Multicolored words:

Uncovering the relationship between reading mechanisms and synesthesia

Laura J. Blazej* & Ariel M. Cohen-Goldberg

Department of Psychology, Tufts University, Medford, MA, USA

**Corresponding author*. Department of Psychology, Tufts University, 490 Boston Ave., Medford, MA 02155, USA.

E-mail address: laura.blazej@tufts.edu (L. J. Blazej)

Abstract

Grapheme-color and lexical-color synesthesia, the association of colors with letters and words, respectively, are some of the most commonly studied forms of synesthesia, yet relatively little is known about how synesthesia arises from and interfaces with the reading process. To date, synesthetic experiences in reading have only been reported in relation to a word's graphemes and meaning. We present a case study of WBL, a 21-year old male who experiences synesthetic colors for letters and words. Over 3 months, we obtained nearly 3,000 color judgments for visually presented monomorphemic, prefixed, suffixed, and compound words as well as judgments for pseudocompound words (e.g., *carpet*), and nonwords. In Experiment 1, we show that word color is nearly always determined by the color of the first letter. Furthermore, WBL reported two separate colors for prefixed and compound words approximately 14% of the time, with the additional color determined by the first letter of the second morpheme. In Experiment 2, we further investigated how various morphological factors influenced WBL's percepts using the compound norms of Juhasz, Lai, and Woodcock (2014). In a logistic regression analysis of color judgments for nearly 400 compounds, we observed that the likelihood that WBL would perceive a compound as bearing 1 lexical color or 2 lexical colors was influenced by a variety of factors including stem frequency, compound frequency, and the relationship between the meaning of the compound and the meaning of its stems. This constitutes the first study reporting an effect of morphological structure in synesthesia and demonstrates that synesthetic colors result from a complex interaction of perceptual, graphemic, morphological, and semantic factors.

Keywords: synesthesia, lexical-color, grapheme-color, morphology, modularity

Multicolored words:

Uncovering the relationship between reading mechanisms and synesthesia

1. Introduction

Synesthesia is a relatively rare phenomenon in which experiences in one domain or modality systematically lead to additional experiences in the same or different modality. For example, synesthetic individuals may experience tastes when hearing sounds (e.g., “expect” tastes like potato chips, Ward & Simner, 2003), colors when seeing letters (e.g., “H” appears yellow; Ginsberg, 1923), or tactile sensations when tasting foods (e.g., chicken feels prickly; Cytowic, 2002). Although some of the most commonly studied forms of synesthesia—grapheme-color and lexical-color synesthesia—are fundamentally based in reading, relatively little is known about how synesthesia arises from and interfaces with the reading process. Put another way, relatively little is known about synesthesia as a *psycholinguistic* phenomenon (Simner, 2007). Understanding the properties of reading-related synesthetic percepts could shed light on the nature of synesthesia, providing fine-grained information about the sorts of information and mental processes that give rise to these experiences. This information could also potentially inform psycholinguistic theories of reading by, for example, providing evidence in support of various hypotheses concerning the processes or representations involved in reading. In this paper we investigate the perceptions of an individual who experiences grapheme-color and lexical-color synesthesia, experiencing colors for letters and words when reading. His pattern of performance reveals that his color perceptions arise through a complex interaction of multiple levels of linguistic structure, indicating for the first time that synesthesia is intimately related to the functioning of the reading system. To situate this work, we first describe the architecture of the reading system and interpret existing research on grapheme- and lexical-color synesthesia within this framework.

1.1. Word Recognition

Although psycholinguistic theories of reading differ in their specifics, there is general consensus about the primary stages of processing involved in word recognition. The first stage of processing is orthographic encoding, in which a retina-centered visual image is transformed into a word-centered string of letters. This process, which involves recognizing letters and their positions, is generally held to first involve the extraction of low-level visual features (e.g., | \ — /) that are combined into higher-level allographic structural representations representing the basic visual properties of the stimulus letter. Many theories hold that these structural representations are then mapped onto Abstract Letter Identities ('ALIs', sometimes referred to as 'graphemes'), which are theorized to encode the identity of a letter irrespective of its case, font, position, etc. (e.g., Brunsdon, Coltheart, & Nickels, 2006; Jackson & Coltheart, 2001; Schubert & McCloskey 2013; see Rothlein & Rapp, 2014 for a review, and Plaut & Behrmann, 2011 for a differing position). As an example, 'e' and 'c' would have similar allographic (structural) representations but would map onto distinct abstract letter identities while 'e' and 'E', being visually dissimilar variants of the same letter, would have dissimilar allographic representations but would ultimately map onto the same ALI. Following orthographic encoding, the graphemic representation is used to retrieve the corresponding lexical entry from the orthographic lexicon, which in turn provides access to the word's semantic and syntactic information. The word recognition process can thus be roughly divided into three stages: 1) *pre-lexical*, involving information pertaining to visual form and letter identity, 2) *lexical*, involving word-level structure, and 3) *post-lexical*, involving the word's meaning and syntactic properties.

Contemporary psycholinguistic theories generally hold that the reading process is interactive, which means that these stages of processing (and their sub-processes) influence each other (e.g., McClelland & Rumelhart, 1981). Activation is thought to cascade from one stage of processing to the next and may feed back from subsequent to earlier stages. This means that, for example, word-level properties such as frequency and neighborhood density can influence pre-lexical computations (such as letter recognition, e.g., Reicher, 1969) through feedback connections.

1.2. Morphology

A rich body of research has examined how morphologically complex words are processed during reading. Morphologically complex, or ‘multimorphemic’, words are words that are composed of multiple meaningful units, commonly referred to as ‘morphemes’. In English, multimorphemic words comprise prefixed words (e.g., *re-visit*, *un-sub-titled*), suffixed words (e.g., *yawn-ing*, *hope-ful-ness*) and compounds, which are words that contain two or more lexical stems (e.g., *newspaper*, *balloon animal*). The consensus that has emerged from over 40 years of research is that morphologically complex words are decomposed during processing, meaning that the subcomponents of a multimorphemic word are identified during processing and influence the way the word is processed (e.g., the processing of *newspaper* involves the recognition of *news* and *paper*; see Amenta & Crepaldi, 2012 for a review). Research also suggests that readers store whole-word representations for multimorphemic words, though it is debated whether this is true for all or only some multimorphemic words (see Lignos & Gorman, 2012 for a review).

Psycholinguistic theories of reading hold that morphological structure is represented at lexical levels. While the processing of a monomorphemic word would involve the retrieval of a single lexical representation (e.g., <AWNING>), multimorphemic words would involve the retrieval of two or more lexical representations (e.g., <YAWN><ING>). Evidence exists that morphological structure may exist at pre-lexical levels as well. Rastle, Davis, and New (2004) reported that in lexical decision tasks, pseudo-suffixed words prime their pseudo-stems to the same degree that truly suffixed words prime their actual stems. For example, *brother* and *gluten* provide just as much facilitation for *broth* and *glute*, respectively, as *viewer* and *soften* do for *view* and *soft*, respectively. Rastle and colleagues showed that this was not due to simple orthographic similarity (e.g., *brother* primed *broth* better than *brothel* primes *broth*). Since the word *brother* is monomorphemic (i.e., not *broth-er*), these results suggest that decomposition occurs on the basis of orthographic matches to lexical items in addition to true morphological/semantic relatedness. That is, the reading system at least temporarily considers *brother* to be morphologically complex since it can be divided into two independently existing letter strings.

Rastle et al.'s (2004) findings can be accounted for by a pre-lexical stage of decomposition. Under this account, letter recognition processes produce morpho-orthographically grouped representations (B-R-O-T-H and E-R) rather than simple strings of letters (B-R-O-T-H-E-R). These morpho-orthographic groupings may activate an incorrect set of lexical representations (e.g., <BROTH><ER>), which must then be rectified based on the word's true lexical structure. To summarize, morphological structure thus is thought to exist in one form or another at both pre-lexical and lexical levels during reading.

A great debate within the morphological processing literature concerns exactly which words are processed as wholes and which are processed as morphemes. Some theorists have argued that all multimorphemic words are decomposed into their component morphemes (e.g., Taft & Forster, 1975; Stockhall & Marantz, 2006) while others have argued that all familiar words are retrieved as wholes (e.g., Butterworth, 1983; Caramaaza, Miceli, Silveri & Laudanna, 1985; Caramazza 1997). Many others, however, have proposed that both types of processing are available and that the properties of a word and its constituents will determine whether it is processed more holistically or componentially. For example, it has been proposed that multimorphemic words that are higher in frequency will tend to be processed as whole words (Alegre & Gordon, 1999; Biedermann, Beyersmann, Mason, & Nickels, 2013; Nickels, Biedermann, Fieder, & Schiller, 2014) while words with high-frequency constituents will be tend to be processed in a more componential manner (Baayen, 1992; Frauenfelder & Schreuder, 1992; Hay, 2003). It has been similarly proposed that transparent words (words whose meaning is straightforwardly related to the meaning of their constituents, e.g. *mistype*, *regenerate*) will be processed in a more morpheme-based manner while words with opaque semantics will be processed more holistically (e.g., *mistake*, *remember*; Marslen-Wilson, Tyler, Waskler, & Older, 1994; Schreuder & Baayen, 1995). Lastly, a similar role for a word's phonology has been proposed where words whose constituents are easily identified based on their transparency or phonotactic cues are more likely to be processed componentially than words whose phonological form obscures their internal structure (Hay, 2003; Schreuder & Baayen, 1995). For example, it is proposed to be easier to identify that *cultural* is related to *culture* than it is to identify that *natural* is related to *nature*. It is also proposed to be easier to identify that *humidness* is multimorphemic than *humidity* since the sequence /dn/ is phonotactically illegal within English morphemes. In general, these and related theories argue that it is the salience of a multimorphemic word's constituents and the word as a whole that will determine how it is processed.

1.3. Reading Aloud

Finally, the representations and processes described above are theorized to comprise how individuals read when they read for meaning; individuals can also read words aloud, in which case they must generate a pronunciation for a written word. It is commonly believed that there are two general mechanisms for generating a word's phonological form (e.g., Coltheart, Rastle, Perry, Langdon, & Ziegler, 2001). Words that have been encountered before are thought to have their pronunciations stored in long-term memory and thus can be accessed through lexical retrieval. This 'lexical route' to pronunciation is proposed to involve the stages described above; once a word's semantic representation has been retrieved, activation spreads to the word's entry in the phonological lexicon, providing access to its stored phonological form which is then used to drive articulation. It is theorized that pronunciations may also be computed by rule. This 'sub-lexical' route is proposed to transform the string of graphemes produced by letter recognition processes into a string of phonemes using knowledge of the common grapheme-phoneme mappings of the language (e.g., SH → /ʃ/).

1.4. Reading-related synesthesia

We now review previous research on reading-related synesthesia and interpret the various findings in light of the cognitive architecture described above.

1.4.1. Pre-lexical processing

A couple of studies have found that individuals with grapheme-color synesthesia often report that letters with similar visual structures have similar colors (e.g., V, W, X), suggesting that the process that associates colors to letters may operate over relatively early representations in the reading process, specifically levels involving basic physical features (Brang, Rouw, Ramachandran, & Coulson, 2011; Watson, Akins, & Enns, 2012). Other research has shown that color percepts can be linked to the *identity* of the letter rather than its form. For example, some synesthetes report perceiving the same color for visually dissimilar allographs of the same letter (Grossenbacher & Lovelace, 2001; Smilek, Dixon, Cudahy, & Merikle, 2001) as well as typically-presented and mirror-reversed letters (Ramachandran & Seckel, 2015). Other studies have shown that an ambiguous character's color frequently depends on its context (e.g., Z in 'XYZ' and '1Z3'; Dixon, Smilek, Duffy, Zanna, & Merikle, 2006; Kim, Blake, & Kim, 2013; Myles, Dixon, Smilek, & Merikle, 2003), implying top-down information influences which colors are perceived. Lastly, there is evidence that a letter's frequency and order in the alphabet influence aspects of its associated color (Watson et al., 2012; Simner, Ward, Lanz, Jansari, Noonan, Glover, & Oakley, 2005). These findings demonstrate that color percepts can be related to a relatively abstract stage of graphemic processing where visually dissimilar structures are categorized as the same letter/number (e.g., abstract letter identities).

