Synesthesia for manual alphabet letters and numeral signs in second-language users of signed languages

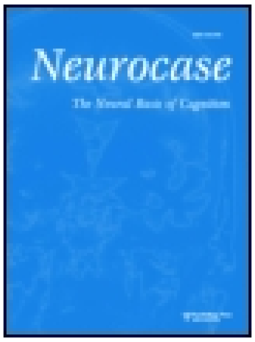
Article *in* Neurocase · June 2016

DOI: 10.1080/13554794.2016.1198489

Joanna Atkinson
UCL

David M Eagleman
Stanford University

Bencie Woll
University College London



Routledge
Taylor & Francis Group

Neurocase

The Neural Basis of Cognition

ISSN: 1355-4794 (Print) 1465-3656 (Online) Journal homepage: http://www.tandfonline.com/loi/nncs20

Synesthesia for manual alphabet letters and numeral signs in second-language users of signed languages

Joanna Atkinson, Tanya Lyons, David Eagleman, Bencie Woll & Jamie Ward

NEUROCASE, 2016
http://dx.doi.org/10.1080/13554794.2016.1198489

Routledge
Taylor & Francis Group

Synesthesia for manual alphabet letters and numeral signs in second-language users of signed languages

Joanna Atkinson[a], Tanya Lyons[b], David Eagleman[c], Bencie Woll[a] and Jamie Ward[b,d]

[a]DCAL Deafness, Cognition and Language Research Centre, University College London, London, UK; [b]School of Psychology, University of Sussex, Brighton, UK; [c]Baylor College of Medicine, Houston, Texas, USA; [d]Sackler Centre for Consciousness Science, University of Sussex, Brighton, UK

ABSTRACT
Many synesthetes experience colors when viewing letters or digits. We document, for the first time, an analogous phenomenon among users of signed languages who showed color synesthesia for fingerspelled letters and signed numerals. Four synesthetes experienced colors when they viewed manual letters and numerals (in two cases, colors were subjectively projected on to the hands). There was a correspondence between the colors experienced for written graphemes and their manual counterparts, suggesting that the development of these two types of synesthesia is interdependent despite the fact that these systems are superficially distinct and rely on different perceptual recognition mechanisms in the brain.

ARTICLE HISTORY
Received 24 June 2015
Accepted 1 June 2016

KEYWORDS
Synesthesia; fingerspelling; British sign language; American sign language; deaf

Introduction

Synesthesia is a phenomenon in which perceptual experiences, such as colors, tastes, or smells are elicited by stimuli that are not usually associated with such experiences (see Ward & Mattingley, 2006; or Cytowic & Eagleman, 2009; for reviews). It affects around 4% of population (Simner et al., 2006) and is thought to arise from maturational neurodevelopmental differences in the brain, which lead to cross-activation in neural areas that do not usually interact (Hubbard, Brang, & Ramachandran, 2011). The most widely documented form is grapheme→color synesthesia, in which written letters, numbers, and words induce color (Simner et al., 2006). For example, seeing a letter "j" might induce a concurrent sensation of the color "red". Letters spoken aloud can also trigger synesthetic colors (Baron-Cohen, Harrison, Goldstein, & Wyke, 1993) but the present study is the first documentation of equivalent synesthesia in the visuomotor language modality, with colors induced by manual fingerspelled letters and numeral signs.

Manual alphabets represent orthographic letters of a writing system using hand configurations to represent each letter, which are combined in sequences of movements to fingerspell written words. The British manual alphabet uses two-handed configurations, while most other systems, including the American manual alphabet, are one-handed (Figures 1 and 2). In all manual alphabets, the hand configurations have been designed to represent some visual features of the corresponding orthographic symbols in at least some letters (see the forms for D in the American Sign Language (ASL) and British Sign Language (BSL) manual alphabets in Figures 1 and 2) but the strength of the relationship varies from letter to letter and is sometimes entirely absent (cf. A, E, I, O, U in the BSL alphabet).

Signed languages, used by Deaf communities around the world, have evolved naturally, with their own phonologies and grammars, and are unrelated to the spoken and written languages that surround them (Sutton-Spence & Woll, 1999). Numeral signs are considered as part of the lexicons of signed languages and they show variation between and within national sign languages (Anderson, 1979; Zeshan, Escobedo Delgado, Panda, & De Vos, 2013). Unlike sign languages, manual alphabets were developed specifically to provide an interface with written language. Fingerspelling is primarily used for names of people and places, or to represent words borrowed from written language into signed language.

