COGNITION

LINGUISTIC DETERMINANTS OF WORD COLOURING IN GRAPHEME-COLOUR SYNAESTHESIA

Julia Simner, Louise Glover and Alice Mowat

(Psychology, School of Philosophy, Psychology and Language Sciences, University of Edinburgh, UK)

Abstract

Previous studies of grapheme-colour synaesthesia have suggested that words tend to be coloured by their initial letter or initial vowel (e.g., Baron-Cohen et al., 1993; Ward et al., 2005). We examine this assumption in two ways. First, we show that letter position and syllable stress have been confounded, such that the initial letters of a word are often in stressed position (e.g., ***'wo**-man, **'ta**-ble, **'ha**-ppy*). With participant JW, we separate these factors (e.g., with stress homographs such as ***'con**-vict vs. con-**'vict***) and show that the primary determinant of word colour is syllable stress, with only a secondary influence of letter position. We show that this effect derives from conceptual rather than perceptual stress, and that the effect is more prominent for synaesthetes whose words are coloured by vowels than by consonants. We examine, too, the time course of word colour generation. Slower colour naming occurs for spoken *versus* written stimuli, as we might expect from the additional requirement of grapheme conversion in the former. Reaction time data provide evidence, too, of incremental processing, since word colour is generated faster when the dominant grapheme is flagged early rather than late in the spoken word. Finally, we examine the role of non-dominant graphemes in word colouring and show faster colour naming when later graphemes match the dominant grapheme (e.g., *ether*) compared to when they do not (e.g., *ethos*). Taken together, our findings suggest that words are coloured incrementally by a process of competition between constituent graphemes, in which stressed graphemes and word-initial graphemes are disproportionately weighted.

Key words: synaesthesia, grapheme-colour, stress

Introduction

Synaesthesia is a familial condition in which perceptual and cognitive activities (e.g., reading, listening to music) trigger exceptional and persistent sensory percepts (e.g., of colour, taste). One of the most prevalent developmental form is assumed to be the grapheme-colour variant (e.g., Baron-Cohen et al., 1987, 1993; Ramachandran and Hubbard, 2001a; Rich and Mattingley, 2002; Ward et al., 2005) in which sensations of colour are generated by letters, numbers and words. Brain imaging techniques have illustrated the neurological basis of the condition, and its similarity to veridical perception. Hence, synaesthetic colour induced by spoken words produces functional Magnetic Resonance Imaging (fMRI) activation in areas normally associated with the colour perception of external stimuli (left V4; Nunn et al., 2002). In this paper, we investigate the mechanisms of grapheme-colour synaesthesia, and show how the choice of colour for any given word is determined, in part, by processes associated with normal language comprehension.

Although lexical units (words) are some of the most common triggers of synaesthetic colour (Galton, 1997; Grossenbacher and Lovelace, 2001) words can become associated with colours in several ways. For lexical-chromatic synaesthetes (such as EP; Baron-Cohen et al., 1987) word colour is assigned holistically and is unaffected by the colour of the word's constituent letters (although these units in isolation may also induce colour). In this variant, there is an effect of lexical semantics, in that high imagery words with inherent real-world colour (e.g., *table* = woody brown) give rise to interference in the naming of synaesthetic colours. The influence of such semantic features reinforces the assumption of high-level lexical processing in this particular manifestation.

In grapheme-colour synaesthesia, however, the colour of a word is determined by the colour of graphemes[1] within the word. Synaesthetes often report that the colour of each grapheme is apparent in the word overall, but that the word's colour is dominated by a particular grapheme (or graphemes) whose colour appears as the most prevailing. Previous studies have emphasised the role of serial letter position (Baron-Cohen et al., 1993; Cytowic, 1989; Marks, 1975; Pierce, 1907; Ward et al., 2005) since, from case to case, words have appeared to be coloured by their initial letter (e.g., *cat* is the colour of the letter *c*) initial vowel (e.g., *cat* is the colour of *a*) or some combination of the two (Paulesu et al., 1995). Ward et al. (2005) and also Paulesu et al. (1995) have shown that the colouring of the word is

[1] Following Henderson (1984) we "employ the term 'grapheme' in the manner of many commentators on writing systems, to denote the minimal functional distinctive unit of any writing system … and not in the phoneme-representing sense adopted by Coltheart (1984)" (Henderson, 1984, p. 15; see also Henderson, 1985). Hence, we use the term in the same way as all previous synaesthesia studies, but include our definition for clarity.

determined by orthography rather than phonology since (e.g., for the initial-letter variant) the words *cat* and *cite* are coloured the same, while *nice* and *knock* are coloured differently to each other. Despite this orthographic influence, however, grapheme-colour synaesthesia is triggered by both written and spoken words. In this paper, we examine in more detail the mechanisms by which words are associated with colours. We ask firstly, whether serial position (initial letter/vowel) is indeed the critical determinant of grapheme dominance within the word, and secondly, what role non-dominant graphemes might play in establishing word colour. We use our findings to present a mechanistic account of grapheme-colour synaesthesia.

