERP study, Barnett et al. (2008) found greater amplitude in the waveforms of synesthetes, compared to controls, when viewing simple black and white stimuli. The stimuli did not induce synesthetic percepts, thereby indicating that early visual systems in synesthetes contain fundamental differences from non-synesthetes. This early response also lends support to the idea that synesthesia stems from neural interconnectivity. The authors suggest that these early differences may increase the tendency to develop paired associations (Barnett et al., 2008). With regards to color vision, synesthetes have been found to perform better on tests of color perception, indicating they may have better discernment and view general color differently from non-synesthetes (Yaro & Ward, 2007).

**Summary**

Perception researchers often study synesthesia as an intriguing anomaly that can provide insight into universal experiences of perception and help create distinctions between what is unique and what is universal. My specific research questions explore these issues and add to existing research on synesthesia by exploring important issues such as bidirectionality and serial versus parallel processing in the synesthete brain. Experiment 1 seeks to determine whether colors and graphemes can function as interchangeable representations of numerosity in grapheme-color synesthetes. The answer to this first question will be derived by examining the accuracy with which grapheme-color synesthetes can solve simple math problems formed out of graphemes.
and/or colors. Experiment 2 explores the manner by which numerosity is accessed when synesthetes are presented colors rather than graphemes (i.e. in a serial or parallel fashion). The answer to this second question will be derived by examining A) the reaction times with which synesthetes are able to solve such equations and B) the latencies of ERP waveforms associated with colors and graphemes. The answers to these questions will help create a larger understanding within the field of synesthesia research regarding bidirectionality in grapheme-color synesthesia.
Experiment 1

Introduction

Can a color patch give cognitive access to, for example, the ‘threeness’ that is ordinarily accessed through the grapheme ‘3’? If so, is there evidence to suggest that this access happens via serial or parallel processing? Experiment 1 attempts to answer these questions by looking at synesthete accuracy and reaction times on a simple arithmetic verification task. If colors cannot provide cognitive access to numerosity for synesthetes, we would expect to see synesthetes performing around chance (50%) when colors appear on a true/false verification task. If however, synesthetes can use their color associations to access numerosity, we would expect them to perform as well on the task as they do when regular graphemes are presented. Figure 1 displays what the data might look like in these two possibilities.

Figure 1. Theoretical accuracy data for synesthete participants. Synesthetes would perform at chance on color trials if colors do not provide access to numerosity, but would be just as accurate as on grapheme trials if they do grant cognitive access.
For our second research question, serial processing would imply increased reaction time as we replace graphemes with colors, as it would take synesthetes longer to translate the colors into graphemes, which then would be used to access numerosity. If, instead, synesthetes use parallel processing, we would expect reaction times to remain fairly constant across condition types, as synesthetes would take an equal amount of time to access numerosity with either graphemes or colors. Figure 2 shows what reaction time data might look like if synesthetes use serial versus parallel processing.

Figure 2. Theoretical reaction time data for synesthete participants. If synesthetes use serial processing, they would take more time for each additional color presented, while parallel processing would require equal time for graphemes and colors.

Methods

Participants and recruitment. Three female grapheme-color synesthetes and four non-synesthete controls participated in the experiment. These participants were recruited through undergraduate psychology course announcements. As a screening process, potential synesthctic participants were assessed using the standardized
Synesthesia Battery, which displays colors for the participant’s graphemes, measures the consistency of these colors, and uses a modified Stroop test to determine accuracy at determining whether a grapheme is presented in the correct color (David M. Eagleman, Arielle D. Kagan, Stephanie S. Nelson, Deepak Sagaram, & Anand K. Sarma, 2007). Consistency scores under 1.00 and accuracy scores over 85% are considered synesthetic by Eagleman et al. (2007), and all participants met this requirement. All three synesthete participants reported normal-to-corrected color vision and right-handedness.

**Experimental design and stimuli.** Color associations for each participant were obtained using the standardized test battery for synesthesia research (D. M. Eagleman, A. D. Kagan, S. S. Nelson, D. Sagaram, & A. K. Sarma, 2007). Participants were randomly presented with black numbers (0-9) and letters (A-Z) and picked the corresponding color from a color palette (for more information, see Eagleman et al., 2007). Average RGB (red-green-blue color model) values were obtained for each grapheme and used to create the stimuli used in the main experiment. Color associations for each participant, displayed in Figure 3, show how each synesthete has unique color associations.