A number of studies have demonstrated that other aspects of pre-lexical processing influence color percepts. For example, Rapp, McCloskey, Rothlein, Lipka, and Vindiola (2009) described a grapheme-color synesthete who perceived colors for vowel letters but not consonant letters, consistent with psycholinguistic theories positing that orthographic consonants and vowels are processed/represented differently from each other (e.g., Berent & Perfetti, 1995; Cubelli, 1991). Word-level colors in cases of lexical-color synesthesia have been variously reported to be determined by the first letter (e.g., Baron-Cohen, Harrison, Goldstein, & Wyke, 1993; Paulesu, Harrison, Baron-Cohen, Watson, Goldstein, Heather, Frackowiak, & Frith, 1995), first consonant/vowel (e.g., Ward, Simner, & Auyeung, 2005), stressed vowel letter (e.g., Simner, Glover, & Mowat, 2006), and in Mandarin characters, radical function and position (Hung, Simner, Shillcock, & Eagleman, 2014), suggesting that the underlying synesthetic processes are sensitive to not just letter identity but structural prominence of one sort or another. Simner et al. (2006) also report evidence that lexical colors may be determined by competition among a word's letters, consistent with spreading activation theories of reading (e.g., McClelland & Rumelhart, 1981). Lastly, data from Japanese indicate that Hiragana characters that are phonologically similar tend to have similar colors, suggesting that sub-lexical orthography-phonology processes may be involved in reading-based synesthesias (Asano & Yokosawa, 2013; see also Moos, Smith, Miller, & Simmons, 2014).

1.4.2. Post-lexical processing

While the studies above point to a critical role of graphemic levels of processing in reading related synesthesia, another strand of research has demonstrated that semantic representations play a decisive role in lexical-color synesthesia, that is, the perception of colors for entire words. Rich, Bradshaw, and Mattingley (2005) found that words of concepts that are typically ordered in a sequence (days of the week, months of the year) are often colored according to different principles than words for non-sequential concepts (e.g., names, occupations; see also Participant KA reported in Ward et al., 2005). Color words frequently take on the color they refer to (e.g., *orange* being reported as orange; Asano & Yokosawa, 2012; Rich et al., 2005) and to a lesser extent, individual words have been reported to take on a color associated with their meaning (e.g., *banana* perceived as yellow; Rich et al., 2005; Yokoyama, Noguchi, Koga, Tachibana, Saiki, Kakigi, & Kita, 2014). Lastly, a number of reports indicate that for some individuals, lexical colors may be restricted to a particular semantic class such as proper names (e.g., Simner et al., 2006; Ward, 2004; Weiss, Shah, Toni, Zilles, & Fink, 2001; as cited in Simner, 2007). In a recent fMRI study of an individual who experiences all three sorts of lexical colors (some lexical colors are determined by the initial letter, some by the word's order in a sequence, and some words by their conceptual features, e.g., *banana*-yellow), Yokoyama et al. (2014) found that distinct brain areas were involved in each percept, supporting both the reality and distinctiveness of semantically-driven synesthetic percepts.

1.5. Present Investigation

The studies described above provide exquisitely detailed information about the factors that govern reading-related synesthetic associations[1]. Specifically, they indicate that colors become associated with different sorts of representations used by the reading system (graphemes/character radicals, semantic features) and individuals experience these colors when the associated representations become active in one way or another during processing (though see Simner, 2012 for concerns as to whether certain grapheme-color findings reflect online processing or just the initial learning experience). Unfortunately, major gaps in our understanding of how synesthesia emerges from the reading process remain.

Researchers have tended to cast synesthesia as either a low-level (sensory/perceptual; e.g., Ramachandran & Hubbard, 2001) or high-level (semantic; e.g., Chiou & Rich, 2014; Nikolić, 2009) phenomenon (though see Mroczko-Wąsowicz & Nikolić, 2014 for an integrative perspective). While the fact that abstract letter identities play a role in color-grapheme synesthesia indicates that synesthetic experiences are not derived entirely from low-level

---

[1] While the studies reviewed in Sections 1.4.1 and 1.4.2 all involve a participant's native orthography, we note that synesthetic studies of cross-linguistic and later- and experimentally-learned graphemes provide converging evidence for the same levels of processing: visual form, sound, and meaning (e.g., Asano & Yokosawa, 2011; 2012; Blair & Berryhill, 2013; Jürgens & Nikolić, 2012; Mroczko, Metzinger, Singer & Mikolić, 2009; Shin & Kim, 2014; Witthoft & Winawer, 2006).

perceptual information, the question remains as to whether synesthesia may be influenced by all levels of the reading process or only the very early and late stages.

One answer to this question would be if it were possible to find evidence for the involvement of lexical processes in synesthetic experiences. As discussed in Section 1.1, lexical processes are responsible for retrieving the lexical units that mediate between graphemes and meaning and thus reflect an intermediate stage of the reading process. If it could be shown that lexical processing influences synesthetic experiences, this would indicate that synesthesia is neither exclusively a low-level nor a high-level phenomenon.

Unfortunately, though some of the phenomena described above may seem lexical in nature, none of them directly reflect lexical processing. While individuals have been reported who experience 1) a color derived from a word's meaning that is 2) spatially co-extensive with the word as a whole—facts that *seem* to implicate word-level processing—neither of these properties truly arise from lexical stages of processing. Specifically, while psycholinguistic theories of word processing posit that lexical entries provide access to a word's meaning, it is the meaning itself that ultimately drives the color in these cases. Second, the fact that lexical color is experienced as co-extensive with the word itself may simply be due to a process whereby synesthetic experiences are delimited by whitespaces, a pre-lexical property. Determining whether the apparent lack of lexical influence is something that defines reading-related synesthesia or is simply an as-yet unreported phenomenon is of critical theoretical importance for our understanding of the synesthetic phenomenon.

A related question concerns the flow of information between the cognitive systems underlying synesthesia and reading (Mroczko-Wąsowicz & Nikolić, 2014). The fact that the synesthetic percepts that have been reported to date relate primarily to the endpoints of the reading process raises the possibility that synesthesia and the reading system are *functionally modular* in the sense of being informationally encapsulated. In such an arrangement, very little information about the reading process would determine an individual's synesthetic experiences. For example, it could be the case that only the final outputs of the reading process—the letter that is ultimately recognized, the meaning of the recognized word—determine which color an individual will experience. The reading system would in essence be a black box and synesthetic experiences would be only superficially related to orthographic processing, being determined only by what emerges from that box.

It also is possible, however, that synesthesia arises more directly from the inner workings of the reading system. If this were true, synesthetic experiences would be influenced by the *specific computations* that subserve the reading process. In this scenario, the reading system would be 'penetrable' to synesthesia and the qualities of synesthetic percepts would be determined not only by the final outputs but the various factors that influence the reading process itself. The fact that a word's lexical color in some cases bears traces of letter competition (Simner et al., 2006) is consistent with the notion that the reading system is cognitively penetrable to synesthesia. That is, the synesthetic experience appears in those cases to be influenced by the mechanisms responsible for letter selection (see also Moos, Simmons, Simner & Smith, 2013 who report visual synesthetic percepts associated with sub-phonemic vocal features).

In the present study we report the case of WBL, an individual who experiences colors for both letters and words when reading. In order for lexical stages of processing to be implicated in synesthesia, it is necessary to demonstrate that aspects of *lexical* processing influence an individual's percepts. One way to do so would be to demonstrate that factors known to influence lexical processing (e.g., lexical frequency, neighborhood density) also influence synesthetic percepts. Another way would be to demonstrate an influence of lexical morphological structure, for example demonstrating a difference between words that comprise one and two lexical units (e.g., mono- and multimorphemic words). Although influences of lexical frequency and morphology have been informally reported (Kubitza, 2006; Mankin, 2014; Mankin, Thompkins, Ward, & Simner, 2015) to our knowledge no such studies have been published to date.

To address whether lexical representations can play a critical role in reading-related synesthesia and whether the processes that underlie synesthesia and the reading process are modular or interactive, we examined WBL's perception of multimorphemic words. In Experiment 1 we established the basic properties of WBL's lexical-color synesthesia, ascertaining what determines a word's color, whether his word-coloring is a productive process, and whether his lexical percepts are influenced by a word's morphological structure. To anticipate the results regarding the latter issue, we find that WBL always perceives one lexical color for monomorphemic words but frequently perceives two lexical colors for bimorphemic words. This establishes that lexical (morphological) structure can play a critical role in reading-related synesthesia. In Experiment 2, we investigated the degree to which the internal dynamics of the reading process determines WBL's percepts. To do so, we analyzed how psycholinguistic properties from different stages of processing influence WBL's perceptions of compound words. We find a complex interaction of perceptual, graphemic, lexical, and semantic factors, indicating that synesthetic percepts are influenced by the specific computations carried out by the reading system. This indicates that the reading system is penetrable rather than modular, and that orthographic-based synesthesia is intimately—rather than superficially—related to the reading system.

Before continuing we wish to note that as a case study, our investigation informs cognitive theorizing by helping to delimit the space of possible functional and neural architectures. This research contributes to a set of findings that theories of synesthesia and reading must ultimately be able to account for (e.g., Caramazza, 1986). We readily acknowledge, however, that there is considerable heterogeneity in how synesthesia manifests across individuals (e.g, Novich, Cheng, & Eagleman, 2011; Rich, Bradshaw, & Mattingly, 2005; Simner, Mulvenna, Sagiv, Tsakanikos, Witherby, Fraser, Scott, & Ward, 2006) and in the way that the reading architecture develops in different individuals (e.g., Duñabeitia, Perea, & Carreiras, 2015; Welcome & Joanisse, 2012) and languages (e.g, Frost, 2012).

1.6. Case Description: WBL

WBL is a 21-year-old, right-handed male who had some graduate-level education at the time of testing. He recalled experiencing synesthesia since approximately age 7. He experienced three concussions in his life, one from a car accident and two from wrestling, but he reported that the incidents did not induce or change his color perceptions. WBL was diagnosed with dyslexia at 20 years old, which manifests primarily as difficulty with sentence comprehension and spelling. He has also been diagnosed with bipolar disorder, although WBL reports that neither condition affects his synesthetic experiences. He is a native English-speaker, and has studied French and Mandarin.

To verify the authenticity of WBL's synesthesia, we administered the online Synesthesia Battery (Eagleman, Kagan, Nelson, Sagaram, & Sarma, 2007; http://www.synesthete.org/), which includes a grapheme-color consistency test and a speeded congruency test. In the grapheme-color portion of the battery, the participant is presented with each number and letter (in uppercase) three times in random order and is asked to select the color that matches their perceptions from a digital color picker capable of displaying 16.7 million colors. According to Eagleman et al. (2007), consistency scores below 1.0 and speeded congruency accuracy above 85% are consistent with synesthetic performance. WBL scored 0.85 on the consistency test and was 91.7% accurate on the speeded congruency test, validating that WBL does in fact have synesthesia.

Recently, Rothen, Seth, Witzel, and Ward (2013) suggested that the sensitivity of the Synesthesia battery could be improved by using perceptually accurate measures of color difference. To verify that WBL is categorized as synesthetic under their stricter measure, we converted WBL's RGB values into CIELAB, a more uniform color space that better accords with human perception. All color conversions and similarity calculations were carried out in Python using the *colormath* module (Taylor, 2014). Following Rothen et al.'s (2013) procedure, we calculated the pairwise Euclidean distance of the 3 CIELAB color judgments that WBL produced for each grapheme.[2] Each grapheme's three distances were then summed together and the mean summed distance for the entire set of letters and numbers (A-Z, 0-9) was calculated. WBL's average summed distance was 53.7, falling well below the 109.2 cutoff suggested by Rothen et al. (2013) and even the average value they report for their synesthetic cohort (69.5). As a final measure of his color consistency, WBL was readministered the Synesthesia Battery three months after the initial administration. This time, he scored 0.54 on the consistency test and was 95.8% accurate on the speeded congruency test, again scoring below the 1.0 consistency threshold and above the 85% accuracy threshold suggested by Eagleman et al. (2007). WBL's average summed CIELAB distance was 35.8, again well below the 109.2 cutoff suggested by

[2] Various methods of calculating distance in CIELAB color space have been proposed. Calculating the Euclidean distance between the L*, a*, and b* values of two CIELAB colors is referred to as 'ΔE1976' and is the method we use throughout this investigation.

Rothen et al. (2013). To quantify the consistency of WBL's colors across time, we calculated the average CIELAB value for each grapheme in the first administration and calculated its Euclidean distance from the average value of the second administration. The average difference across the two administrations was 14.5 and the maximum difference was 34 (letter Y). Figure 1 presents WBL's color selections from the first and second administrations.

In addition to grapheme-color synesthesia, WBL reported experiencing musical pitch-color, number-spatial, weekday-color, and month-spatial synesthesia. Most notably for our investigation, he also experiences lexical-color synesthesia, meaning he experiences colors for whole words. WBL is considered an associator since he sees the colors in his mind's eye rather than projecting the color onto words (Dixon, Smilek, & Merikle, 2004).

2. Experiment 1

The goal of Experiment 1 was to establish the basic facts of WBL's lexical-color synesthesia. In particular, we sought to determine the factors that determine his lexical colors, whether these colors are productive, and whether morphological structure influences his lexical color percepts.