The apparent dominance of the initial letter or vowel in word colouring has been attributed to processes of word recognition (Ramachandran and Hubbard, 2001a, 2001b; Ward et al., 2005). The first letters in a word are thought to be easier to identify because they are visually less crowded (Mason, 1982). Other psycholinguistic models, too, posit a special status for initial letters, suggesting either that they are processed first in grapheme-phoneme conversion (Coltheart and Rastle, 1994) or that they form the primary components of the lexical access code (Taft, 1979; Marslen-Wilson, 1987). However, such theories of lexical processing have encountered difficulties outside the domain of written word comprehension, or the processing of single spoken words. In continuous speech, word boundaries are not clearly marked (Mattys and Samuel, 1997) and less than half the words in English (e.g., *pan*) can be distinguished from the onsets of longer words (c.f., *panda*; Lindfield et al., 1999a; Luce, 1986). This difficulty in establishing word boundaries suggests, by extension, that the initial letters of any given word are not inherently flagged. As a result, theories of word recognition have come to consider the role of word prosody, since this feature provides critical cues for word segmentation.

Cutler and Norris (1988) and also Cutler and Butterfield (1992) suggest that English listeners take stressed syllables to be the start of a word, and segment the speech stream at these points to initiate lexical access. Moreover, Grosjean and Gee (1987) suggest that the cohort of candidates activated during lexical access is gathered on the basis of the word's stressed syllable, rather than its initial syllable. Hence, the word *patrol* (*pa-**'trol***) for example, would be accessed not through its initial letters in a left-to-right fashion, but through the stressed syllable (*trol*). Evidence for these models comes from studies showing that lexical access is severely impaired when stressed (but not unstressed) syllables are mispronounced (Mattys and Samuel, 1997) and that word identification is more difficult in the absence of word stress, compared to other acoustic features (e.g., duration alone; Lindfield et al., 1999b).

The importance of lexical stress in models of word processing leads us to question its role in the generation of synaesthetic colour. Although previous research has attributed word colour to the initial letter or vowel, it is a feature of English that serial position and word stress are confounded. Hence, words are more likely to have first-syllable stress than any other metrical pattern (e.g., Cutler, 1990; Cutler and Carter, 1987) and a stressed syllable in English is 74% likely to be the initial syllable of a word (Cutler, 1990; Cutler and Carter, 1987). The potential for confound is heightened further by the fact that stimuli in synaesthesia research have tended to be nouns, and nouns especially tend to have first-syllable stress (e.g., 94% of those in the corpus of Kucera and Francis, 1967; Kelly and Bock, 1988). For example, all 119 stimuli words in Ward et al. (2005) were nominal (nouns and proper nouns) and there was a preponderance of nouns, too, in Baron-Cohen et al. (1987, 1993). The pairing of English metrical stress and the dominance of nouns in testing, suggests that an effect of stress on synaesthetic colour may have been overlooked.

In the studies presented here, we test the word-colour associations of a participant who (in standard words lists with first-stress dominance) generates word colour according to the initial vowel. In Experiment 1, we present spoken homographs that differ only on the placement of lexical stress (e.g., ***'con**-vict vs. con-**'vict***). If word colour is determined by letter position then both versions of each homograph pair will be identically coloured (i.e., according to the initial vowel) but if lexical stress is critical, words will be coloured differently (i.e., according to the colour of the stressed vowel). Experiment 2 tackles a potential drawback of this comparison, that such homographs confound lexical stress with grammatical class. Hence first-stress homographs (e.g., ***'con**-vict*) tend to be nominal, while second-stressed items (e.g., *con-**'vict***) tend to be verbal. Elsewhere, studies have shown behavioural differences in the processing of nouns and verbs, which might indicate a functional difference in the processing of different word classes (e.g., Caramazza and Hillis, 1991; Gomes et al., 1997). To ensure that effects reported here are correctly attributed to lexical stress rather than grammatical class, we present a second study in which words with first and second stress are compared within the class of nouns (e.g., ***'ca**-non vs. ca-**'det***) and within the class of verbs (e.g., ***'jo**-stle vs. mo-**'lest***). We examine whether stress influences are perceptual or conceptual, by presenting our materials additionally in written rather than spoken form (Experiment 3). If colour generation relies on conceptual stress, we anticipate a stress influence in both spoken and written stimuli.