![Figure 3. Color associations for synesthete participants.](image-url)
For the main experiment, trials consisted of simple mathematical problems using randomly generated single digits ranging from 0 to 9 in the form $X [+ - \times \div] Y = Z$. For one participant (TC1), only digits ranging from 1 to 9 were used as she did not have a color association for the number ‘0’ that could be represented on a computer display. As illustrated in Figure 4, four distinct forms of the equations were presented. In the control condition, all three numbers were presented without any color substitutions. In the other conditions, one, two or all three of the graphemes were replaced with a square color patch (3.5º visual angle). The color of each patch matched the synesthetic color the subject associates with the number it replaced. Which of the three grapheme(s) were replaced in the one- and two-color conditions was randomly determined on each trial. The numerical stimuli subtended a vertical visual angle of 2.7º and a horizontal visual angle of 0.9-1.5º. The operators subtended a vertical visual angle of 0.3-0.9º and a horizontal visual angle of 0.8-1.1º. All problems had a true integer answer of 9 or less (e.g., 3 + 4 = 7). This restricted range of numbers was selected because not all synesthetes in our study reported having distinct color associations for numbers greater than nine. The numbers associated with the color patches and explicitly presented numbers formed an equation that could either be true (e.g., color corresponding to the number ‘3’ + 4 = 7) or false (e.g., color corresponding to the number ‘9’ ÷ 3 = 4).
Figure 4. Experiment 1 design. A sample true math problem used in the experiment for each of the four conditions, using MC2's color associations. Synesthetes received a version of the program in which their own color associations were displayed. Equation types occurred randomly, and only single-digit arithmetic was used.

On each trial, a fixation cross appeared for 500ms followed by an equation that was presented until the participant responded. The task was to press ‘T’ if the presented solution was true and ‘F’ if the presented solution was false. Participants were instructed to respond as quickly and accurately as possible. Reaction times (RTs) for each trial were recorded starting at the time the problem appeared on the screen. 64 trials each of the zero-, one-, two- or three- color conditions were presented in a pseudorandom order for a total of 256 trials. Each condition contained an equal number of problem types (16 of each: addition, multiplication, subtraction and division) and an equal number of true and false trials. The type of problem (e.g., true division) and number of color patches was
pseudorandomly chosen on each trial. It is important to note that to a non-synesthete, the equations in all but the zero-color condition make no sense: does blue + 7 = 8? As such, a non-synesthete would have to guess whether each equation was true and would be expected to perform at a chance level of 50% for all conditions.

Prior to the main experiment, each subject completed a practice session containing 16 problems with all black numbers presented on a grey background. This practice session was done to A) put the subject in the mindset of doing math problems and B) to our great relief, confirm that the subjects could accurately perform simple math problems. A grey background was used throughout the experiment because none of the participants had color associations for grey.

Results

Accuracy. Not surprisingly, all participants were 100% accurate in the zero-color condition. Each synesthete performed significantly above chance for all three color substitution conditions (all $p < 0.001$). Mean accuracy across subject in the one-, two- and three-color conditions was 99.48%, 98.44% and 97.40%, respectively. These results appear in Figure 5, which shows how synesthetes performed very accurately in all trials while controls performed around chance (50%) whenever an equation with a color present was displayed. One-sample t-tests revealed that performance was significantly above chance (50%) for all the colored conditions: one-color ($t(2) = 95.00, p < .001$), two-color ($t(2) = 47.00, p < .001$), three-color ($t(2) = 19.64, p < .003$). Additionally, a 2 (trial-type: true or false) $\times$ 4 (number of color patches: none, one, two, three) $\times$ 4 (equation type: addition, subtraction, multiplication, division) repeated measures ANOVA was performed. Importantly, the main effect of condition (number of color patches) was
nonsignificant \( F(3, 6) = .93, \text{ns} \). Therefore, the synesthetes we tested performed well above chance at a similar level of accuracy regardless of whether they verified equations containing only black digits or one, two or three of those digits was replaced with a color patch. Moreover, the main effects of trial-type \( F(3, 6) = 1.49, \text{ns} \) and equation type \( F(3, 6) = 0.95, \text{ns} \) did not reach significance. Additionally, no significant interactions were observed (All \( F < 1.0, \text{ns} \)). While the number of subjects is small (N = 3) and the observed power of the ANOVA was only 0.17, even if these null results represent Type 2 errors, it is clear that these synesthetes can indeed compute with colors and that the associated cost in accuracy is negligible.