2.1. Methods

2.1.1. Design and materials

We created a list of 1,194 target words. The list was comprised of 100 prefixed words, 100 suffixed words, 100 compound words, 66 pseudocompound monomorphemic words (words that orthographically contain other words but that are not morphological compounds e.g., *carpet*, *pumpkin, hemlock*), 100 nonwords, and 728 monomorphemic words, 358 of which are individual stems of the compound words. Values for stimulus length, orthographic neighborhood size, average bigram frequency, and lexical frequency are given in Table 1.[3] This list was divided into blocks in which the multimorphemic words always made up no more than 50% of the total words, and the nonwords made up their own block. The order within each block was completely randomized.

Stimuli were presented one word at a time in a full screen PowerPoint presentation. Each word was shown in the center of the screen in lowercase black Calibri font, size 44, on a white background, with the trial number in the bottom right corner. Color judgments were chosen from an online color picker (http://html-color-codes.info/#HTML_Color_Picker) capable of displaying 16.7 million colors, from which corresponding RGB hex values could be easily copied. Responses were collected in an Excel spreadsheet that contained a column indicating the trial number, a column to type or paste the hex color value, and a column to write in comments or notes. The monitor used to present the words was either a 20-inch HP w2007 or a 21.5-inch iMac, and the monitor used to choose colors and collect responses was a 27-inch iMac computer. All of the computers had identical display settings across sessions; chromaticity coordinates of the iMac monitor used to make color selections are provided in Appendix A.

2.1.2. Procedure

WBL was tested in 90-minute sessions on a weekly basis for five weeks and was compensated $15 per session. During testing, he was seated in front of two computers. The primary computer had the Excel spreadsheet open on the left side of the screen and the online

[3] The lexical frequency values reported here are log-transformed values derived from the SUBTLEX-US corpus (Brysbaert & New, 2009). This frequency norm is described in more detail below.

color picker on the right side of the screen. The secondary computer showed the PowerPoint presenting each word one at a time. WBL pressed the spacebar on the secondary computer to proceed through the list of words at his own pace. For each word, he would use the primary computer to choose the color he associated, then copy and paste the hex value into the Excel spreadsheet. Trial numbers were used to ensure that the color judgments would get matched with the correct word.

WBL was instructed to select a color for each target word. If he had no color association, did not recognize the target word, or had any other comments, he was instructed to make a note in the comments column in the response sheet. Although we hypothesized he would perceive 2 colors for bimorphemic words, our instructions did not make reference to 2-color judgments. WBL was instructed that he could also take breaks at any point for any duration during testing. WBL made judgments for approximately 250 words per 90-minute session.

2.2. Results

WBL made lexical color judgments for all 1,194 words. To learn about the factors that determined the overall color he perceived for words, each of the 728 monomorphemic words was subjectively coded as to the likely source of the color. Coding proceeded using the following procedure: if a word's color seems visually similar to the first letter in the word, categorize it as matching the first letter; else, if it seems to possibly relate to the meaning of the word, categorize it as matching the semantics; else, if it seems to match a different letter in the word, categorize it as matching a different letter; else, categorize it as indeterminate. For the color judgments of the 728 monomorphemic words, 94.5% matched the color of the first letter, 2.2% matched another letter, 1.0% were based on the semantic meaning (e.g., *blood* was judged as red although B is colored green), and 2.3% were categorized as indeterminate. This indicates that WBL's color judgments are overwhelmingly determined by the color of the first letter. To provide some validation of this coding, the CIELAB distance between each monomorphemic word's lexical color and the color of its first letter was calculated. Responses that had been categorized as matching the first letter had on average a much smaller distance to their first letter (*M* = 19.7, *SD* = 13.6) than responses that had been classified otherwise (*M* = 108.3, *SD* = 56.4; t(39.26) = -9.92, p < .001). This suggests that our subjective coding was largely driven by objective color similarity, giving us confidence that WBL's lexical color percepts were indeed usually driven by the color of the first letter in the word.

Examination of WBL's responses indicated that the only words that systematically did not match the color of the first letter were words that begin with I or O. Although WBL judged these letters to be white in isolation, when they appeared at the beginning of a word he frequently judged the lexical color to be a lighter shade of another letter in the word. For example, *item* was reported as 'item' (individual letter colors, based on WBL's alphabet: item), *improvise* was reported as 'improvise' (improvise), *owe* was reported as 'owe' (owe), and *of* was reported as 'of' (of). It may be the case that stem-initial O and I took on the color of another letter in the word or did not strongly contribute its own white percept, leading the colors of other letters in the word to become more prominent. It may also be the case that this pattern was a product of the way we presented the stimuli in this experiment. Smilek et al. (2001) found that a grapheme-color synesthete took longer to verify whether a field of letters contained a particular letter when the background color matched the synesthetic color of the target letter. Accordingly, it is possible that presenting the stimuli on a white background may have reduced the salience of these letters' synesthetic color.[4]

Given that phonological representations play a crucial role in the reading process and reading-related synesthesias (e.g., Asano & Yokosawa, 2011; 2012; Shin & Kim, 2014), we next sought to determine whether it is a word's initial letter or phoneme that determines the word's overall color. As can be seen in Figure 2, words that began with the same letter but different phonemes (e.g., *captain, coat, cider,* and *cyclic*) were judged to have the same color. This is strikingly manifest in the A-initial words listed in Figure 2 which begin with /eɪ/, /ə/, /aɪ/, and /æ/, respectively. . Likewise, words that began with the same phoneme but different letters were colored differently (e.g., *keep*, *kerosene*, and *koala* were green while *captain* and *coat* were yellow). This unambiguously indicates that WBL's lexical color percepts are derived from the word's orthography.

Next, we examined WBL's judgments to nonwords to determine whether his lexical colors are an active component of the reading process. For the 100 nonword color judgments, 88.0% matched the first letter, 10.0% matched another letter, and 2.0% were indeterminate. The fact that nonwords were colored in the same way as real words demonstrates that WBL's lexical colors are produced by a productive, "rule"-based process as opposed to simply being stored and retrieved for each word. It also demonstrates that WBL's lexical colors do not depend on semantics and provides further evidence that they are primarily determined by the first letter in the word.

Turning now to the multimorphemic words, WBL frequently reported perceiving these words as containing two lexical colors. WBL's notes indicated that these lexical colors were

[4] We thank an anonymous reviewer for this suggestion and hope to investigate this issue in future testing sessions.

spatially aligned with each morpheme, for example writing for *dreamland* “distinctly blue AND yellow (dream = 0716B3, land = C4D90B)”. We first analyzed his responses to determine the source of the lexical color, using only the leftmost color (i.e., ignoring the rightmost color, if present). Of his 300 multimorphemic judgments, 92.0% matched the first letter, 4.0% matched another letter in the word, 0.7% was based on the semantic meaning, and 3.3% were indeterminate. This indicates that the lexical colors he perceived for multimorphemic words were also primarily based on the color of the first letter. We then assessed the rate at which he perceived multimorphemic words as having two colors. Since these stimuli were selected before we determined that the first letter drove WBL’s lexical colors, some multimorphemic words had morphemes that by chance began with the same letter (e.g., *pinpoint*) or that began with different letters that had similar colors. On the assumption that WBL could not perceive two distinct colors for words containing identical or similarly colored morpheme-initial letters, we removed words with letters that were judged too similar in color, operationally defined as a LAB Euclidean distance of less than 30. This comprised 110 letter pairs out of 676 total combinations in English. Visual inspection confirmed that the remaining letter combinations were noticeably different colors. After excluding the multimorphemic words in which the first letters of each morpheme had a very similar color (53/300), WBL reported two colors for 12.4% of the prefixed words (11/89), 1.3% of the suffixed words (1/78—*goodness*), and 16.3% of the compound words (13/80). These judgments contrast sharply with the monomorphemic words and nonwords—none of which were judged as bearing two colors—indicating that his lexical colors were influenced by a word’s morphological structure.

As discussed in Section 1.2, morphological structure has been hypothesized to be present at both pre-lexical orthographic and lexical levels of processing. In order to determine whether

WBL's bichromatic judgments reflected true morphological (lexical) structure or simply the presence of common letter strings, his 66 pseudocompound color judgments were analyzed. Analysis of the overall source of the color indicated that 97.0% matched the first letter, 3.0% matched another letter, 0% was based on the semantic meaning, and 0% was indeterminate. Critically, after removing words whose letters were too similar in color (distance <30 in LAB space; 17/66), only 1 out of the remaining 49 pseudocompounds (2%—*bulldoze*) was judged as having distinctly two colors. Using a Fisher exact test, this distribution of bichromatic judgments for pseudosuffixed words was found to be significantly different from what would be expected based on the compound distribution ($p = .017$).[5] All of the proportions of bichromatic judgments for Experiment 1 are summarized in Table 1.

One issue that is important to address is that word length was not controlled across the different morphological types, leaving open the possibility that length and not morphological structure was the driving force behind the different pattern of judgments for mono- and multimorphemic words.[6] We performed a post-hoc test to determine whether morphology still influenced WBL's judgments when word length was controlled. To control for word length, we extracted all of WBL's judgments to monomorphemic and compound words that were 8 or more letters in length (the mean length of the compounds). The resulting 59 monomorphemic words and 52 compound words did not differ in length (8.8 letters vs. 8.7 letters, $t(108.8) = -.75$, $p =$

[5] The significant difference in the proportion of 1 vs. 2 color judgments between compound and pseudo-compounds did not depend on and was not an artifact of the process that excluded items with visually similar morpheme-initial colors. He perceived significantly fewer pseudocompounds as having 2 colors when all items are retained ($p = .009$).

[6] We thank an anonymous reviewer for pointing out this issue.

.45). Crucially, 0/59 of the monomorphemic words had been judged to be bichromatic while 12/52 (23%) of the compounds had been judged to be bichromatic, a difference that was revealed by a two-tailed Fisher exact test to be statistically significant (p = .00005). This confirms that morphological structure contributed to WBL's color judgments independently of length.

2.3. Discussion

It is well established in the literature that lexical colors are frequently determined by the color associated with the first letter in the word (Baron-Cohen et al., 1993; Paulesu et al., 1995). The same appears to be true for WBL, who perceives both words and nonwords as bearing the color of the first letter in the word. Critically, WBL's lexical color percepts are additionally determined by a word's morphological structure—WBL frequently reported perceiving two lexical colors for prefixed and compound words but not monomorphemic words. One aspect of these results that does not fit with this general picture is that WBL rarely reported suffixed words as having two colors. This may be because the suffixes that appeared in this stimulus set tended to be very short (mean letter length = 2) and may not have been very salient. We investigate this issue further in Experiment 2.

The fact that WBL experienced bichromatic percepts for multimorphemic words but not pseudocompounds suggests that these morphological effects arise at lexical levels of processing rather than pre-lexical graphemic stages. Given that we are particularly interested in lexical stages of processing, it is critical to consider whether other stages could conceivably account for these results. Could a word's semantics be driving WBL's bichromatic percepts? Many multimorphemic words are semantically transparent in that their meaning can be interpreted as a relatively straightforward combination of the meaning of their parts (e.g., *teacup*, *unhappy*). Could it be the case that when reading morphologically complex words, it is not the presence of multiple morphemes that trigger WBL's bichromatic experiences but the presence of multiple components of meaning? Here, the answer appears to be unambiguously 'no'. Linguists have argued that although it is possible to identify overlaps in meaning between, say, compounds and their constituent stems, a word's morphological structure is not reducible to its meaning. As Badecker (2001) argues, languages frequently contain monomorphemic and multimorphemic synonyms (e.g., *daybreak*/*dawn*, *hot chocolate*/*cocoa*, *icebox*/*freezer*). Likewise, languages differ as to whether the same concept is expressed by a single or multiple morphemes (French *papillon*, vs. English *butterfly*; Hittmair-Delazer, Andree, Semenza, De Bleser, & Benke, 1994). This indicates that a word's meaning is not sufficient to determine if it has a unitary form or one that is composed of other forms that exist in the language (see also Jackendoff, 2010).

Returning to orthography, although the common letter strings found in pseudocompounds (e.g., *carpet*) were not sufficient to trigger bichromatic percepts, other orthographic phenomena exist that correlate with morphological structure, leaving open the possibility that WBL's percepts were not truly related to morphological structure. Morpheme boundaries are often marked by low frequency bigrams (Seidenberg, 1987), and there is some evidence that readers may exploit such bigram 'troughs' and other orthographic information as cues to morpheme boundaries (Bertram, Pollatsek, & Hyönä, 2004; Lemhöfer, Koester, & Schreuder, 2011; though see Kuperman, Bertram, & Baayen, 2008). Thus, it is possible that low-probability bigrams invite bichromatic percepts rather than true morphological structure.

In Experiment 2 we sought to provide more compelling evidence for a true role of morphology and lexical levels of processing. We also sought to ascertain whether the nuances of the reading process—that is, the properties of various component computations—influenced WBL's synesthesia. Although WBL's bichromatic percepts may not arise exclusively from orthographic or semantic stages of processing, it is entirely possible that these levels interact and play an important role in determining their form, implicating an interactive rather than modular relationship between reading and synesthesia.