In our studies we look also at the time course of processing. In Experiments 2 and 3 we examine whether processing takes place incrementally (rather than, say, only once the word has fully unfolded). For evidence of incremental processing, we anticipate that the spoken stimuli of Experiment 2 will produce faster colour naming for words with first-syllable *versus* second-syllable stress. This is because the dominant (stressed) vowel appears earlier in the speech stream for the former, compared to the latter. In Experiment 3, however, there is no acoustic cue to stress placement (in the written stimuli) which instead, can only be correctly assigned after lexical access (when we learn, for example, that similar looking words such as *cater versus cadet* and *reckon versus relate* have opposing stress patterns). Since our target words are matched on length and frequency, lexical access should take place at approximately the same time across conditions (i.e., first- vs. second-syllable stress) and no difference should be found in the speed of colour naming. Finally, by comparing global reaction times across spoken and written stimuli (Experiments 2 *vs.* 3) we provide information about synaesthetic colouring across modalities. Psycholinguistic studies suggest that cognitive processes establish the graphemic content of words during spoken language comprehension (Donnenwerth-Nolan et al., 1981; Halle et al., 2000; Jakimik et al., 1985). Hence, Donnenwerth-Nolan et al. (1981) showed that people are faster to assert that two words rhyme when they share graphemes (*pie vs. tie*) compared to when they do not (*pie vs. rye*). We show speeded colour generation in written *versus* spoken language, which is compatible with the notionthat colour generation is tied to grapheme processing, and is delayed in spoken language comprehension by the additional step of grapheme conversion.

Our final aim for the current investigation is to test the hypothesis that word colour is established from a word's component graphemes by a process of competition. Anecdotal reports suggest that this may be the case, since first-hand accounts of word colouring describe a tension between composite colours within the word (notwithstanding the dominance of one particular grapheme). We test such a model of competition in Experiment 4, in which we measure the speed of colour generation in words where the dominant vowel is followed either by a second instance of the same vowel (e.g., *ether*) or by a different vowel (e.g., *ethos*). If word colour is generated through competition, we expect slower colour naming in the latter, where a competing grapheme introduces a contrasting colour. This is compared to the former case, where such competition reinforces the colour of the dominant grapheme.

Like other contemporary studies of synaesthesia, we first provide objective evidence for the genuineness of our synaesthete case. Following Baron-Cohen et al. (1993) and others, we show that our synaesthete, JW, is significantly more consistent in colour associations than a group of non-synaesthetic controls.

Experimental Investigation

Case History

JW is a 23-year-old, left-handed female graduate, who has had synaesthesia all her life. She reports colours for (spoken and written) letters, numbers, days of the week, months of the year, and English words, and experiences this as a sensation projected in her mind's eye. Her mother also reports coloured words, but her twin sister does not. JW has no family history of neurological disease, and no significant medical complaint. Although colours are assigned idiosyncratically to the days of the week, all other words (including months) are coloured by a dominant vowel. From a written list of 80 words (Ward et al., 2005) JW assigned word colour according to the initial vowel, although all words in this list had first-syllable stress.

Test of Genuineness

JW provided colours for the 80 words described above on two separate occasions separated by 10 months. Consistency scores for 35 control participants were taken from Ward and Simner (2003). Controls were asked to freely associate colours to the stimulus words, and to recall those associations in a retest two weeks later. JW was significantly more consistent over time than controls (92% *vs.* 44% respectively; $Z = 3.69$, $p < .001$) and we take this as a hallmark of genuineness (Baron-Cohen et al., 1993).

Experiment 1

In this study we test the hypothesis that vowel-triggered word colouring is determined by lexical stress rather than letter ordering. We predict that stress homographs (e.g., ***'con**-vict vs. con-**'vict***) will tend to be coloured differently, each by the vowel in the stressed syllable.

Method

Materials. Forty-three pairs of disyllabic homographs were selected, which differed on the placement of syllable stress (i.e., first- *vs.* second-syllable; e.g., ***'con**-vict vs. con-**'vict***). All words had a different vowel in the first and second syllable, and were balanced across conditions on their frequency in the British National Corpus (first stress: mean 1109, SD 2128; second stress: mean 1037, SD 2009). One hundred and seventy-four disyllabic words (nouns, verbs and adjectives) were used as fillers. All words were digitally recorded into wave files, and the complete list of target items is shown in the Appendix.