![Overall Accuracy](image)

**Figure 5.** Experiment 1 accuracy. Synesthetes performed above 97% accuracy on all trial types, whether color or number. Controls were very accurate at normal math involving graphemes but appeared to guess whenever equations involving color appeared, performing around chance (50%).

**Reaction time.** The median reaction times for each subject are shown in Figure 6. Examination of Figure 6 shows a slight, though non-significant, linear increase in RT as the number of substituted colors increased from zero to three. This trend appears to be
driven by subject TC1 for whom each additional color increases RT by ~250ms. Additionally, subject DN1 appears to have a small RT cost associated with using colors independent of the number of colors in the equations. DN1 responds to the zero-color trials ~100ms faster than any of the color substitution trials. In contrast to the other two, MC2 is able to verify the equations using colors as fast or even faster (one-color) than the zero-color trials. One may speculate that the fact MC2 is a ‘projector’ type synesthete as compared to the other two ‘associators’ may account for this difference. At a group level, collapsing across equation type and trial-type, a one-way repeated-measures ANOVA found no significant difference \((F(3, 6) = 2.64, \text{ns})\) of the number of colors in the equation on reaction time.

For completeness-sake, as was done for the accuracy data, we analyzed the data shown in Figure 6 on the basis of trial-type (true/false), number of colors (zero-three), and equation type \((+ − \times ÷)\) and performed a \(2 \times 4 \times 4\) repeated measures ANOVA on the median RTs. Similarly to accuracy, no significant main effects were observed for the number of color patches in the equation \((F(3, 6) = 3.12, \text{ns})\) or trial-type \((F(1, 2) = 0.41, \text{ns};\) see Figure 4). Interestingly, there was a main effect of equation type \((F(3, 6) = 6.95, p < .05, \eta^2 = 0.61)\). A paired sample t-tests revealed a significant difference between the subtraction and multiplication problem types \((t(2) = 4.40, p < .05)\). On average, multiplication problems were verified ~131ms faster than subtraction problems. This may reflect the nature of the rote memory for multiplication problems as opposed to relying on magnitude estimation (S. Dehaene, Piazza, Pinel, & Cohen, 2003). Importantly, the interaction between the number of color patches and trial-type \((F(3, 6) = 1.14, \text{ns})\) was not significant, indicating that the faster times in solving the multiplication problems
were not specific to any of the color substitution conditions. Additionally, no other interactions reached significance (All $F < 2.0$, ns). Again, although the number of subjects is small and these group-based analyses are underpowered, the data indicate negligible costs in reaction time associated with verifying the equations using colors rather than graphemes. Notably, these costs are specific to the individual and may depend upon the ‘projector/associator’ nature of the synesthete.

Figure 6. Experiment 1 reaction times. Synesthetes showed no significant differences between reaction times in the trial conditions.
Experiment 2

Introduction

Experiment 2’s purpose was to corroborate the findings of Experiment 1 using slightly different experimental protocol and EEG recording. Again, high accuracy scores would indicate that colors provide cognitive access to numerosity. If synesthetes use a parallel process, with numerosity being accessed by either the grapheme or color, we would not expect to see reaction time differences between trials with grapheme or color solutions; reaction time differences would imply serial processes. Figure 7 shows what we might expect to see in terms of the timing of waveform peaks in serial processing versus parallel processing. As discussed, in a serial processing model, synesthetes would take more time to access numerosity when viewing colors than when viewing graphemes.