3. Experiment 2

In order to determine how reading processes and morphological structure influence synesthetic experiences, we conducted an in-depth investigation of WBL's perception of compound words. As multimorphemic words, compounds provide a window onto the role that lexical processing plays in synesthesia. Moreover, compounds are composed entirely of lexical stems (independently existing words), allowing us to investigate rather straightforwardly the contribution that many stages of processing make to WBL's synesthetic experiences. Compounds offer the opportunity, for example, to assess whether orthographic properties such as bigram frequency, lexical features such as word and stem frequency, and semantic features such as concreteness influence the number of synethetic colors that WBL perceives.

As described in Section 1.2, psycholinguistic studies on morphology have suggested that various factors may influence the degree to which a compound is processed as an independent word or as a collection of its parts. In these studies, researchers make typically inferences about morphological processing by determining how a particular behavioral outcome (e.g., lexical decision latencies, eye movements) is influenced by a word's various properties (e.g., compound frequency, stem frequency). While there are numerous ways in which one could analyze synesthetic color judgments, we built on Experiment 1's primary finding that monomorphemic words were always perceived as bearing a single lexical color while bimorphemic words were often perceived as having two colors. It is reasonable that the number of lexical colors WBL perceives for a given compound relates to that word was processed morphologically. A unitary lexical color (e.g., perceiving *waterproof* as *waterproof*) would suggest that the properties of the compound and/or its constituents led WBL to process the word in a more holistic fashion. Meanwhile, a judgment of two colors (e.g., perceiving waterproof as *waterproof*) would be consistent with the notion that some properties led componential processing to dominate for that word, causing each stem's initial letter to become prominent and contribute a distinct lexical color. The goal of Experiment 2 thus was to determine how various psycholinguistic properties contribute to the number of lexical colors WBL perceives, allowing us to make inferences about which stages of the reading process may contribute to synesthetic experiences. To this end, the dependent variable was whether each compound was perceived as having one or two lexical colors and logistic regression was used to determine how psycholinguistic properties contributed to these percepts.

3.1. Methods

3.1.1. Design and materials

Recently, Juhasz, Lai, and Woodcock (2014) published a detailed database of semantic norms for English compounds. This database contains ratings of 6 semantic variables (described in Section 3.1.2.1 below) for 629 English compound words, each collected from an average of 15 participants. Juhasz et al. (2014) found that many of these variables predicted lexical decision and oral reading latencies even when other variables such as lexical frequency and letter length were controlled, suggesting that they play an important role in the way English compounds are typically processed. The compound stimuli for Experiment 2 were selected from the Juhasz database in order to make use of these new semantic norms.

To create the list of compounds, we started with the entire set of 629 compounds listed in Juhasz et al. (2014), all of which are bimorphemic and spelled without a space or hyphen. Any compound that had been tested in Experiment 1 or whose stem-initial letters were judged too similar in color for WBL to reliably distinguish (stems with identical first letters and/or whose color distance in CIELAB space was <30) were excluded. This resulted in a set 435 compounds.

Since making judgments solely to compound words could bias WBL's morphological processing (e.g., Cohen-Shikora & Balota, 2013), we also created a set of filler words comprising 399 bimorphemic suffixed words (containing derivational and inflectional suffixes) and 766 monomorphemic words. In addition to increasing the morphological diversity of the stimuli, the filler items served to some extent as controls, allowing us to gauge whether the general character of WBL's lexical color judgments was comparable across Experiments 1 and 2.

All together, the critical and filler stimuli formed a list of 1600 words that was approximately half mono- and half multimorphemic (psycholinguistic properties are listed in Table 2). Among the suffixed words, nearly all of the suffixes were longer than one letter (mean suffix length: 2.6; min = 1, max = 4). The order of trials was completely randomized.

3.1.2. Procedure

WBL was tested in seven 60- to 90-minute sessions over three weeks. He was compensated $5 per 30 minutes of testing. Testing followed the same procedure as Experiment 1.

As in Experiment 1, each response was manually categorized according to the likely source of the lexical color (e.g., first/other letter, word meaning, etc.) and was coded for whether WBL reported 1 or 2 lexical colors. The primary analysis examined the psycholinguistic factors that influenced WBL's synesthetic experiences of the compound stimuli. Each compound response was given a binary coding: responses with a single lexical color (e.g., *waterproof*) were coded as '0' and responses with 2 colors (e.g., *waterproof*) were coded as '1' (WBL never reported compounds as having any other number of lexical colors). Responses were coded in this manner irrespective of whether the lexical color(s) matched the color of the first letter in the word/stem(s) since our question of interest concerned the relative importance of the stems vs. the whole word, not the relative importance of the individual letters.

Logistic regressions were then fit to these binary data to determine which psycholinguistic properties influenced the number of lexical colors WBL perceived. We selected a number of properties from different stages of the reading process that have been shown to influence reading. For our analyses, we divided these properties into two groups, semantic and non-semantic. All analyses were conducted using the *glm* function of the *stats* package in R (version 3.2.1).

3.1.2.1. Non-Semantic Variables.

The following non-semantic variables were included in our analyses. Trial Number encoded the number of the trial in which the compound stimulus was presented and was designed to control for possible changes in the way that WBL responded over the duration of the experiment. Two variables encoding letter color similarity were created to evaluate the possibility that the perceptual nature of WBL's experiences influenced his perception of multimorphemic words. Since WBL's lexical colors were primarily determined by the color of the stem-initial letter, it is conceivable that WBL would find it easier to judge a compound as having two colors if the colors of its stem-initial letters were relatively dissimilar. Likewise, morpheme segmentation may be facilitated when the letters that straddle the morpheme boundary have dissimilar colors. To test these possibilities, we defined Stem-Initial Letter Color Distance and Boundary Letter Color Distance, which respectively encoded the CIELAB distance of the first letter of each stem (e.g., T and M in *treadmill*) and the final letter of the left stem and the first letter of the right stem (e.g., D and M in *treadmill*). As before, this calculation utilized the grapheme colors WBL provided in the initial administration of the Synesthesia Battery.

To account for the possibility that bigram frequency was driving WBL's bichromatic percepts, the variable Boundary Bigram Frequency was created which encoded the token frequency of the bigram straddling the compound boundary (e.g., 'DM' in *treadmill*). Values for this variable were obtained from the lowercase bigram counts reported by Jones and Mewhort (2004) from their New York Times corpus.

Moving to lexical levels, the variables Left Stem Neighborhood Density and Right Stem Neighborhood Density encoded the number of each stem's orthographic neighbors (Coltheart, Davelaar, Jonasson, & Besner, 1977). Compound POS encoded the part of speech of the compound as whole. While some compounds have only a single part of speech (e.g., *treadmill*), others have multiple and are ambiguous in isolation (e.g., *wallpaper* and *trademark* are both nouns and verbs). For words where multiple parts of speech were listed, we selected the one identified as most frequent. Neighborhood density and part of speech values were obtained from the English Lexicon Project website ('ELP'; Balota et al., 2007).

Finally, given the central role that lexical frequency has been reported to play in morphological processing, we sought to determine whether stem and compound frequency play a role in WBL's synesthetic percepts. When considering which frequency counts to use, however, we were faced with the fact that frequency norms and transformations (raw/log) differ in how well they reflect mental processing. As we will describe below, we adopted an exploratory approach and empirically determined which frequency properties best predicted WBL's color judgments.

3.1.2.2. Semantic Variables.

The semantic variables we analyzed were the 6 properties reported by Juhasz et al. (2014): familiarity (typically thought of as a form of subjective frequency), age of acquisition (when in life a word is typically learned), imageability (how easily the word evokes a visual image), sensory experience (how easily the word evokes perceptual experiences more generally), transparency (the extent to which the meaning of the compound is related to the meaning of its stems), and lexeme meaning dominance (the extent to which the meaning of the compound relates primarily to the meaning of the left stem, the right stem, or both stems equally). Although it is beyond the scope of this paper to describe the procedures by which the entire set of norms was collected, Appendix B provides information about the rating scales that were used.

We additionally tested for an interaction between Lexeme Meaning Dominance and Stem Frequency. In an eyetracking study, Inhoff, Starr, Solomon, and Placke (2008) found that stem frequency interacted with lexeme meaning dominance in lexical decision, oral reading, and silent sentence reading tasks. They found that meaning-dominant stems (stems that primarily bear the meaning of the word as a whole, e.g., *hop* in *hopscotch*) exhibited larger frequency effects than stems that were not meaning-dominant (e.g., *straw* in *strawberry*).

3.1.2.3. Modeling Procedure.

The analysis proceeded in two stages; the non-semantic variables were analyzed first, followed by the semantic variables. We adopted this approach because many of the semantic variables are substantially correlated with each other and model estimates can become unreliable in the presence of collinearity. Juhasz et al. (2014) dealt with this issue in their own analysis by adding each semantic variable individually to a baseline model containing a set of nuisance variables and assessing whether it significantly increased the fit of the model to the data (see also

Kuperman, 2013). We used the same procedure for our own analysis except instead of adding the semantic variables to a baseline model of nuisance variables, we added them to a model containing the non-semantic variables.

The first step in our analysis of the non-semantic variables was to explore how best to enter frequency into the model. We considered two norms: the HAL frequency norms ('Hypertext Analog to Language'; Lund & Burgess, 1996) which were derived from nearly 400 million words of Usenet newsgroup text, and the SUBTLEX-US norms (Brysbaert & New, 2009), which were derived from a corpus of over 8,000 US film and television scripts (51 million words). As Brysbaert and New (2009) discuss, the size and content of a frequency norm's source material will influence how accurately it reflects the average English speaker's experience with language. Being derived from "spoken" language, the SUBTLEX database may better capture speakers' everyday use of language while the HAL database may better capture speaker's experience with written language.[7] We also considered whether raw or log-transformed frequency counts should be used in the present analysis. A half-century of psycholinguistic research has shown that performance on language tasks is often best predicted by log-transformed frequency counts (e.g., lexical frequency stands in a logarithmic relationship with

[7] Both SUBTLEX and HAL are 'surface' counts, which means they reflect how often each letter string appears in isolation and do not take into account morphological relationships (e.g., the frequency of *mill* does not include its appearance in *mills*, *milled, milling, windmill*, etc.). Brysbaert & New (2009) found that surface counts and root-based 'lemma' counts (which typically sum over a word's inflectional variants) faired equally well in accounting for English lexical decision and oral reading reaction times and accuracy, suggesting that surface counts are adequate for the present purposes.

RTs, visual duration thresholds, and recognition accuracy; Howes & Solomon, 1951; Oldfield & Wingfield, 1965; Rubenstein & Pollack, 1963; Whaley, 1978), indicating that to some extent, differences in frequency at the high end of the scale are less cognitively relevant for language processing than frequency differences at the low end. Since the present study is one of the first to examine lexical frequency in synesthesia, we sought to determine whether this relationship holds here as well. While the multiple comparisons conducted in these assessments may inflate the Type I error rate, we believe that it is beneficial to have data on these questions given the fledgling status of research in this area.

For the exploratory frequency analysis we created 4 models. Each model contained the variable Trial Number as well as Left Root Frequency, Right Root Frequency, and Compound Frequency. The frequency norms crossed with the transformations were varied across the four models (HAL/SUBTLEX x raw/log) —the first model used raw HAL frequency values, the second used raw SUBTLEX values, the third used log HAL values and the fourth used log SUBTLEX values. Each model was fit to WBL's binary color judgments and its Akaike Information Criterion value ('AIC', an information-theoretic measure of how well a model fits the data; Akaike 1973) was determined. The model containing Log SUBTLEX counts had the lowest AIC value (indicating the best fit), and so these frequency values were selected for our overall analysis.[8]

A baseline model containing the non-semantic variables (including log SUBTLEX frequency values) was then created and analyzed. Subsequently, each semantic variable was

[8] It is important to note that the models all had roughly similar AIC values, suggesting that they may have roughly equal predictive value in this domain (Log SUBTLEX: 288.8, Raw HAL: 289.2, Raw SUBTLEX: 293.0, Log HAL: 294.8).

separately added to the baseline model to determine if it significantly improved the fit of the baseline model. Predictor significance was confirmed using model comparison. In this procedure, the log-likelihood of one model is compared to the log-likelihood of a second model that contains all of the same variables and an additional variable of interest. Differences in the likelihood of nested models approximately follow a chi-square distribution (Agresti, 2002), and so a significant chi-square test of model likelihood indicates that the variable of interest significantly improved the fit of the model. In cases where two variables are correlated, pairwise model comparisons can be used to ascertain whether one variable is superior to the other. In this procedure, a model containing the baseline variables and one of the variables of interest is compared to a model containing the baseline variables and both variables of interest. This determines whether the added variable of interest accounts for a significant amount of the variance in the data above and beyond the former. A second comparison is made with the variables reversed, testing for whether the reverse situation holds. If each variable significantly improves on the other, this indicates that each variable accounts for distinct portions of the variance. If one variable significantly improves upon the other but the other does not, this indicates that the former accounts for a superset of the variance of the latter. Lastly, if neither variable improves upon the other, this indicates that both variables account for the same portions of the variance and are equivalent with respect to the DV.