Procedure. JW heard spoken words via headphones and was asked to state her synaesthetic colour for each as quickly and accurately as possible into a microphone. Each vocal response triggered the presentation of an on-screen icon, which prompted the participant to press the space bar to advance to the next word at her own pace. The materials were presented in a pseudo-randomised order, with each half of every homograph pair in the opposite half of the list from its counterpart, and with an equal number of first- and second-syllable stress homographs in each half of the experiment. The experiment lasted approximately 20 minutes.

Results

Data showed that 93% of first-syllable stress words were coloured by the vowel of the initial syllable (and 7% by the second syllable) compared to only 19% of second-syllable stress words. These latter were most often coloured by the vowel in the second syllable (in 81% of cases). A chi-square analysis showed that synaesthetic word colour was significantly determined by syllable stress [χ^2 (1) = 48.28, p < .001]. There was a numerical tendency for syllable stress to have a greater impact on words with first *versus* second-syllable stress (93% *vs*. 81%) but this effect was non-significant [χ^2 (1) = 2.606, p = ns].

Discussion

Our data provide evidence that the determinant of word colour in (vowel-dominant) grapheme-colour synaesthesia is syllable stress rather than letter position. Words tended to be coloured by the vowel in the stressed syllable, rather than simply the initial vowel. There was some suggestion, however, that letter position may also be implicated in word colouring, since stressed first syllables were numerically more likely to dominate word colour than stressed second syllables. We investigate this possibility in more detail in Experiments 2 and 3.

Experiment 2

The materials of Experiment 1 confound words stress with grammatical class, such that words with first-syllable stress tend to be nominal, and words with second-syllable stress tend to be verbal. In this study we compare colour judgements for words with first- *versus* second-syllable stress independently for nouns and verbs. An effect of lexical stress that is independent of grammatical class should show itself in both groups. We test also for incremental processing and predict faster responses for words with first- *versus* second-syllable stress, since acoustic cues to stress placement come earlier in the speech stream for the former.

Method

Materials. Forty disyllabic nouns with first-syllable stress, and a different vowel in each syllable (e.g., ***'ca**-non*) were balanced pair-wise in character length, syllable length and frequency with 40 nouns with second-syllable stress (e.g., *ca-**'det***). In first- and second-stressed items respectively, the mean character length was 6.7 (SD 1.2) and 6.6 (SD 1.2) and the mean frequency (Kucera and Francis, 1967) was 12.0 (SD 20.9) and 11.6 (SD 20.7). Forty-two pairs of disyllabic verbs were balanced in the same fashion (e.g., ***'jo**-stle vs. mo-**'lest***) with respective mean character lengths of 6.1 (SD .7) and 6.2 (SD .8) and mean frequencies of 6.9 (SD 11.3) and 7.1 (SD 12.6). All words were digitally recorded into wave files, and the complete list of target items is shown in the Appendix.

Procedure. The procedure was identical to Experiment 1 except that items were fully randomised, and JW was asked to state her colour responses into a microphone attached to a millisecond timing device. This device recorded the time between the onset of each stimulus and the initiation of the participant's response. The experiment lasted approximately 10 minutes.

Results

One noun and one verb (and each of their matched counterparts) were removed from the analysis, since the colour attributed to them was unrelated to the vowels in the word. Stress placement had a significant effect on the vowel that dominated word colour, for both nouns [χ^2 (1) = 43.587, p < .001] and verbs [χ^2 (1) = 63.560, p < .001]. Data showed that 92% of nouns with first-syllable stress were coloured by the initial vowel, compared to 18% of those with second-syllable stress. For verbs, these figures were 98% and 9% respectively. Collapsing across groups, the influence of the stressed vowel was numerically greater for words with first-syllable stress (95%) compared to second-syllable stress (87%). This difference was significant [χ^2 (1) = 5.316, p < .05] suggesting that a stressed syllable is more likely to dominate word colour if it is also the initial syllable.

The time course of colour attribution was examined by comparing reaction times for words with first- *versus* second-syllable stress (after the removal of 17 items that were not coloured by the stressed vowel). Colour was faster to name for words with first-syllable stress (1130 msec) compared to second-syllable stress (1360 msec), and this was true for both nouns (1157 *vs*. 1424 msec respectively) and verbs (1106 *vs*. 1306 msec respectively). Independent sample t-tests show these differences to be significant [$t(145) = 6.30$, $p < .001$, $t(67) = 4.39$, $p < .001$, $t(76) = 4.79$, $p < .001$][2].