![Serial Processing vs Parallel Processing](image)

Figure 7. Theoretical reaction time data for synesthete participants. If synesthetes use serial processing, the peak of the waveform on color trials would occur later than the peak for grapheme trials, while waveform peaks in parallel processing would occur around the same time.
In order to compare the latencies of waveform peaks, we need to know what peaks correspond with actual known waveforms. The work of Jasinski and Coch (2012) points the way to which peaks we should look at, as they have found clear differences in the true versus false waveforms on a similar arithmetic verification task. These differences correspond to an individual’s ability to cognitively access numerosity and solve equations, as differences between the way individuals process true and false equations shows they are capable of telling which equations are true and which are false. A negative response peaking on average around 280 ms appears to correlate with recognition of false equations, while a positive response with an average peak around 300 ms relates to recognition of true equations. Figure 8 displays these typical responses, which have been found in non-synesthetes. Our goal was to find these responses in synesthetes on grapheme and color trials and compare the peak latencies to determine whether synesthetes are using serial or parallel processing.

![Known True/False Differences](image)

Figure 8. Example of known differences between true and false waveforms. Looking at non-synesthetes, Jasinski and Coch (2012) have shown a stronger negative response for false trials peaking around 280 ms and a stronger positive response for true trials around 300 ms.
Methods

Participants and recruitment. Three female grapheme-color synesthetes and ten non-synesthete controls participated in the experiment. Two of the synesthetes had previously participated in Experiment 1, while the third synesthete was recruited through an undergraduate psychology course announcement. Non-synesthete participants were also recruited through course announcements, or were undergraduate research assistants in psychology labs. All synesthete participants were assessed using the Synesthesia Battery. Two synesthetes met the requirements for synesthesia, with consistency scores under 1.00 and accuracy scores over 85% (David M. Eagleman et al., 2007). The third synesthete participant measured at a .49 consistency, but was slightly under the accuracy cutoff, with a score of 83.33%. This lower accuracy score could have been due to the fact that two of her numbers have identical colors, making it difficult for her to differentiate in the Battery. We ran her on our own screening test in the lab and found her to qualify as synesthetic. All participants reported normal-to-corrected vision and right-handedness.

Experimental design and stimuli. Color associations for each synesthete participant were obtained using a program created by our lab, which is similar to the standardized test battery created by Eagleman, et al. (2007). Synesthete participants were randomly presented with black numbers (0-9) and picked the corresponding color from a randomly rotating color palette. Average RGB color values were obtained for each grapheme and used to create the stimuli used in the main experiment. All synesthete participants entered their colors on the same computer used for later stimulus presentation to avoid color differences due to different settings on monitors or lighting conditions.

For Experiment 2, trials consisted of simple mathematical problems using
randomly generated single digits ranging from 0 to 9 in the form $X [+ - \times \div] Y = Z$. For one participant (TK1), only digits ranging from 0 to 6 and 8 were used, as her color association for 9 was identical to her association for 8, and she had no color association for 7. Again, the solutions presented formed equations that could be either true or false. In this experiment, only the solution to the equation was replaced by color in order to identify a clear point of interest within the EEG data. Synesthetes received a version of the task in which graphemes were replaced with their synesthetic color associations while control participants received one of two synesthete versions of the task. The program for TK1 was not used for control participants, as it was missing the digits 7 and 9. Control participants ran in the full synesthete version so that we could compare color accuracy, reaction time, and EEG signal for non-synesthetes and synesthetes.

In this version of the task, we presented a fixation point for 1000 milliseconds (ms), the problem for 500 ms, followed by a 500 ms pause, the solution to the equation for 750 ms, and finally another 500 ms pause before participants could answer whether the equation was true or false, as shown in Figure 9. This delay was designed to minimize noise in the EEG signal. The task was to press the left arrow key if the presented solution was true and the right arrow key if the presented solution was false. Participants were instructed to respond as quickly and accurately as possible. Reaction times (RTs) for each trial were recorded starting at the time the screen displayed the question, “True or false?” 30 trials of each unique condition combining color or grapheme, true or false, and the four operator types were presented in a pseudorandom order for a total of 480 trials. Each condition contained an equal amount of problem types and an equal amount of true and false trials. The type of problem (e.g., true color division) was pseudorandomly chosen
on each trial. Prior to the main experiment, participants completed a randomized practice session in order to allow them to become used to the timing of the program.