3.2. Results

3.2.1. Overall Results

The overall pattern of WBL's responses was similar to Experiment 1. As before, lexical colors were nearly always determined by the first letter in the word. Considering the monomorphemic words, 95.2% were coded as matching the first letter, 4.1% matched a different letter, 0.4% were coded as reflecting their meaning, and 0.1% were coded as indeterminate. The general validity of this coding was again reflected in the fact that the words coded as matching their first letter were statistically and substantially closer in color to the color of their first letter ($M = 15.9$, $SD = 11.7$) than words coded otherwise ($M = 71.7$, $SD = 51.9$; $t(36.19) = -6.54$, $p < .001$). As can be seen in Table 2, the proportion of trials for which WBL reported perceiving two colors shows the same general pattern across word types as Experiment 1—compound words were frequently perceived as bichromatic while monomorphemic and suffixed words were not. The two monomorphemic words that were reported as bichromatic were *ma'am* and *bedlam*.

Examination of the responses indicated that WBL judged compounds containing stem-initial O and I (e.g., *outsmart*, *carryover*) as monochromatic 100% of the time. As before, these lexical colors appeared to always be related to the color of another letter in the word. For example, WBL reported *oatmeal* as 'oatmeal' (individual letters: oatmeal), *output* as 'output' (output), and *oxcart* as 'oxcart' (oxcart). Since this unique property appeared to dominate the way these compounds were perceived, we excluded all compounds with O or I as the first letter of the left or right stem from further analysis (48 compounds with stem-initial O and 1 compound with stem-initial I). Finally, it was determined while preparing the data for analysis that the compound *hitherto* contained a stem (*to*) whose lexical frequency was more than 15 standard deviations higher than the average stem in the compound set. As this extremely high frequency may cause it to be processed differently from other stems, we excluded this word from the compound analysis. This resulted in a final data set of 385 compound responses.

3.2.2. Compound Analysis

The results of the baseline model containing the non-semantic variables are presented in Table 3 (all variables were centered and scaled to facilitate comparison). Higher values of Trial Number, Stem Initial Color Difference, Left Stem Frequency, and Right Stem Length were found to significantly promote the perception of two colors (e.g., one for each stem in the compound) while higher values of Compound Frequency were found to significantly promote the perception of a single color for the compound. The remaining variables did not reach significance.

Since Left Stem Length was moderately correlated with Left Stem Frequency (r = -.3) and Right Stem Length was correlated with both Right Stem Frequency (r = -.3) and Right Stem ND (r = -.6), pairwise model comparisons were used to pinpoint which of these variables were significant in the model. Left Stem Frequency significantly improved on Left Stem Length ($\chi^2(1) = 6.63$, $p = .01$) but Left Stem Length did not significantly improve upon Left Stem Frequency ($\chi^2(1) = .13$, $p = .72$), indicating that the frequency of the left stem and not its letter length influences the number of colors that WBL perceives. The same procedure found that Right Stem Length contributed above and beyond Right Stem Frequency ($\chi^2(1) = 4.72$, $p = .03$) but not vice versa ($\chi^2(1) = .005$, $p = .94$), confirming that the length of the right stem and not its frequency was significant. Finally, Right Stem Length contributed above and beyond Right Stem ND ($\chi^2(1) = 4.72$, $p = .03$) but not vice versa ($\chi^2(1) = .11$, $p = .74$), confirming the former's significance in the model. To summarize, the frequency of the left stem and the letter length of the right stem were the stem-based lexical properties that contributed to WBL's synesthetic percepts.

In the second stage of the analysis, each semantic variable was individually added to the full set of non-semantic variables to see if it significantly improved the fit of the model. None of the semantic variables were found to be significant: Familiarity ($\chi^2(1) = .01$, $p = .91$); Age of

Acquisition ($\chi^2(1) = .88$, $p = .35$); Imageability ($\chi^2(1) = .1.12$, $p = .29$); Sensory Experience ($\chi^2(1) < .01$, $p = .97$); Transparency ($\chi^2(1) = 1.59$, $p = .21$); and Lexeme Meaning Dominance ($\chi^2(1) = 2.39$, $p = .12$). Interestingly, model comparisons revealed a significant interaction of Lexeme Meaning Dominance and Left Stem Frequency ($\chi^2(1) = 9.71$, $p = .002$), with the effect of left stem frequency increasing with LMD. Figure 3 presents the partial effects of this interaction; the panels depict the effect of Left Stem Frequency for low, medium, and high values of LMD (from left to right). When LMD is low (compounds whose meaning is carried primarily by the meaning of the left stem), the effect of left stem frequency is negligible (Figure 3, left panel). When LMD is high (compounds whose meaning carried primarily by the meaning of the right stem), there is a strong effect of left stem frequency, with higher frequency leading to a greater likelihood of judging a compound as bichromatic (Figure 3, right panel). LMD did not significantly interact with Right Stem Length ($\chi^2(1) = .68$, $p = .41$) or Right Stem Frequency ($\chi^2(1) = .98$, $p = .32$). To summarize, the frequency of the left stem appears to primarily matter when it does not carry the meaning of the compound. The final model containing all of the variables found to be significant is presented in Table 4.

3.3. Discussion

The results from the compound analysis revealed that many psycholinguistic properties influenced whether WBL perceived a compound as mono- or bichromatic. This indicates that WBL's synesthetic experiences are intimately related to the inner workings of the reading process. These results will now be reviewed.

In the overall compound analysis, the nuisance variable Trial Number emerged as a significant positive predictor, indicating that WBL became more likely over time to report compounds as having two colors. In the first half Experiment 2, WBL judged 75% of the compounds as having two colors while in the latter half, 80% were judged as having two colors. Although we constructed the stimulus list to balance the types of morphological structure WBL was exposed to, it is possible that the repeated appearance of bimorphemic words (particularly over the course of the entire investigation) biased WBL towards componential morphological processing (see e.g., Cohen-Shikora & Balota, 2013 for evidence that styles of morphological processing can be primed). This general bias may also account for why WBL reported more compounds as bichromatic in Experiment 2 than Experiment 1. Despite this apparent bias, the analysis found that both stem and compound frequency influenced WBL's synesthetic experiences of compounds, suggesting that both morpheme-based and whole-word representations were involved in WBL's processing of compound words. Moreover, we observe that these properties influenced his processing in accordance with existing theories of morphological processing. Compounds with higher frequency left stems and longer right stems were more likely to be perceived as bichromatic, indicating that the more salient the stems were as individual components, the more likely they were to receive their own color. It is interesting that letter length rather than frequency mattered for the right stems. In an eye tracking study, Bertram & Hyönä (2003) found that Finnish readers decomposed longer but not shorter compounds into their component morphemes (though see Juhasz, 2008). They theorize that that word/stem length influences morphological processing by determining the number of fixations needed to fully process the word. More fixations may lead to componential processing (perhaps by drawing attention to word's subparts) while fewer fixations may lead to more holistic processing. It is also possible that length simply serves as a probabilistic cue to morphological status (e.g., longer words are more likely to be multimorphemic than shorter words in English). The fact that WBL was more likely to experience two colors in compounds with longer right stems is compatible with these hypotheses. The fact that left stem frequency and right stem length where both significant provides further support for the notion advanced in Experiment 1 that WBL's propensity to judge compounds as bichromatic is not driven solely by word length.

Contrary to the pattern observed with the stems, the more frequent the word was as a whole, the less likely WBL was to perceive two colors. This is consistent with the now-large body of evidence that higher frequency multimorphemic words develop their own lexical representations (e.g., Lignos & Gorman, 2012; Biedermann et al., 2013). It also suggests that these whole-word representations are atomic rather than morphologically organized (e.g., <treadmill>, not <tread#mill>), otherwise they would expected to facilitate WBL's recognition of the individual stems as well.

An effect of compound semantics—specifically lexeme meaning dominance—was also observed. This was found whereby the frequency of the left stem only played a strong role in words where the left stem did not carry the meaning of the word as a whole. This finding indicates that semantic representations—particularly those of the individual stems—influenced WBL's synesthetic experiences in addition to lexical representations. Interestingly, this interaction is the opposite of what was observed by Inhoff et al. (2008), who reported stronger frequency effects in meaning-dominant stems, a fact which may be due to task differences.

Finally, an effect of color similarity was observed whereby compounds whose stems began with dissimilarly colored letters were more likely to be perceived as bichromatic than compounds with similarly colored stem-initial letters. This indicates that although WBL experienced these colors in his mind's eye, their chromatic properties were perceptually real enough to behave in accordance with the general properties of color vision.

One somewhat perplexing result of the analysis is that, by and large, the meaning of the compound as a whole did not influence WBL's color perceptions. This is interesting, given the abundant evidence that meaning is automatically retrieved during reading. It is also particularly interesting given that the variables used in this study have been shown to have robust effects in lexical decision and oral reading tasks (Juhasz et al., 2014; Kuperman, 2013). One possibility is that this simply reflects individual differences in processing. For example, it is possible that WBL's morphological processing may simply rely more heavily on decompositional processes than other individuals, leading to a relatively weaker effect of word-level properties. It is also possible—if not likely—that the color identification task used in the present experiment shifted WBL's attention away from the properties of the compound towards lower level/componential features.

An intriguing possibility is that this may be a side effect of the synesthesia itself. Radvansky, Gibson, & McNerney (2011) reported a series of memory experiments conducted with grapheme-color synesthetes. They found that when recalling items from semantically organized lists (e.g., foods), the synesthetes exhibited fewer false memories (e.g., recalling the word *eggs* when it did not appear in the list) than non-synesthetic controls. Similarly, while non-synesthetic individuals typically exhibit an advantage for recalling semantically anomalous items (the von Restorff isolation effect, e.g., better recall for *violin* when embedded in a list of foods), the synesthetic individuals exhibited no such advantage. Radvansky and colleagues hypothesized that some aspect of the synesthetic experience may cause grapheme-color synesthetes to emphasize surface-level properties at the expense of semantic properties when reading. In WBL's case, it is possible that the comparative salience of the orthographic form (because of its colors) may have shifted WBL's processing over time towards lower-level features, resulting in a relative de-emphasis of semantic processing. This may have lead to a relative reliance on morphological decomposition rather than whole-word access, for example. More work is clearly needed to determine if this is a consistent pattern in reading-related synesthesias.

4. General Discussion

Despite many decades of research, the nature of synesthesia as a reading phenomenon has remained unclear. Moreover, debates about synesthesia's fundamental nature have tended to characterize it as either exclusively a low-level perceptual phenomenon or exclusively a high-level semantic phenomenon. To address these questions, we examined the performance of WBL, a synesthetic individual who experiences colors when reading letters and words. He consistently reported experiencing one lexical color when reading monomorphemic words and non-words and two lexical colors when reading prefixed and compound words. When perceiving two lexical colors, each morpheme took on the color of its first letter. A detailed analysis of his responses to compounds revealed that his synesthetic percepts were influenced by perceptual, lexical/morphological, and semantic factors.

The data rule out early and late stages of the reading process as the exclusive locus of WBL's bichromatic experiences. An exclusive graphemic locus is ruled out since only truly multimorphemic words were perceived as bichromatic—monomorphemic words and pseudocompounds were nearly always perceived as monochromatic. Moreover, the frequency and color similarity of the bigram straddling the compound boundary did not predict WBL's performance, indicating that he was not relying on orthographic decomposition strategies.

Semantic stages of processing are also ruled out as the exclusive source of his percepts. We conclude this because 1) semantic information alone is insufficient to determine morphological structure (e.g., *daybreak*/*dawn*; Badecker, 2001; Hittmair-Delazer et al., 1994), 2) the semantic properties of the compound as a whole did not influence WBL's likelihood of perceiving two colors, and 3) the colors he perceived for multimorphemic words were not semantically driven (the colors of e.g., *beetroot*, *dunghill*, *coffeepot*, *fireplace*, and *hellfire* were determined by the first letter of each morpheme rather than the meaning of either stem or the word as a whole).

In contrast, the data strongly indicate that WBL's bichromatic percepts were driven by morphological structure at lexical stages of processing. This is indicated by the fact that he perceived two colors exclusively for truly multimorphemic words and by the fact that lexical frequency (left stem and compound frequency) influenced the likelihood that he would perceive a compound as bichromatic.