Discussion

Our data show that syllable stress, rather than letter ordering was the primary determinant of word colour. In the majority of cases, a word's colour was dictated by the vowel in the stressed syllable, rather than the initial vowel. However, letter position, too, plays a significant role in the colouring mechanism, since a stressed vowel was more likely to dominate word colour if it was also the initial vowel. This supports a trend found in Experiment 1, and implicates both word stress and letter position in the synaesthetic process. Response times for colour naming provide evidence about the time course of the synaesthetic process. Our data suggest that synaesthetic colour is generated incrementally as the information in the word unfolds, rather than taking place only once a word has been fully uttered. In words with first-syllable stress, the vowel that determines word colouring is flagged earlier in the speech stream than in words with second-syllable stress. Response times were faster for the former than the latter, as we might expect if the participant were acting on the dominant (stressed) syllable as soon as it was encountered in the speech stream.

Experiment 3

In this study we present our materials in written form to test whether stress effects are perceptual or abstract. A stress effect that relies on perceptual prominence should disappear in this modality, but remain if its influence holds at an abstract/linguistic level. Should the effects of lexical prosody be abstract in nature, we additionally predict no difference in naming speeds for words with first- *versus* second-syllable stress. This is because accurate stress assignment cannot take place until after lexical access (which should proceed at the same rate for our matched stimuli). Finally, we compare global response times across Experiments 2 and 3, and predict that the role of grapheme processing will manifest itself as slower response times for spoken *versus* written materials.

Method

Materials. The materials were taken from Experiment 2 but compiled in written form.

Procedure. Target words were presented one-by-one, in black font 14 against a white background at the centre of a computer screen. Each word was immediately preceded by a fixation point, which appeared at the same on-screen location for 1000 msec. JW was instructed to focus on the fixation point, and to state the colour of the word that appeared there as quickly and accurately as possible. All other aspects were identical to Experiment 2, and the study lasted approximately 10 minutes. To draw attention away from the feature of lexical stress, this study was presented prior to Experiments 1 and 2.

Results

Two verbs (and their matched counterparts) whose colours were unrelated to constituent vowels were removed from the analysis. As before, stress placement had a significant effect on the vowel that dominated word colour, for both nouns [$\chi^2(1) = 26.6$, $p < .001$] and verbs [$\chi^2(1) = 62.2$, $p < .001$]. Data showed that 83% of nouns with first-syllable stress were coloured by the initial vowel, compared to 17% of those with second-syllable stress. For verbs, these figures were 100% and 12% respectively. Collapsing across groups, the influence of the stressed vowel was significantly greater for words with first-syllable stress (92%) compared to second-syllable stress [79%; $\chi^2(1) = 4.88$, $p < .05$] illustrating again that a stressed syllable is more likely to dominate word colour if it is also the initial syllable. We found no evidence that stress had a differential effect across written and spoken modalities (Experiment 2 *vs*. 3). Word colour was dictated by the stressed vowel in 89% of spoken words, and 85% of written words [$\chi^2(1) = 1.37$, $p = ns$].

As before, we examined the time course of colour attribution for words with first- and second-syllable stress (and 22 items that were coloured by non-stressed vowels were removed from the analysis). Unlike in Experiment 2, there was no significant difference in colour naming for words with first-syllable stress compared to second-syllable stress [969 *vs*. 1025 msec, $t(140) = 1.46$, $p = ns$] and this was true for both nouns [1022 *vs*. 1056 msec, $t(62) < 1$] and verbs [929 *vs*. 998 msec, $t(76) = 1.4$, $p = ns$]. Finally, a paired-sample comparison of matched responses across Experiments 3 and 2 show that naming speeds for synaesthetic colour are faster for written *versus* spoken words [994 *vs*. 1206 msec respectively, $t(129) = 9.24$, $p < .001$].

Discussion

Our data suggest that synaesthetic word colouring is sensitive to abstract rather than perceptual stress, since lexical prosody dictates word

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[2] An anonymous reviewer points out that spoken words with second syllable stress may take longer to utter than spoken words with first syllable stress. This was not so for the materials of Experiment 1 (mean utterance times = 677 msec and 674 msec respectively) but was indeed the case for the materials of Experiment 2 (mean utterance times = 599 msec and 494 msec respectively). Nonetheless, two post-hoc analyses on the data of Experiment 2 reveal that our findings are independent of this factor. First, we re-analysed our data after factoring out the utterance time for each item. This adjustment revealed the same significant pattern of results as before (i.e., word colouring was faster to name for words with first syllable stress (637 msec) compared to second syllable stress [763 msec; $t(145) = 3.3$, $p < .01$] and this was true for both nouns [684 *vs*. 843; $t(67) = 2.57$, $p < .02$] and verbs [594 *vs*. 693; $t(76) = 2.23$, $p < .05$]. Second, a post hoc analysis of 80 items (40 nouns and 40 verbs) that were balanced on length of utterance (as well as characters and syllables) across conditions again revealed the same significant pattern of results as before. Word colouring was faster to name for words with first syllable stress (1122) compared to second syllable stress [1344; $t(78) = 4.76$, $p < .001$] and this was true for both nouns [1150 *vs*. 1377; $t(38) = 3.25$, $p < .01$] and verbs [1096 *vs*. 1310; $t(38) = 3.5$, $p < .01$].