![Grapheme Trials](image)

![Color Trials](image)

**Grapheme Trials**

<table>
<thead>
<tr>
<th>500 ms</th>
<th>500 ms</th>
<th>750 ms</th>
<th>500 ms</th>
<th>Response</th>
</tr>
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<tbody>
<tr>
<td>2 + 3</td>
<td>Blank</td>
<td>5</td>
<td>Blank</td>
<td>T/F?</td>
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</table>

**Color Trials**

<table>
<thead>
<tr>
<th>500 ms</th>
<th>500 ms</th>
<th>750 ms</th>
<th>500 ms</th>
<th>Response</th>
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<tbody>
<tr>
<td>2 + 3</td>
<td>Blank</td>
<td>5</td>
<td>Blank</td>
<td>T/F?</td>
</tr>
</tbody>
</table>

**ERPs & Behavioral Responses Recorded**

Figure 9. Experiment 2 design. The solution to the problem appeared as either a color or grapheme.

EEG data was recorded using a two-channel and ground electrode system to record the EEG signal. I attached these electrodes to participants’ scalps using a conductive gel. The stimulus program displayed a pulse of white under a diode sensor on the screen whenever a solution was presented. The signal was recorded using Audacity, an audio recording software program, with the diode pulse on the first channel and the raw EEG signal on the second channel. I analyzed the audio EEG signal using EEGLab, a MATLAB program. The diode pulse provided the correct latency from which to sync raw EEG data. Raw signals of the individual trial types were combined and averaged to create ERP (event related potential) waveforms for every trial type and within every participant. These ERP waveforms were then used to compare the results of synesthetes and non-synesthetes, as well as synesthetes’ results on color versus grapheme solution trials.
Results

Behavioral results: accuracy. I averaged accuracy across operator types and then compared the accuracy results based on solution type of either grapheme or color. Using paired-sample t-tests, we found that synesthete accuracy was not significantly different between grapheme and color trials, with the mean accuracy for grapheme trials at 96.76% and for color trials at 96.55%. This finding corroborates Experiment 1 results, indicating that synesthetes can indeed solve arithmetic equations using color. Non-synesthete participants were as accurate on grapheme trials as synesthetes, with a mean accuracy rating of 95.77%. However, an independent samples t-test showed that control participants were significantly less accurate on color trials than synesthete participants, with a color trial mean accuracy of 54.93%. This result was expected, as equations with color solutions would be meaningless to control participants, who would perform around chance (50%). Accuracy within and between groups can be seen in Figure 10; these results correspond with the idea that synesthetes have cognitive access to numerosity through their color associations.

Figure 10. Experiment 2 accuracy. Synesthetes showed no significant difference in accuracy between color and number. Controls were less accurate on color trials.
Behavioral results: reaction times. Reaction times 4 standard deviations or greater away from the mean were categorized as outliers and thrown out of analysis. Mean reaction times for synesthetes were 587.77 ms on grapheme trials and 515.2 ms on color trials. While color trial reaction times were faster than grapheme trials, a paired samples t-test revealed that this difference was not significant. Control participants had mean reaction times of 588.4 ms for grapheme trials and 635.61 ms for color trials. A paired samples t-test demonstrated that this difference was statistically significant. Figure 11 illustrates the differences in reaction times between control participants and synesthete participants on grapheme and color trials, and in particular highlights the lack of significant difference between synesthetes and non-synesthetes on grapheme trials.

![Mean Reaction Time](image)

Figure 11. Experiment 2 reaction times. Controls were significantly slower at color trials, while synesthetes showed no significant difference in reaction times.

EEG results. Using EEGLab and MATLAB, I ran a series of t-tests on the grand averages for control participants’ true versus false equations, and found significant differences between ~165 ms to ~225 ms, and from 350-400 ms, as shown in Figure 12.
In the 165-225 ms window, true equations created a more negative response, while the 350-400 ms window paralleled an increased negative response for false equations. While the latencies are slightly different, these findings parallel those of Jasinski and Coch (2012), with the first response similar to the N280, and the second paralleling the P300. For synesthetes, the only significant difference on color trials in true and false equation waveforms occurred around 125 ms as a more negative response to true equations, while significant differences for grapheme trials occurred later. These areas of significance can be seen on Figure 13; when comparing to Figure 12, one can see that the characteristic true/false verification responses are missing. Synesthetes therefore did not show the either the N280 or P300 results, so comparison of waveform peak latencies was not possible.