How might fingerspelling synesthesia relate to existing explanations of synesthesia such as Ramachandran & Hubbard's cross-activation theory and adjacency principle (2001a; 2001b: Hubbard et al., 2011)? They suggest that genetic factors might lead to failure of neurodevelopmental synaptic pruning, such that adjacent brain regions remain connected into adulthood leading to cross-activation (Ramachandran & Hubbard, 2001a; 2001b). They state that written letters/numbers act as synesthetic inducers because V4 color processing is adjacent to the Visual Word Form Area (VWFA,(Cohen & Dehaene, 2004)), which has a key role in mapping orthographic input onto lexical representations. Crucially, the VWFA is cross-modal and activated, during functional magnetic resonance imaging, by any orthographic input whether printed letters/words, fingerspelling (Waters et al., 2007), or Braille (Reich, Szwed, Cohen, & Amedi, 2011). Studies of both BSL and ASL have reported that watching fingerspelling activates a neural circuit that closely overlaps with reading print. Signed languages are strongly left lateralized, harnessing areas such as the left inferior frontal gyrus, the VWFA, and the lexico-semantic areas of the left middle temporal gyrus (Emmorey, McCullough, & Weisberg, 2015; Waters et al., 2007). The perception of fingerspelling is, however, additionally linked to activity in bilateral regions dedicated to motion perception and the hand and arm regions of motor cortex (Waters et al., 2007). Given the extremely close correspondence of

CONTACT Joanna Atkinson joanna.atkinson@ucl.ac.uk

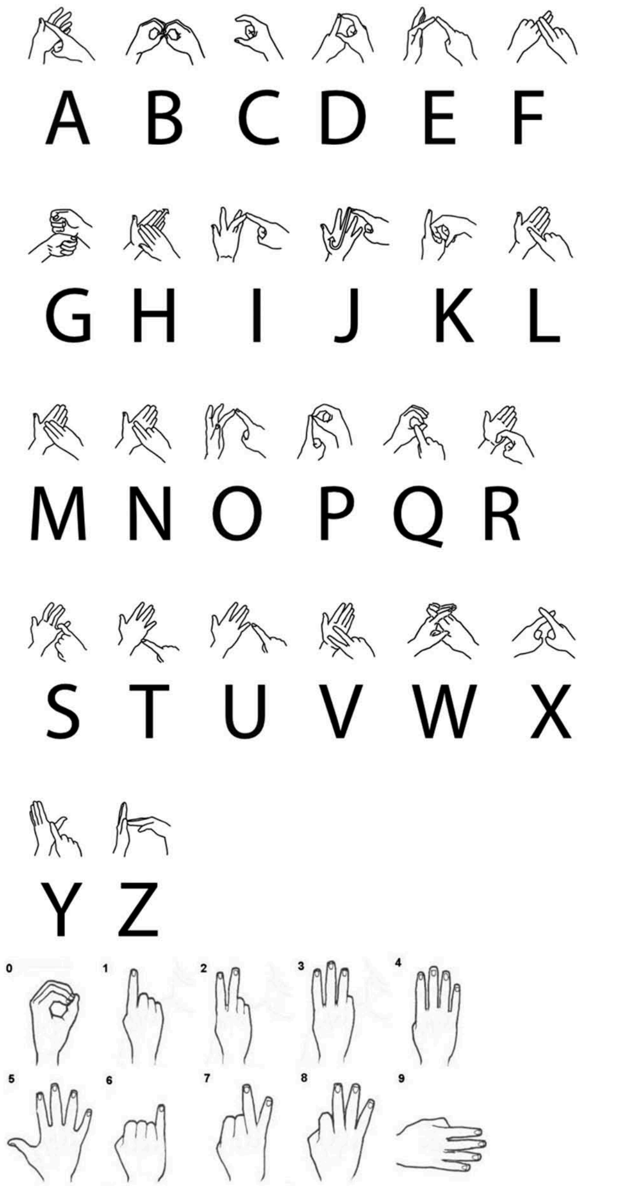


Figure 1. British manual alphabet and BSL numerals (South West region) (Images: http://en.wikipedia.org/wiki/Fingerspelling, Wikipedia Commons Free Media Repository, http://www.rod-parrott.pwp.blueyonder.co.uk/site/numbers).