Intriguingly, while the data provide strong support for the necessary involvement of morphological structure, they also indicate that WBL's percepts did not arise *solely* at lexical levels of processing. On the one hand, the lexical colors that WBL perceived were nearly always determined by the synesthetic color of the first letter in the morpheme, indicating that his percepts fundamentally involved graphemic information. That is, although it is conceivable that a morpheme's color would be primarily determined by its meaning or position within the word (e.g., the first morpheme is always red while the second is always green), this was not the case. On the other hand, the likelihood of perceiving a compound as having one or two colors was also influenced by whether its meaning was related primarily to the meaning of the left stem or the right stem, pointing to a role for semantics. WBL's synesthesia thus appears to be the product of intricate interactions between many components of the reading system.

We propose that WBL's percepts arise from the gradient, interactive processes that comprise the reading process. When viewing a multimorphemic word such as *jaywalk*, the visual stimulus is first converted into a string of abstract letter identities (graphemes: <J><A><Y><W><A><L><K>). Morphological decomposition subsequently occurs, providing access to the word's component morphemes at lexical levels (<JAY><WALK>). The fact that compound frequency was a significant predictor of WBL's percepts suggests that a whole-word lexical representation was also retrieved, at least in some cases (e.g., <JAYWALK>). The semantic information of these three lexical representations is then retrieved (e.g., "bird", "moving by advancing each foot in turn", "crossing a street unlawfully"). Bidirectional connections then allow stems whose meanings overlap with that of the compound to receive feedback activation from semantic levels, boosting their activation (e.g., the meaning of *jaywalk* sends activation back to <WALK> but not <JAY>). This activation adds to frequency-based resting activation, causing lexeme meaning dominance to interact with lexical frequency.

Lexical activation in turn feeds back to grapheme levels, particularly the initial letters, increasing the salience of their associated colors and creating the percept of word-level colors. Since these letters were undoubtedly activated during the initial bottom-up phase of word recognition, our results suggest that WBL's lexical percepts are primarily influenced by grapheme activation *subsequent* to lexical activation (otherwise, lexical properties such as morphological structure and frequency would not influence WBL's percepts). Once these letters are activated, the perceptual similarity of their associated colors influences how many colors WBL ultimately perceives.

4.1. Implications for psycholinguistic theories

Focusing on the reading aspects of these results, our data provide converging evidence for a number of psycholinguistic claims about the reading process. First, the fact that WBL often perceived multiple colors for multimorphemic but not monomorphemic words provides support for the claim that multimorphemic words are decomposed into their component lexical units during the reading process. While this conclusion has been supported by a vast number of behavioral, cognitive neuroscientific, and cognitive neuropsychological studies (see Amenta & Crepaldi, 2012), this is the first study we know of to present synesthetic evidence to this effect. The fact that compound frequency was similarly influential provides support to theories positing the existence of whole-word representations for multimorphemic words. Our results also support claims that the relationship between stem and compound meaning—lexeme meaning dominance—influences word processing (Inhoff et al., 2008). Lastly, even though the interaction we observed between lexeme meaning dominance and left stem frequency runs in the opposite direction of the effect reported by Inhoff et al. (2008), the very fact that it significantly influenced WBL's color perceptions provides evidence that these factors interact during compound processing.

Finally, one interesting pattern that emerged from WBL's data is that while compounds and prefixed words frequently gave rise to bichromatic experiences, suffixed words almost never did so (WBL reported two colors for only 1.0-2.5% of suffixed words). Although we hypothesized in Experiment 1 that the high rate of monochromatic reports could have been due to the fact that suffixes used in that experiment tended to be very short and thus not very salient (mean length = 2), this was less likely in Experiment 2, where the average suffix length was 2.7

and 14% of the words had suffix length 4 or 5 (comparable to the mean letter length of right stems in Experiment 2, which was 4.2). This fact also likely cannot be explained by supposing that morphemes must have rich semantic content to be perceived as carrying lexical color. Two pieces of evidence rule this hypothesis out. Most straightforwardly, WBL nearly always perceived lexical colors for nonwords, which clearly have no semantic content. Secondly, WBL perceived distinct colors for prefixes like *en-* (*enslave*) and *mis-* (*misrepresent*), even though their meanings are arguably just as abstract as that of the plural *–s* and *–est*, neither of which were ever perceived with their own color.

One important way in which suffixes differ from prefixes and lexical stems is that the latter may appear at the beginning of a word while suffixes may not. A recent set of studies has suggested that this may have a profound influence on the way morphemes come to be represented. Crepaldi, Rastle, and Davis (2010) found that although participants are slower to reject suffixed nonwords than orthographic controls (*gasful* > *gasfil*), this difference disappeared when suffixes appeared before their stems (*fulgas* = *filgas*; see Blazej & Cohen-Goldberg, submitted and Crepaldi, Hemsworth, Davis, & Rastle, 2015 for results supporting this conclusion). Subsequently, Crepaldi, Rastle, Davis, and Lupker (2013) showed that transposed compounds primed their regular forms (e.g., *moonhoney–HONEYMOON*) better than monomorphemic controls (e.g., *quiltran–TRANQUIL*). Together, these studies suggest that readers recognize compound stems no matter where in a word they appear but only recognize suffixes when they appear at the end of a word. They propose that suffixes have position-specific representations while lexical stems have position-invariant representations (e.g., <MOON> but <–FUL>; see Jacobs & Dell, 2014 for a different but related proposal).

Crepaldi and colleagues' proposal that morphemes can develop position-specific representations can parsimoniously account for the data reported here. In our description of WBL's lexical colors, we have stated that they were determined by the first letter of the morpheme. A more accurate description, however, may be that WBL's lexical colors were determined by the word-initial letter in the morpheme, that is, *the letter in the morpheme that can appear word-initially*. In prefixes and lexical stems, this is simply the first letter of the morpheme. Suffixes, however, have no letter that can appear word-initially and thus should not be perceived as bearing lexical color. Intriguingly, while WBL did perceive 11 suffixed words as having separate colors for the stem and suffix, all of those suffixes were homographic with lexical stems. These words were *motherhood*, *mainland*, *goodness*, *bothersome*, *troublesome*, *wholesome*, *chairman*, *clockwise*, *lengthwise*, *southward*, and *stepwise*.[9] The fact that these data are perhaps most parsimoniously explained by the notion of position-specific representations provides some support for Crepaldi et al.'s claims and further, suggests that readers may represent homographic affixes as hybrids of affixes and lexical stems. More research is clearly needed to test this hypothesis.

4.2. Implications for theories of synesthesia

Turning now to the questions we originally posed in Section 1.5, the data have important implications for theories of synesthesia. First, WBL's case provides strong evidence that lexical level representations can play a fundamental role in reading-related synesthesia. Whereas previous reports have implied that lexical representations play only a relatively minor role

---

[9] Many dictionaries list –*land* and –*man* as combining forms, which is likely why the English Lexicon Project lists *mainland* and *chairman* as suffixed words. We readily acknowledge that they may be processed more like compound stems than suffixes during reading.

(primarily by providing access to semantic representations that are ultimately what determine the individual's experience), the present study finds that the morphological organization, frequency, and semantic profile of a multimorphemic word's lexical components can all have a critical influence on synesthetic experiences. This implies that synesthesia is neither exclusively a low-level nor a high-level phenomenon, but rather spans all of the levels of representation that may be involved in a particular domain (e.g., Mroczko-Wąsowicz & Nikolić, 2014).

Second, WBL's pattern of performance implies that synesthetic experiences can be intimately linked to the functioning of the 'host' cognitive system, in this case the reading system. Rather than being determined exclusively by the output of letter selection processes (e.g., the color associated with the left-most grapheme) or word recognition process (e.g., the word's meaning), WBL's word-level colors are determined by many fine-grained aspects of the reading process acting in concert. This suggests that synesthesia is enmeshed with basic cognitive processes, giving rise to experiences that are directly related to their computations rather than modularly arising from their peripheral inputs and outputs.

Acknowledgements

We would like to thank Sarah Pratt for help with many stages of this study, Brenda Rapp for many insightful discussions, and Dr. Gislin Dagniele at the Johns Hopkins Wilmer Eye Institute for his assistance in obtaining chromaticity coordinates. We would also like to thank two anonymous reviewers for their very helpful feedback and WBL for making this study possible.

References

Amenta, S., & Crepaldi, D. (2012). Morphological processing as we know it: An analytical review of morphological effects in visual word identification. *Frontiers in Psychology*, *3*(July), 1–12. doi:10.3389/fpsyg.2012.00232

Asano, M., & Yokosawa, K. (2011). Synesthetic colors are elicited by sound quality in Japanese synesthetes. *Consciousness and Cognition*, *20*(4), 1816–1823. doi:10.1016/j.concog.2011.05.012

Asano, M., & Yokosawa, K. (2012). Synesthetic colors for Japanese late acquired graphemes. *Consciousness and Cognition*, *21*, 983–993. doi:10.1016/j.concog.2012.02.005

Asano, M., & Yokosawa, K. (2013). Grapheme learning and grapheme-color synesthesia: toward a comprehensive model of grapheme-color association. *Frontiers in Human Neuroscience*, *7*(November), 757. doi:10.3389/fnhum.2013.00757

Badecker, W. (2001). Lexical composition and the production of compounds: Evidence from errors in naming. *Language and Cognitive Processes*, *16*(4), 337–366. doi:10.1080/01690960042000120

Balota, D. A., Yap, M. J., Cortese, M. J., Hutchison, K. A., Kessler, B., Loftis, B., … Treiman, R. (2007). The English Lexicon Project. *Behavior Research Methods*, *39*(3), 445–59. doi:10.3758/BF03193014

Baron-Cohen, S., Harrison, J., Goldstein, L. H., & Wkye, M. (1993). Coloured speech perception: Is synaesthesia what happens when modularity breaks down? *Perception*, *22*, 419–426.

Berent, I., & Perfetti, C. A. (1995). A rose is a REEZ: The two-cycles model of phonology assembly in reading English. *Psychological Review*, *102*(1), 146–184. doi:10.1037/0033-295X.102.1.146

Bertram, R., & Hyönä, J. (2003). The length of a complex word modifies the role of morphological structure: Evidence from eye movements when reading short and long Finnish compounds. *Journal of Memory and Language*, *48*(3), 615–634. doi:10.1016/S0749-596X(02)00539-9

Bertram, R., Pollatsek, A., & Hyönä, J. (2004). Morphological parsing and the use of segmentation cues in reading Finnish compounds. *Journal of Memory and Language*, *51*(3), 325–345. doi:10.1016/j.jml.2004.06.005

Blair, C. D., & Berryhill, M. E. (2013). Synesthetic grapheme-color percepts exist for newly encountered Hebrew, Devanagari, Armenian and Cyrillic graphemes. *Consiousness and Cognition*, *22*(3), 944–954. doi:10.1016/j.concog.2013.06.002

Brang, D., Rouw, R., Ramachandran, V. S., & Coulson, S. (2011). Similarly shaped letters evoke similar colors in grapheme-color synesthesia. *Neuropsychologia*, *49*(5), 1355–1358. doi:10.1016/j.neuropsychologia.2011.01.002

Brunsdon, R., Coltheart, M., & Nickels, L. (2006). Severe developmental letter-processing impairment: A treatment case study. *Cognitive Neuropsychology*, *23*(6), 795–821. doi:10.1080/02643290500310863

Brysbaert, M., & New, B. (2009). Moving beyond Kučera and Francis: A critical evaluation of current word frequency norms and the introduction of a new and improved word frequency measure for American English. *Behavior Research Methods*, *41*(4), 977–990. doi:10.3758/BRM.41.4.977

Chiou, R., & Rich, A. N. (2014). The role of conceptual knowledge in understanding synesthesia: Evaluating contemporary findings from a "hub-and-spokes" perspective. *Frontiers in Psychology*, *5*, 1–18. doi:10.3389/fpsyg.2014.00105

Coltheart, M., Davelaar, E., Jonasson, T., & Besner, D. (1977). Access to the internal lexicon. In S. Dornic (Ed.), *Attention and Performance VI* (pp. 535–555). Hillsdale, NJ: Erlbaum.

Coltheart, M., Rastle, K., Perry, C., Langdon, R., & Ziegler, J. (2001). DRC: A dual route cascaded model of visual word recognition and reading aloud. *Psychological Review*, *108*(1), 204–256. doi:10.1037/0033-295X.108.1.204

Crepaldi, D., Hemsworth, L., Davis, C. J., & Rastle, K. (2015). Masked suffix priming and morpheme positional constraints. *The Quarterly Journal of Experimental Psychology*, 1–41. doi:10.1080/17470218.2015.1027713

Crepaldi, D., Rastle, K., & Davis, C. J. (2010). Morphemes in their place: Evidence for position-specific identification of suffixes. *Memory & Cognition*, *38*(3), 312–21. doi:10.3758/MC.38.3.312

Crepaldi, D., Rastle, K., Davis, C. J., & Lupker, S. J. (2013). Seeing stems everywhere: Position-independent identification of stem morphemes. *Journal of Experimental Psychology: Human Perception and Performance*, *39*(2), 510–525. doi:10.1037/a0029713

Cubelli, R. (1991). A selective deficit for writing vowels in acquired dysgraphic. *Nature*, *354*, 258–260.