Figure 12. Control grapheme results. Findings are similar to those of Jasinski and Coch (2012), with significant differences corresponding to the N280 and P300 responses.
Figure 13. Synesthete color and grapheme true/false comparisons. Typical N280 and P300 responses are not present; therefore we were unable to analyze latencies.
Although not related to our initial questions, we did find some interesting results in the synesthete waveforms. Looking only at synesthetes and collapsing across true and false, there was an area of significant difference of a more negative response for color trials from around 220 to 240 ms. This time period, which can be seen in Figure 14, corresponds to the N280 response found in the control participants on grapheme trials and in the work by Jasinski and Coch (2012); however, the second, positive P300 response is missing. We looked at the difference waves between color and number trials, regardless of true or false status, and compared the difference waves of control participants and synesthete participants. Figure 15 shows the significant differences between these two waveforms. In this analysis, there was significance between 180 and 200 ms (greater negative response in synesthetes), between 325 and 370 ms (greater positive response in synesthetes), and in the area of 700 to 850 ms (more negative in synesthetes). When comparing the true/false difference waves of synesthetes and non-synesthetes, we found many areas of significance, which indicates that the way synesthetes processes both graphemes and their associate colors is very different from the way non-synesthetes process graphemes.
Figure 14. Synesthete color versus grapheme comparison. Synesthetes showed significant differences in the way they processed graphemes versus colors around the N280 point.

Figure 15. Differences between true/false difference waves of synesthetes and non-synesthetes. Synesthetes process both graphemes and colors differently than non-synesthetes, as indicated by the many areas of significant differences.
Discussion and Conclusion

Analysis

In Experiments 1 and 2, we found that synesthetes can use colors to cognitively access numerosity, and appear to access numerosity in a parallel manner. Experiment 1 showed that synesthetes are able to successfully and quickly solve math equations in which numbers are replaced with their associated colors. The participants answered with over 90% accuracy, and were able to respond to color trials as quickly as grapheme trials. This accuracy indicates at least implicit bidirectionality, since the squares of color functioned as well as graphemes in accessing numerosity. As previously discussed, bidirectionality in synesthetic percepts supports the theory that synesthesia is the result of hyperconnectivity and cross activation in the brain (Hubbard & Ramachandran, 2005). The similar reaction times across conditions indicates parallel processing, as color trials do not appear to cost synesthetes extra time to process. Experiment 2 corroborated these findings, with all synesthete participants performing at over 93% accuracy, and again answering grapheme and color trials with similar speed. It is important to note that reaction times in the two experiments cannot be directly compared, as the starting points differ; in Experiment 1, reaction times were recorded from the moment the entire equation appeared on the screen, while in Experiment 2, reaction times were recorded only from the moment participants were prompted to answer.

In terms of the EEG data, results are not so clear. At the outset of this thesis, our goal was to compare synesthete waveforms on true versus false equations to the known pattern of true and false waveforms in non-synesthetes, as shown in the work of Jasinski and Coch (Jasinski & Coch, 2012). However, while our control participants did show
this pattern, our synesthete participants did not show this characteristic waveform. While individual control participants showed similar patterns in their waveform data, each synesthete had a unique waveform, which made it difficult to accurately analyze the data when averaged together. The averaged synesthete waveform for grapheme solutions was strongly influenced by TK1, who showed a completely different pattern than any other participant, whether control or synesthete. Due to this lack of the characteristic true/false difference waveform, we were unable to analyze waveform latencies in synesthetes on grapheme versus color trials.