colouring in written language. Both nouns and verbs tend to be coloured by the stressed vowel, although the influence is greater for initial vowels (implicating both lexical stress and letter ordering). The effects of lexical stress are seen equally in the colouring of spoken and written words, but the time course of processing differs. Unlike in spoken materials, written stressed vowels trigger colour at the same speed for words with first- and second-syllable stress. In written materials, there is no temporally situated acoustic cue to indicate which syllable is stressed, and hence dominant for synaesthetic colour. Instead, stress patterns can only be known after lexical access, which proceeds at the same speed across our balanced conditions.

We additionally found that synaesthetic colour emerges faster in written compared to spoken language. This advantage for the written form might suggest that synaesthetic processing relies on graphemic units, which must be generated from the phonemic representation (with an associated time penalty) for spoken stimuli. However, we are reluctant to draw strong conclusions from this finding for two reasons. First, our dependent measure of colour naming latencies for spoken stimuli (mean 1206 msec) includes the time taken for the spoken word to be uttered (mean 547 msec) and so may be artificially inflated (although the exact extent of this is unclear, since we know that synaesthetic colour is initiated some time *before* the offset of the spoken word). Second, our finding of slower colour naming latencies for spoken words might simply reflect a difference in the processing of spoken *versus* written words (e.g., Turner et al., 1998). A direct comparison of lexical access speeds across modalities has proved difficult in the literature, simply because the spoken word, unlike the written form, will always unfold over time (thereby producing a methodological confound). For these two reasons therefore, we draw conclusions from our direct cross-modal comparison only tentatively.

Experiment 4

In this study we examine the role of non-dominant graphemes in word colouring. We test colour naming speed for words where the dominant vowel is followed by a competitor with the same colour (e.g., *ether*) or a different colour (e.g., *ethos*). Slower response times for the latter would provide evidence for a mechanism of competition between constituent graphemes.

Method

Materials. We selected 76 mono-morphemic disyllabic words with identical first and second vowels, and whose lexical stress fell on the initial syllable (e.g., *ether*). Each word was balanced pair-wise (on length, frequency, number of syllables, grammatical class, lexical stress and initial vowel) to matched control words whose first and second vowels differed (e.g., *ethos*). In shared- and differing-vowel conditions respectively, the mean character length was 5.9 (SD .9) and 5.9 (SD .8) and the mean frequency (Kucera and Francis, 1967) was 12.6 (SD 23.2) and 12.5 (SD 22.8). The 152 target words were added to a list of 108 fillers of varying lengths and grammatical class. The complete list of target items is shown in the Appendix.

Procedure. The procedure was identical to that of Experiment 3.

Results

Mean response times for colour naming were 770 msec in the shared-vowel condition (e.g., *ether*) compared to 870 msec when the vowels differed (e.g., *ethos*), and a paired sample t-test shows that this difference is highly significant [$t(75) = 4.68$, $p < .001$].

Discussion

Our study illustrates the role of non-dominant graphemes in the synaesthetic colouring of words. Although word colour is determined by a dominant grapheme (here, the initial/stressed vowel) the colour emerges through competition with surrounding graphemes. When surrounding graphemes reinforce the colour of the dominant vowel (as in words such as *ether*) word colour settles faster than when the colour of these graphemes compete (as in *ethos*). These results, and those from Experiments 1 to 3 are combined into a mechanistic account of word colouring in the General Discussion below.

General Discussion

Over four studies, we provide evidence for the nature of vowel-triggered word colouring in a case of grapheme-colour synaesthesia. With comparisons both across and within grammatical classes, we showed that JW's words tend to be coloured by their stressed vowel, and that a stressed vowel is more likely to dominate if it is also the initial vowel. We showed that the influence of stress on word colouring holds equally with written and spoken stimuli, but that colour naming proceeds more quickly in the former. Colour generation was faster for first- *versus* second-syllable stressed words, but only with spoken stimuli. Finally, we showed that word colouring is established more quickly when the colour of a non-dominant grapheme is the same (e.g., *ether*) rather than different (e.g., *ethos*) to the dominant vowel.