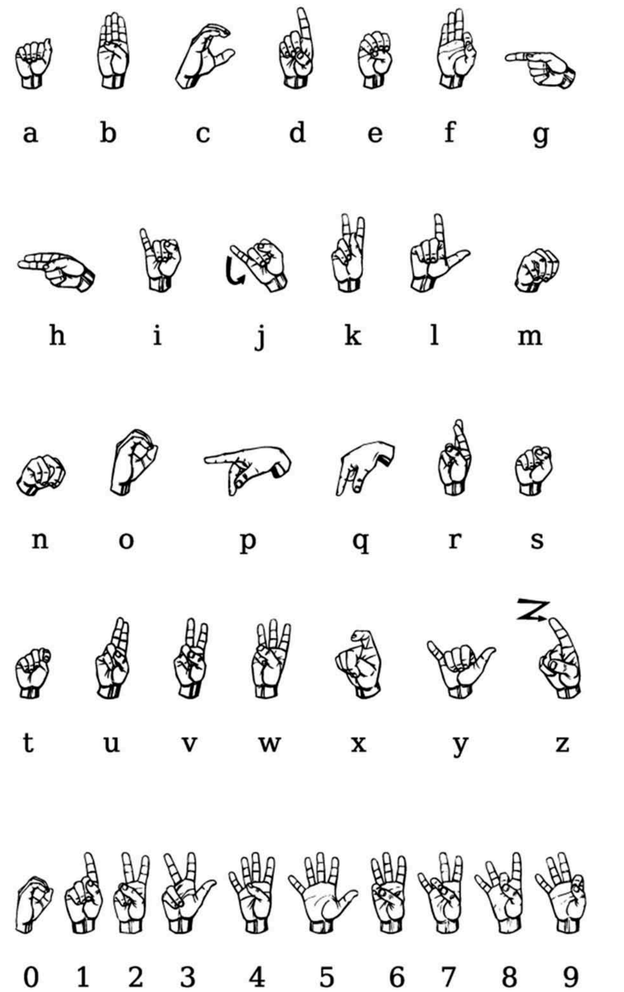


Figure 2. American manual alphabet and ASL numerals (Image: http://en.wikipedia.org/wiki/American_manual_alphabet, Wikipedia Commons Free Media Repository).

brain regions involved in processing print and fingerspelling, we predict that color experiences for fingerspelling are equally phenomenologically possible. Despite this, there are no previously documented cases of manual alphabet/numeral sign→color synesthesia as far as we are aware.

It is also unclear how this type of synaesthesia, if it exists, is related to grapheme→color synaesthesia although we hypothesise that there would be a correspondence of colors across the different modalities. There is substantial evidence that synesthetic colors can be transferred from one kind of symbolic representation to another. This can happen at multiple levels. Transfer of color may occur through conceptual rather than perceptual links between the inducing stimuli. For example, Ward, Tsakanikos, and Bray (2006) identified three cases of color synesthesia for musical notation, where the colors elicited by written notes were related to their corresponding graphemes (e.g., the musical notation for A and the written letter A both elicited the same color) suggesting developmental transfer from letter names to the names of notes despite the arbitrary nature of the conceptual link.

The form, the corresponding sound, and the semantic meaning of Braille characters can all act as triggers for synesthetic color. Steven and Blakemore (2004) described the experience of color synesthesia in six blind participants with prior experience of color vision. Several participants had strong color responses for Braille characters, which were induced either through touching the dots or imagining them when they heard or thought about a letter, number, or musical note. For some individuals, the colors seen were in Braille formation like an LED display, while others saw blocks of associative colors. One participant (JF) had tactile-color synesthesia exclusively for Braille, but not for other textures, or for dots arranged in unrelated spatial arrangements. Interestingly, his evoked colors were determined by the geometric pattern of the dots, not by their specific meaning. Identical Braille characters with different meanings (letter I, numeral 9, and musical note A quaver) all provoked exactly the same synesthetic color. Similar Braille characters, which differed by only one dot, elicited similar colors (e.g., R and H were both dark brown). His synesthetic colors were only experienced when hearing or thinking about Roman letters, Arabic numbers, or musical tones, if he thought about touching the corresponding Braille character.

One participant perceived different colors for alphabetical letters and musical notes represented by the same Braille character, indicating that the colors can be semantically determined for some Braille synesthetes. Furthermore, for most of the group, colors were dependent on semantic context, meaning that MARCH only generated a color when heard in the context of time of year, rather than other homophonic contexts (e.g., 'the troops MARCH up the hill'). The exception was one participant whose colored Braille experiences were perceptually triggered by phonological identity, who would perceive the same color whatever context the word was heard in.

Other studies suggest that transfer of colors between alphabet systems (Roman to Greek or Cyrillic) may be caused by perceptual links, rather than conceptual ones, based on similarity of visual shape (Mills et al., 2002; Rich, Bradshaw, & Mattingley, 2005). When graphemes are visually distinctive (i.e., do not correspond closely to another grapheme in the second alphabet), then the transfer of colors tended to be driven by phonemic similarity (Mills et al., 2002; Witthoft & Winawer, 2006). Within a language there is evidence that similarly shaped letters tend to share similar colors (Brang, Rouw, Ramachandran, & Coulson, 2011; Watson, Akins, Spiker, Crawford, & Enns, 2014).

Non-alphabetic scripts are informative because characters tend to be at the morphemic or lexical level. Asano and Yokosawa (2011) found that Japanese synesthetes showed transfer of colors to the Kanji logographic Japanese script from earlier acquired phonemic Hiragana and Katakana writing systems. This appeared to be determined by perceptual links via phonology, and conceptual links via meaning, but with little influence of visuo-spatial appearance.