**Limitations**

The lack of characteristic true or false waveforms precluded an analysis of our initial question regarding serial versus parallel processing of graphemes and colors in the synesthete brain. We, therefore, are unable to draw a conclusion from the EEG/ERP data as to whether synesthetes access numerosity in a serial or parallel fashion. Similarities in behavioral reaction times show that color does not require extra processing time to access numerosity, but the ERP latencies could not be used to find such a difference in the time window during which processing occurred. This issue could be due to the equipment used, as the protocol for Experiment 2 involved only one recording electrode on a system with much potential for noise in the recorded electrical signal. Attempting the same experiment with a high resolution EEG system could reduce noise, which could in turn show the expected true/false waveform. Alternatively, the stimuli and timing used in the experiment could have affected the response and caused us to miss the characteristic waveform. For example, when synesthetes view a grapheme there could be an inherent difference in waveform as compared to control participants, as synesthetes also perceive
their synesthetic color associations, even if the grapheme is presented achromatically. An additional limitation to the research in this thesis is low power due to few synesthete subjects. While we did find areas of significance, there may be more significant differences to discover with greater power, including the characteristic true/false difference waveform we were looking for. A possible solution to this problem would be to collaborate with other synesthete researchers who have access to a larger pool of synesthete participants.

**Implications and Future Directions**

In the comparison of the difference waves between synesthetes and non-synesthetes, synesthetes had a significantly more negative response late in the recording period, which, in fact, occurred after the average response time for synesthetes. While this finding does not tell us anything about how synesthetes access numerosity in order to make a decision, it does indicate that there are differences in what occurs after the synesthete responds. Anecdotally, synesthetes often report an emotional response to viewing their colors, with a positive valence when colors are congruent and negative valence for incongruency between the color and the grapheme (Callejas, Acosta, & Lupiáñez, 2007). The late significance found in Experiment 2 could relate to emotional response to the synesthetic percept as compared to non-synesthetes, who presumably do not have the emotional response to stimuli. The possibility of an emotional component within synesthetes’ ERP waveforms would be an interesting future direction for study.

The variability between synesthete participants also raises the question of different types of synesthesia. As discussed in the literature review, researchers often classify synesthetes as either projectors or associators (D. Smilek et al., 2002). This
classification system is problematic, as synesthetes may not know they are projectors or may be led by questioning to believe they are one or the other type (Simner, 2012).

However, further ERP research with grapheme-color synesthetes could show two distinct waveform patterns for the types, which could contribute to researchers’ ability to accurately classify synesthete participants.

Another possible future study would involve testing slight color variations around the synesthetic color association. It is possible that the colors used in this experiment acted not as explicit bidirectional links to numerosity but as mnemonic categories to access numerosity within the context of the task. Anecdotally, synesthetes report that colors displayed on the screen may not be precisely right, and may be lacking texture or luminance properties. There may then be a range of color values around the displayed color that could work to access the associated numerosity, just as various fonts can provide access to concepts. Further research on this issue could help clarify whether synesthetes use serial or parallel processing to cognitively access numerosity.

Synesthesia research is important in its own right as a means of increasing understanding of synesthesia itself, a neurological condition that affects approximately one to five percent of the population. Synesthesia is special as a neurological phenomenon in that it can facilitate performance on tasks, such as memory or creativity (Smilek, Dixon, Cudahy & Merikle, 2002a; Ward, 2013). Understanding precisely how synesthesia can be used to increase performance is worthy research in its own right. If, as some posit, synesthesia is on a spectrum, with many people possessing some slight synesthetic percepts and a small number qualifying fully as synesthetes, research on synesthesia could then apply to a much larger percentage of the population (Simner,
Research on synesthesia can increase understanding of how the brain works in non-synesthetes; for example, the suggested neurological sources of synesthesia, interconnectivity and disinhibition, are present in non-synesthete brains as well.

As one of the first experiments to require bidirectional percepts in order to complete the task, the findings of this thesis pave the way for other researchers to use explicit tasks as opposed to the more common implicit Stroop experiments that look for facilitation or interference. Although the ERP data did not add to the conclusions of this research, psychophysics results showed that grapheme-color synesthetes were able to complete the task as quickly and accurately as non-synesthetes, using graphemes and colors interchangeably. We, therefore, found answers to our two research questions: synesthetes can use color associations to cognitively access numerosity, as evidenced by high accuracy results, and this access appears to occur in a parallel manner, as evidenced by similar reaction times on grapheme and color trials. These findings provide further evidence of bidirectionality in grapheme-color synesthesia, an issue that is hotly debated amongst synesthesia researchers, and contribute to scientific understanding of how grapheme-color synesthetes use their color associations in the brain.
References