Cytowic, R. E. (2002). *Synesthesia: A union of the senses* (2nd ed.). Cambridge, MA: MIT Press.

Dixon, M. J., Smilek, D., Duffy, P. L., Zanna, M. P., & Merikle, P. M. (2006). The role of meaning in grapheme-colour synaesthesia. *Cortex*, *42*(2), 243–252.

Dixon, M. J., Smilek, D., & Merikle, P. M. (2004). Not all synaesthetes are created equal: projector versus associator synaesthetes. *Cognitive, Affective & Behavioral Neuroscience*, *4*(3), 335–343. doi:10.3758/CABN.4.3.335

Eagleman, D. M., Kagan, A. D., Nelson, S. S., Sagaram, D., & Sarma, A. K. (2007). A standardized test battery for the study of synesthesia. *Journal of Neuroscience Methods*, *159*(1), 139–45. doi:10.1016/j.jneumeth.2006.07.012

Ginsberg, L. (1923). A case of synaesthesia. *The American Journal of Psychology*, *34*(4), 582–589.

Grossenbacher, P. G., & Lovelace, C. T. (2001). Mechanisms of synesthesia: Cognitive and physiological constraints. *Trends in Cognitive Sciences*, *5*(1), 36–41. doi:10.1016/S1364-6613(00)01571-0

Hittmair-Delazer, M., Andree, B., Semenza, C., De Bleser, R., & Benke, T. (1994). Naming by German compounds. *Journal of Neurolinguistics*, *8*(1), 27–41. doi:10.1016/0911-6044(94)90004-3

Howes, D. H., & Solomon, R. L. (1951). Visual duration threshold as a function of word-probability. *Journal of Experimental Psychology*, *41*(6), 401–410.

Hung, W. Y., Simner, J., Shillcock, R., & Eagleman, D. M. (2014). Synaesthesia in Chinese characters: The role of radical function and position. *Consciousness and Cognition*, *24*, 38–48. doi:10.1016/j.concog.2013.12.009

Inhoff, A. W., Starr, M. S., Solomon, M., & Placke, L. (2008). Eye movements during the reading of compound words and the influence of lexeme meaning. *Memory & Cognition*, *36*(3), 675–687. doi:10.3758/MC.36.3.675

Jackendoff, R. (2010). The Ecology of English Noun-Noun Compounds. In *Meaning and the Lexicon* (pp. 415–451). Oxford: Oxford University Press.

Jackson, N. E., & Coltheart, M. (2001). *Routes to reading success and failure*. New York: Psychology Press.

Jacobs, C. L., & Dell, G. S. (2014). “hotdog”, not “hot” “dog”: the phonological planning of compound words. *Language, Cognition and Neuroscience*, *29*(4), 512–523. doi:10.1080/23273798.2014.892144

Jones, M. N., & Mewhort, D. J. K. (2004). Case-sensitive letter and bigram frequency counts from large-scale English corpora. *Behavior Research Methods, Instruments, & Computers : A Journal of the Psychonomic Society, Inc*, *36*(3), 388–396. doi:10.3758/BF03195586

Juhasz, B. J. (2008). The processing of compound words in English: Effects of word length on eye movements during reading. *Language and Cognitive Processes*, *23*(7/8), 1057–1088. doi:10.1080/01690960802144434

Juhasz, B. J., Lai, Y. H., & Woodcock, M. L. (2014). A database of 629 English compound words: ratings of familiarity, lexeme meaning dominance, semantic transparency, age of acquisition, imageability, and sensory experience. *Behavior Research Methods*. doi:10.3758/s13428-014-0523-6

Jürgens, U. M., & Nikolić, D. (2012). Ideaesthesia: Conceptual processes assign similar colours to similar shapes. *Translational Neuroscience*, *3*(1), 22–27. doi:10.2478/s13380-012-0010-4

Kim, S., Blake, R., & Kim, C. Y. (2013). Is "Σ" purple or green? Bistable grapheme-color synesthesia induced by ambiguous characters. *Consciousness and Cognition*, *22*(3), 955–964. doi:10.1016/j.concog.2013.05.012

Kubitza, A. (2006). Word frequency effect for word colour in german compounds (case study). In *UK Synaesthesia Association Annual Conference*. Universität Erfurt, Germany. Retrieved from http://www.uksynaesthesia.com/abstracts07.htm

Kuperman, V. (2013). Accentuate the positive: Semantic access in English compounds. *Frontiers in Psychology*, *4*(April), 1–10. doi:10.3389/fpsyg.2013.00203

Kuperman, V., Bertram, R., & Baayen, R. H. (2008). Morphological dynamics in compound processing. *Language and Cognitive Processes*, *23*(7-8), 1089–1132. doi:10.1080/01690960802193688

Lemhöfer, K., Koester, D., & Schreuder, R. (2011). When bicycle pump is harder to read than bicycle bell: Effects of parsing cues in first and second language compound reading. *Psychonomic Bulletin & Review*, *18*(2), 364–370. doi:10.3758/s13423-010-0044-y

Lignos, C., & Gorman, K. (2012). Revisiting frequency and storage in morphological processing. *Proceedings of CLS*, *48*, 447–461.

Lund, K., & Burgess, C. (1996). Producing high-dimensional semantic spaces from lexical co-occurrence. *Behavior Research Methods, Instruments, & Computers*, *28*(2), 203–208.

Mankin, J. (2014). One-colour "Rainbows": Synaesthetic colouring of compound words. In *UK Synaesthesia Association Annual Conference*. Goldsmiths University of London, UK. Retrieved from http://www.uksynaesthesia.com/UKSA2014FINALPROGRAMME.pdf

McClelland, J. L., & Rumelhart, D. E. (1981). An interactive activation model of context effects in letter perception: Part I. An account of basic findings. *Psychological Review*, *88*(5), 375–407.

Moos, A., Smith, R., Miller, S. R., & Simmons, D. R. (2014). Cross-modal associations in synaesthesia: Vowel colours in the ear of the beholder. *I-Perception*, *5*(2), 132–142. doi:10.1068/i0626

Mroczko, A., Metzinger, T., Singer, W., & Nikolić, D. (2009). Immediate transfer of synesthesia to a novel inducer. *Journal of Vision*, *9*(12), 25.1–8. doi:10.1167/9.12.25

Mroczko-Wąsowicz, A., & Nikolić, D. (2014). Semantic mechanisms may be responsible for developing synesthesia. *Frontiers in Human Neuroscience*, *8*(August), 1–13. doi:10.3389/fnhum.2014.00509

Myles, K. M., Dixon, M. J., Smilek, D., & Merikle, P. M. (2003). Seeing double: The role of meaning in alphanumeric-colour synaesthesia. *Brain and Cognition*, *53*(2), 342–345. doi:10.1016/S0278-2626(03)00139-8

Nikolić, D. (2009). Is synaesthesia actually ideaesthesia? An inquiry into the nature of the phenomenon. In *Proceedings of the Third International Congress on Synaesthesia, Science & Art*. Granada, Spain.

Oldfield, R. C., & Wingfield, A. (1965). Response latencies in naming objects. *The Quarterly Journal of Experimental Psychology*, *17*(4), 273–281. doi:10.1080/17470216508416445

Paulesu, E., Harrison, J., Baron-Cohen, S., Watson, J. D. G., Goldstein, L., Heather, J., … Frith, C. D. (1995). The physiology of coloured hearing. A PET activation study of colour-word synaesthesia. *Brain*, *118*, 1073. doi:10.1093/brain/118.4.1073

Plaut, D. C., & Behrmann, M. (2011). Complementary neural representations for faces and words: A computational exploration. *Cognitive Neuropsychology*, *28*(3-4), 251–275. doi:10.1080/02643294.2011.609812

Radvansky, G. A, Gibson, B. S., & McNerney, M. W. (2011). Synesthesia and memory: Color congruency, von Restorff, and false memory effects. *Journal of Experimental Psychology. Learning, Memory, and Cognition*, *37*(1), 219–229. doi:10.1037/a0021329

Ramachandran, V. S., & Hubbard, E. M. (2001). Synesthesia - A window into perception, thought and language. *Journal of Consciousness Studies*, *8*(12), 3–34.

Ramachandran, V. S., & Seckel, E. (2015). Synesthetic colors induced by graphemes that have not been consciously perceived. *Neurocase: The Neural Basis of Cognition*, *21*(2), 216–219. doi:10.1080/13554794.2014.890728

Rapp, B. C., McCloskey, M., Rothlein, D., Lipka, K. & Vindiola, M. (2009). Vowel-specific synesthesia: Evidence for orthographic consonants and vowels. Paper presented at the annual meeting of the Psychonomic Society. Boston, MA.

Rastle, K., Davis, M. H., & New, B. (2004). The broth in my brother's brothel: Morpho-orthographic segmentation in visual word recognition. *Psychonomic Bulletin & Review*, *11*(6), 1090–1098. doi:10.3758/BF03196742

Reicher, G. M. (1969). Perceptual recognition as a function of meaninfulness of stimulus material. *Journal of Experimental Psychology*, *81*(2), 275–280. doi:10.1037/h0027768

Rich, A. N., Bradshaw, J. L., & Mattingley, J. B. (2005). A systematic, large-scale study of synaesthesia: Implications for the role of early experience in lexical-colour associations. *Cognition*, *98*, 53–84. doi:10.1016/j.cognition.2004.11.003

Rothen, N., Seth, A. K., Witzel, C., & Ward, J. (2013). Diagnosing synaesthesia with online colour pickers: Maximising sensitivity and specificity. *Journal of Neuroscience Methods*, *215*(1), 156–160. doi:10.1016/j.jneumeth.2013.02.009

Rothlein, D., & Rapp, B. (2014). The similarity structure of distributed neural responses reveals the multiple representations of letters. *NeuroImage*, *89*, 331–344. doi:10.1016/j.neuroimage.2013.11.054

Rubenstein, H., & Pollack, I. (1963). Word predictability and intelligibility. *Journal of Verbal Learning and Verbal Behavior*, *2*, 147–158. doi:10.1016/S0022-5371(63)80079-1

Schubert, T., & McCloskey, M. (2013). Prelexical representations and processes in reading: Evidence from acquired dyslexia. *Cognitive Neuropsychology*, *30*(6), 360–95. doi:10.1080/02643294.2014.880677

Seidenberg, M. S. (1987). Sublexical structures in visual word recognition: Access units or orthographic redundancy? In M. Coltheart (Ed.), *Attention and Performance XII: The Psychology of Reading* (pp. 245–263). Hillsdale, NJ: Erlbaum.

Shin, E., & Kim, C. Y. (2014). Both "나" and "な" are yellow: Cross-linguistic investigation in search of the determinants of synesthetic color. *Neuropsychologia*, *65*, 25–36. doi:10.1016/j.neuropsychologia.2014.09.032

Simner, J. (2007). Beyond perception: synaesthesia as a psycholinguistic phenomenon. *Trends in Cognitive Sciences*, *11*(1), 23–29. doi:10.1016/j.tics.2006.10.010

Simner, J. (2012). Defining synaesthesia. *British Journal of Psychology*, *103*(1), 1–15. doi:10.1348/000712610X528305

Simner, J., Glover, L., & Mowat, A. (2006). Linguistic determinants of word colouring in grapheme-colour synaesthesia. *Cortex*, *42*(1984), 281–289. doi:10.1016/S0010-9452(08)70353-8

Simner, J., Ward, J., Lanz, M., Jansari, A., Noonan, K., Glover, L., & Oakley, D. A. (2005). Non-random associations of graphemes to colours in synaesthetic and non-synaesthetic populations. *Cognitive Neuropsychology*, *22*(8), 1069–85. doi:10.1080/02643290500200122

Smilek, D., Dixon, M. J., Cudahy, C., & Merikle, P. M. (2001). Synaesthetic photisms influence visual perception. *Journal of Cognitive Neuroscience*, *13*(7), 930–936.

Taylor, G. (2014). python-colormath. (Version 2.1.1). Available from https://github.com/gtaylor/python-colormath/

Ward, J. (2004). Emotionally mediated synaesthesia. *Cognitive Neuropsychology*, *21*(March 2015), 761–772. doi:10.1080/02643290342000393

Ward, J., & Simner, J. (2003). Lexical-gustatory synaesthesia: Linguistic and conceptual factors. *Cognition*, *89*(3), 237–261. doi:10.1016/S0010-0277(03)00122-7

Ward, J., Simner, J., & Auyeung, V. (2005). A comparison of lexical-gustatory and grapheme-colour synaesthesia. *Cognitive Neuropsychology*, *22*(1), 28–41. doi:10.1080/02643290442000022

Watson, M. R., Akins, K. A., & Enns, J. T. (2012). Second-order mappings in grapheme–color synesthesia. *Psychonomic Bulletin & Review*, *19*(2), 211–217. doi:10.3758/s13423-011-0208-4

Weiss, P. H., Shah, N. J., Toni, I., Zilles, K., & Fink, G. R. (2001). Associating colours with people: a case of chromatic-lexical synaesthesia. *Cortex; a Journal Devoted to the Study* *of the Nervous System and Behavior*, *37*(5), 750–753. doi:10.1016/S0010-9452(08)70631-2

Whaley, C. P. (1978). Word—nonword classification time. *Journal of Verbal Learning and Verbal Behavior*, *17*(2), 143–154. doi:10.1016/S0022-5371(78)90110-X

Witthoft, N., & Winawer, J. (2006). Synesthetic colors determined by having colored refrigerator magnets in childhood. *Cortex*, *42*(2), 175–183.