Our data provide support for a mechanism of synaesthesia which generates word colour during grapheme-level processing. The slower colour naming responses for spoken language may suggest a delay incurred by phoneme-to-grapheme conversion rules, or other stages of language processing that establish the graphemic content of words extracted from speech (Donnenwerth-Nolan et al., 1981; Halle et al., 2000; Jakimik et al., 1985). This is a mechanism in which constituent graphemes compete for dominance in overall word colouring. The process takes place more quickly when competition reinforces the colour of a dominant grapheme, rather than detracts from it (cf. *ether*, *ethos*). Within this competition, units are unequally weighted, and grapheme dominance is a priori biased towards vowels that carry lexical stress. The majority of words are coloured by the stressed vowel, although there is evidence, too, for asymmetric weighting according to serial position. We saw that stressed vowels were more likely to dominate word colour if they are also initial vowels, suggesting that initial vowels, too, are disproportionately weighted (although less so than stressed vowels).

The process by which word colour is established is one that takes place incrementally, rather than word-final only. Evidence for incremental processing comes with spoken stimuli, where acoustic features converge to cue the placement of lexical stress in the speech signal, and colour is generated faster for words where this is cued early rather than late. It has been suggested that stressed syllables form the primary lexical access code in speech comprehension (Grosjean and Gee, 1987) and this special status in word retrieval may give rise to the dominance of stressed graphemes in synaesthetic colour. However, this account does not provide the complete story. We saw that lexical stress determines word colouring even in written language. In this modality, stress can only be accurately assigned *after* lexical access (hence there is no advantage for first- *versus* second-stress words, whose colours emerge at the same speed). It seems then, that while lexical stress might determine synaesthetic colour for reasons that are similar to those that give it a special status in lexical access, word colouring does not necessarily take place when (stressed) syllables *initiate* lexical access. Stress effects in written stimuli show that word colouring can be determined by information retrieved *after* the point of lexical access.

The suggestion that some aspects of word colouring may take place subsequent to lexical access provides an interesting addition to previous findings. In comparisons across synaesthesia types, there had been some indication that word colouring fails to show the lexical influences seen in other variants, such as lexical-gustatory synaesthesia. Ward et al. (2005) show that taste, but not colour is sensitive to word frequency and lexicality (word/non-word status) suggesting initially, that word colouring might take place at a pre-lexical level. Moreover, lexical semantics is often irrelevant in word colouring for grapheme-colour synaesthetes, as evidenced by the "alien colour effect" (Gray et al., 2002). In this, a colour term may elicit a sensation other than that dictated by its lexical semantics (e.g., the word *red* may be green). Notwithstanding these apparent resistances to word-level influences, the role of lexical stress in written stimuli suggests that some aspects of word colouring, at least, are tied to (post) lexical processes of word comprehension.

A complete theory of word colouring must examine the extent to which the mechanisms proposed here are true of other cases of grapheme-colour synaesthesia. JW's case was combined with 24 additional English speaking grapheme-colour synaesthetes, recruited from the database of the British Synaesthesia Research Consortium. Each reported colours associated with graphemes, and objective evidence for their experiences is found in Ward et al. (2005), where these participants show significantly higher consistency over time than non-synaesthetic controls. Participants were provided with word lists that tested two aspects of their word colouring. First, monosyllabic word triplets such as *net-bet-but* were presented to test whether word colour was dominated by vowels (where words 1 and 2 are coloured the same) or the initial letter (where 2 and 3 are coloured the same). Second, disyllabic word pairs such as *canon-cadet* were presented to test whether dominant graphemes fall according to serial position (where words would be coloured the same, by the initial letter/vowel) or syllable stress (where words would be coloured differently). Of our 25 participants, 20 produced word colours that were systematically attributable to a given grapheme. Of these, 15 were sensitive to the initial letter of monosyllabic words (which was a consonant in all our stimuli), three were sensitive to the initial vowel, and two to some combination of both. Next we examined our disyllabic words. In our small scale testing, 100% of the vowel-triggered synaesthetes had word colouring that was dictated (to some measurable extent) by the stressed vowel. This was in contrast to only 20% of those triggered by the initial letter[3].

Our comparison suggests, therefore, that the effect of lexical stress on word colouring may be less apparent in synaesthetes whose words are coloured by consonants than by vowels. The roots of this difference would follow from the nature of lexical stress. As an acoustic feature (and by extension perhaps, in its abstract representation) lexical stress is carried more by vowels than consonants (not least because the former constitute a greater proportion, acoustically speaking, of any

[3] For this 20%, the sensitivity to lexical stress showed itself in one of two ways: (a) as a tendency for word colouring to be triggered by the consonant in the onset of the stressed syllable (e.g., sa-**'voy** is coloured by v) or (b) as a shift towards stating more than one colour for words with second syllable stress (e.g., **'sa**-tin = pink; sa-**'voy** = pink + green; where s = pink, v = green).

syllable). It is perhaps not surprising, then, to see its effects more prominently in word colouring triggered by vowels than by consonants. Nonetheless, to incorporate these findings, we need only change the weighting of stressed graphemes in the competitive mechanism of word colouring. For vowel-triggered variants, stressed graphemes may take a greater weighting than for the initial-letter variant. Hence we have presented a mechanistic account of word colouring in grapheme-colour synaesthesia based on a variant in which vowels play a critical role, but where component processes (e.g., grapheme weighting) are free to vary across different manifestations. A crucial next-step would be a systematic comparison of a large number of grapheme-colour synaesthetes, from which we might determine the extent to which different manifestations can be captured by different weightings of component processes within our model of word colouring.

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Julia Simner, Psychology, School of Philosophy, Psychology and Language Sciences, University of Edinburgh, 7 George Square, Edinburgh, EH8 9JZ, UK. e-mail: j.simner@ed.ac.uk

Appendix

Experiment 1

Stress Homographs

compact, content, converse, convict, digest, extract, increase, indent, insert, intern, rebound, recap, recoil, refill, rethink, suspect, upgrade, affix, refit, reprint, alloy, import, fragment, discharge, proceeds, discourse, export, protest, object, transport, retake, invert, recount, rewrite, convert, exploit, permit, combine, upset, refuse, recall, affect, produce.

Experiments 2 and 3

Noun Pairs (First-Second Syllable Stress)

asset-abode, angel-saloon, anvil-adieu, august-advice, anthem-ascent, barrier-balloon, setting-belief, cupboard-buffoon, spinach-brigade, boatman-brocade, canon-cadet, watchmen-canteen, gallows-cartoon, cheetah-chemise, rider-cigar, colleague-complaint, foreground-constraint, footman-corsage, currant-cuisine, ensign-demise, welfare-estate, peasant-expanse, glacier-gazelle, pavement-gazette, ladder-lagoon, ladle-lapel, ditcher-liqueur, station-machine, cottage-morale, flower-motel, choir-motif, ordnance-moustache, homage-ordeal, backlog-platoon, pigment-princess, raisin-ravine, satin-savoy, candour-shampoo, surgeon-trustee, shipment-vignette.

Verb Pairs (First-Second Syllable Stress)

alter-arose, argue-arise, blazon-allege, broaden-concede, cater-amuse, conquer-condemn, jostle-molest, linger-inject, moisten-confine, quicken-mistook, reckon-relate, shorten-procure, smitten-inflame, topple-outwit, covet-cohere, yodel-omit, dangle-accede, grovel-ordain, gurgle-mutate, guzzle-fulfil, haggle-abound, harden-adorn, ponder-oblige, smuggle-subside, dampen-attest, mingle-disarm, perish-detain, stifle-disown, hasten-adore, hover-forbid, prosper-foresee, fasten-adhere, vanish-appoint, cherish-presume, ridden-inform, govern-foreseen, shaken-absorb, frighten-withdrew, differ-ignore, madden-adjust, furnish-survive, happen-accept.

Experiment 4

nether-pelvis, helmet-relict, gender-fetish, defect-mentor, fender-lethal, fervent-zenith, nephew-relish, legend-jersey, member-method, tartar-cavern, nasal-valet, natal-tacit, garland-latent, vacant-canyon, hazard-magnum, ransack-phantom, blatant-spangle, stalwart-chagrin, stagnant-placid, robot-toxin, boron-tonic, vigil-sinus, jewel-melon, ether-ethos, digit-bison, oblong-orphan, tidbit-mildew, rascal-damsel, skewer-cleric, hangar-bandit, vagrant-fascist, clement-blemish, sewer-demon, hebrew-debris, segment-dentist, concord-compact, secret-permit, salad-baton, standard-status, temper-dental, lever-herald, picnic-bishop, fatal-valid, fever-lemon, arab-apex, colon-bonus, madam-basil, pidgin-ginger, carnal-candid, tempest-remnant, serpent-pendant, civic-widow, radar-cabin, critic-triumph, victim-pistol, satan-wager, sever-relay, proton-tropic, clinic-tripod, murmur-muster, sulphur-publish, fragrant-shamrock, naval-naked, virgin-finger, pagan-falcon, velvet-heyday, rampant-hatchet, pilgrim-gingham, skirmish-shipment, comfort-concert, limit-pilot, timid-minus, donor-coral, altar-album, frigid-swivel, motor-novel.