Yokoyama, T., Noguchi, Y., Koga, H., Tachibana, R., Saiki, J., Kakigi, R., & Kita, S. (2014). Multiple neural mechanisms for coloring words in synesthesia. *NeuroImage*, *94*, 360–371. doi:10.1016/j.neuroimage.2014.01.039

Appendix A

Chromaticity coordinates of the 27” iMac (Late 2009 model) that WBL used to make his color selections. Measurements were obtained using a Minolta CS-100 ChromaMeter photometer in a darkened room and were made for pure white (RGB 255, 255, 255), red (255, 0, 0), green (0, 255, 0), and blue (0, 0, 255). As a point of interest, measurements were also made of the colors that WBL reported for the letters A, B, and D in the first administration of the Synesthesia Battery. Interestingly, these colors have similar coordinates to pure red, green, and blue, respectively, demonstrating that WBL can experience highly saturated synesthetic colors. All measurements are reported in CIE Yxy space.

Color	Y	x	y
Pure White	312	.324	.345
Pure Red	65.7	.657	.321
Pure Green	222	.294	.612
Pure Blue	24.9	.152	.071
Synesthetic A	52.1	.654	.308
Synesthetic B	161	.303	.612
Synesthetic D	16.6	.154	.065

Appendix B.

Semantic Variable	**Description of Scale**	**Examples, if given**
Familiarity	1 = Item is not familiar at all, you do not know the meaning, and you are not sure whether the item is a word or not 7 = You know the meaning of the word and use it frequently	1 – xylem 7 - ball
Age of Acquisition	When you first learned the word and its meaning in either written or spoken form	1 – 0-2 years old 7 – 13+ years old
Imageability	1 = Word arouses a mental image with difficulty or not at all 7 = Word arouses a mental image very quickly and easily	1 – something 7 – blackboard
Sensory Experience	1 = The word evokes no personal sensory (taste, touch, sight, sound, or smell) experience 7 = The word evokes a strong personal sensory experience	N/A
Transparency	1 = The two words are not related at all to the meaning of the entire compound word 7 = The words are both completely related to the meaning of the entire compound word	1 – pineapple 7 – dollhouse
Lexeme Meaning Dominance	0 = The meaning of the entire compound word is strictly related to the first word only 10 = The meaning of the entire compound is strictly related to the second word only.	0 – hopscotch 5 – dollhouse 10 – strawberry

Type	Letter Length	Lexical Frequency	Ortho. Neighbors	Mean Bigram Frequency	Bichromatic Judgments
Monomorphemic	5.2 (1.6)	2.7 (1.1)	6.2 (6.8)	3546.3 (1700.1)	0/728 (0%)
Nonword	4.5 (0.6)	--	4.7 (4.2)	2784.7 (1539.9)	0/100 (0%)
Prefixed	8.4 (1.9)	1.4 (0.7)	0.4 (0.6)	4120.6 (1309.0)	11/89 (12.4%)
Suffixed	7.2 (1.8)	1.8 (0.7)	3.5 (4.0)	4584.8 (1526.6)	1/78 (1.3%)
Compound	8.1 (1.3)	1.7 (0.6)	0.2 (0.5)	2956.0 (1255.6)	13/80 (16.3%)
Pseudocompound	6.9 (0.9)	1.9 (0.7)	0.8 (1.3)	3482.6 (1218.3)	1/49 (2%)

Table 1: Psycholinguistic properties (mean and (SD)) for the stimuli administered in Experiment 1. Data for WBL's bichromatic judgments are reported for the subset of prefixed, suffixed, compound, and pseudocompound words whose morpheme-initial letters were judged to be dissimilar in color (see text for details).

Type	Letter Length	Lexical Frequency	Ortho. Neighbors	Mean Bigram Frequency	Bichromatic Judgments
Monomorphemic	5.6 (1.7)	2.2 (1.0)	4.8 (6.1)	3346.8 (1482.9)	2/766 (0.3%)
Suffixed	7.8 (1.6)	1.7 (0.7)	2.2 (3.1)	4678.0 (1451.1)	10/399 (2.5%)
Compound	8.3 (1.4)	1.6 (0.6)	0.2 (0.4)	3071.0 (1171.5)	337/435 (77.5%)

Table 2: Psycholinguistic properties (mean and (SD)) and bichromatic judgments for the stimuli administered in Experiment 2.

Predictor	**Coefficient**	**SE**	***z*-value**	***p*-value**
(Intercept)	2.212	0.192	11.510	<.001
Trial	0.494	0.168	2.941	.003
CIELAB Color Difference of Stem-Initial Letters	0.446	0.193	2.306	.021
CIELAB Color Difference of Stem Boundary Letters	-0.068	0.171	-0.400	.689
Bigram Frequency of Stem Boundary Letters	-0.029	0.161	-0.181	.857
Left Stem Frequency (Log)	0.457	0.182	2.518	.012
Right Stem Frequency (Log)	-0.012	0.171	-0.071	.944
Left Stem Letter Length	-0.079	0.222	-0.357	.721
Right Stem Letter Length	0.461	0.213	2.165	.030
Left Stem Orthographic Neighborhood Density	-0.251	0.203	-1.238	.216
Right Stem Orthographic Neighborhood Density	0.061	0.187	0.326	.744
Compound Frequency	-0.430	0.174	-2.477	.013

Table 3: Summary of the logistic regression model of the non-semantic variables analyzed in Experiment 2. (DV: compound judged as having 1 lexical color = 0; 2 lexical colors = 1). All variables are centered and scaled.

Predictor	**Coefficient**	**SE**	**z-value**	**p-value**
(Intercept)	2.347	0.206	11.372	<.001
Trial	0.455	0.172	2.649	.008
CIELAB Color Difference of Stem-Initial Letters	0.436	0.195	2.236	.025
Left Stem Frequency (Log)	0.380	0.189	2.011	.044
Right Stem Letter Length	0.463	0.177	2.614	.009
Compound Frequency (Log)	-0.422	0.170	-2.485	.013
Lexeme Meaning Dominance	-0.131	0.174	-0.752	.452
Left Root Frequency (Log) x Lexeme Meaning Dominance	0.499	0.165	3.025	.002

Table 4: Summary of the final logistic regression model reported in Experiment 2 (DV: compound judged as having 1 lexical color = 0; 2 lexical colors = 1). All variables are centered and scaled and non-significant variables have been removed.

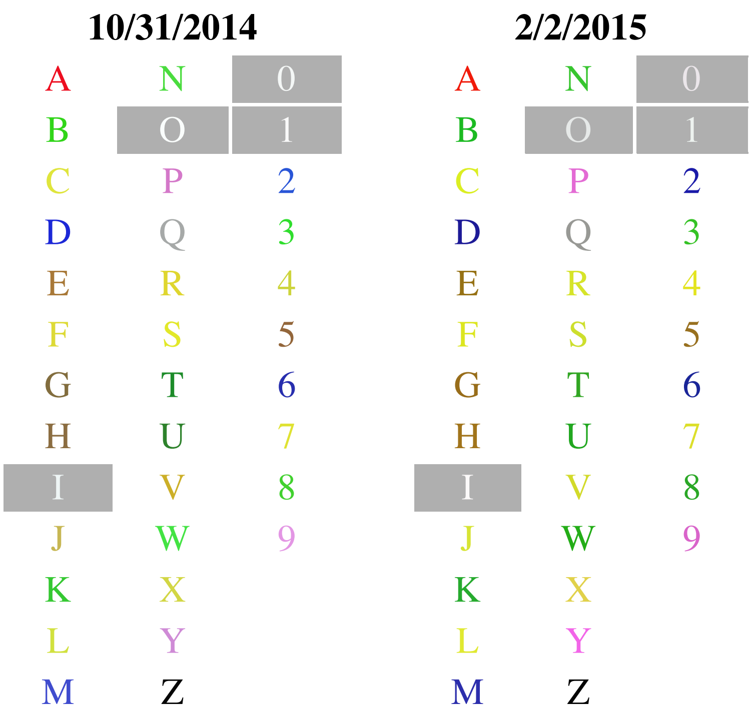

Figure 1: WBL's color selections from the first and second administrations of the Synesthesia Battery.

Monomorphemic	Nonwords	Prefixed	Suffixed	Compound	Pseudocompounds
acorn	blain	biosphere	addresses	aircraft	bulldoze
aficionado	cleep	discontinue	bleached	boyfriend	canteen
aisle	dooge	extramural	calmness	chessboard	carnation
ancestor	frozz	geopolitics	childhood	drawbridge	carpet
bamboo	ghark	illegal	citation	dreamland	cashmere
blood	koose	insincere	cuteness	eyebrow	donkey
captain	lisk	megaton	duckling	grapefruit	forget
cider	merf	midpoint	firmness	handcuff	hemlock
hamster	noak	mislead	goodness	headstrong	margin
invite	prip	multipurpose	momentary	jackpot	mayhem
item	rhiss	nonstick	partnership	peppermint	message
keep	shap	overeat	pavement	plywood	mushroom
measure	sneck	premarital	predictable	pocketbook	partridge
night	spen	readjust	primer	sawmill	pumpkin
orbit	tain	rediscover	scratchy	schoolwork	rampart
owe	thute	subhuman	smirking	taxicab	sonnet
poncho	ulk	supernova	symbolic	touchdown	stubborn
thing	wush	transpose	thoughtful	typecast	tablet
torment	yinge	undercover	tightly	wallflower	tadpole
vampire	zaize	unease	toothless	yearbook	warden

Figure 2: A selection of WBL's lexical color judgments. Grey backgrounds are provided here for some items that are difficult to see against a white background.

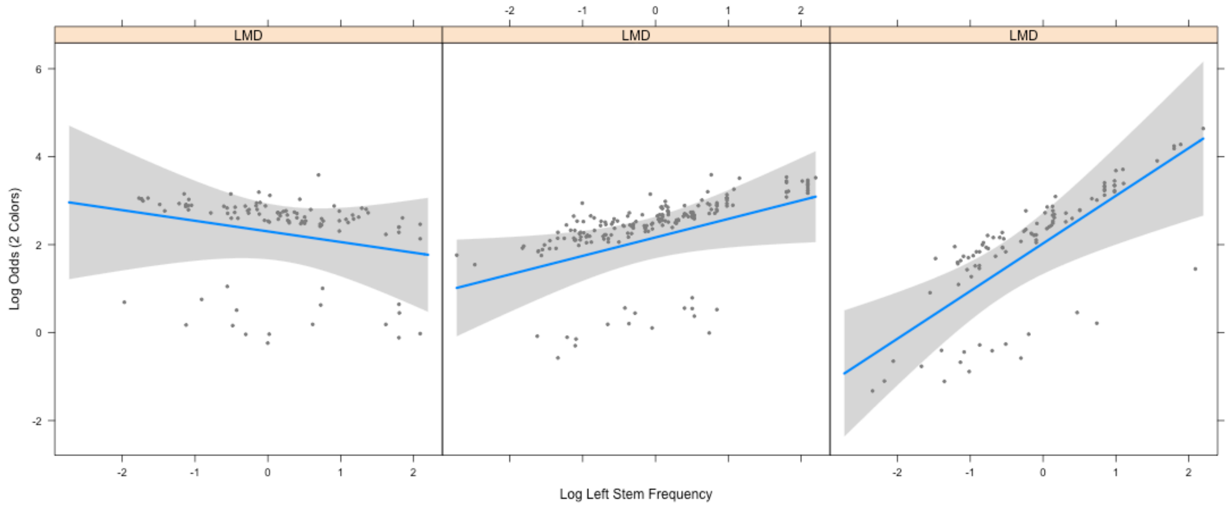

Figure 3: Visualization of the interaction between Lexeme Meaning Dominance (LMD) and Left Root Frequency. From left to right, the panels depict the partial effect of left root frequency for low, medium, and high values of LMD. Compounds with low LMD have meanings that relate strongly to only the left root (e.g., *hopscotch*), compounds with high LMD have meanings that relate strongly to only the right root (e.g., *strawberry*), and compounds with medium LMD have meanings relating to both roots (e.g., *dollhouse*). All variables were centered and scaled.