Age of acquisition is also a factor for synesthesia in relation to Chinese writing systems. Both first- and second-language Chinese speakers experience synesthetic colors for Mandarin characters and words spelled in the phonemic spelling systems of Pinyin and Bopomofo, but their native or earliest acquired writing system determined the nature of transfer between these orthographies (Hung, Simner, Shillcock, & Eagleman, 2014). European second-language learners of Chinese showed robust transfer of colors from the Roman alphabet to Pinyin and Mandarin characters based on initial sounds of the depicted words. For native Chinese speakers who were first exposed to Pinyin or Bopomofo, which represent each Chinese phoneme with a grapheme, there was evidence that colors transferred to Chinese characters were based on shared sounds, rather than on any visual similarities between characters. Interestingly, Chinese people who learned Chinese characters first, before later learning Pinyin or Bopomofo, reported having different synesthetic colors for graphemes depicting the same word in the different systems, despite shared phonology and meaning, suggesting that other factors shaped synesthetic associations for Chinese logographs, when this form of writing is the first system acquired.

Taken collectively, these studies suggest that inducing factors for synesthetic colors are likely to be specific to each language or orthography, and that the salient features of a native language, and its writing system, will scaffold synesthesia for a second language. We extend similar findings to manual alphabets showing that for second-language learners of signed languages their synesthesia may transfer in a systematic way between orthographical systems based on conceptual links, whether or not individual manual letters resemble their corresponding orthographic forms, and where there is no overlap in terms of phonology because they are expressed in completely separate language modalities. We also present some initial evidence that synesthetic colors may transfer, based on perceptual or phonological links, between fingerspelled letters and numerals that share a surface form in terms of handshape and hand orientation.

Method

A between-subjects comparison was conducted, contrasting participants who claim to have synesthesia for specific features of signed language – manual alphabet letters (fingerspelling) and numeral signs – and those who do not. The dependent measure was level of consistency of color selection using the method of Eagleman, Kagan, Nelson, Sagaram, and Sarma (2007). Further analyses investigated whether, for identified synesthetes, the colors for fingerspelled letters and signed numerals are the same as those for written letters and digits. Ethical approval was obtained from the Research Governance Committee of the School of Life Sciences, University of Sussex.

Participants

Participants were recruited via sites and forums used by the Deaf and synesthesia communities including Facebook and Listserv groups. Participants were also recruited via the UCL Deafness Cognition and Language Research Centre database. The inclusion criteria were good knowledge of either BSL or ASL and their respective manual alphabets. Both deaf and hearing participants were invited to participate, including people who self-identified as having synesthesia, and those who had never experienced synesthetic phenomena. The advert was in written English with links to signed versions in ASL and BSL.

Data were collected from fifty participants, aged 16–59 years ($M = 35.02$, $SD = 10.92$), who reported knowledge of either BSL or ASL. A total of 33 participants (20 female) completed the British test, 13 (11 female) did the American test, and 4 people did both tests (but only the scores from their first-acquired sign language were entered into the analyses). Eight people described themselves as deaf and one as hard-of-hearing, and they all rated themselves as highly fluent signers. Of the 41 hearing participants, 23 were self-reported fluent signers of ASL or BSL (including fingerspelling), 10 reported intermediate signing ability but proficiency in fingerspelling, and for 8 people this was unreported. A total of 7 participants self-identified as having another type of synesthesia, with 4 reporting grapheme→color synesthesia.

Procedure

Two versions of the color selection task were designed to replicate the existing grapheme→color synesthesia test within the Synesthesia Battery hosted at http://www.synesthete.org. These enabled participants to view individual graphemes depicting letters or numerals and to respond with an exact hue using a color picker. We adapted this format for signed stimuli by replacing graphemes with 2-second video-clips of individual manual letters and signed numerals. The first test used the two-handed British manual alphabet and BSL numeral signs, and the second used directly equivalent stimuli taken from the one-handed American manual alphabet and ASL numeral signs. The stimuli consisted of 26 manual alphabet signs (A through Z) and 10 numeral signs (1–10). There is considerable regional variation in BSL numerals; those used in the test were from the Southwest of England. The stimuli were produced by a Deaf left-handed male who is a native user of BSL and highly fluent in ASL, working as an international translator in both languages. He wore a plain black shirt and stood in front of a plain blue screen. The model was instructed not to produce English mouthings during fingerspelling and sign production. His hands started and ended in a neutral rest position (either with clasped hands, or with arms to the sides).

The BSL and ASL version of the tests were incorporated into the Synesthesia Battery as "British Sign Language → color" and "American Sign Language → color", and participants were invited to log on and complete the test in their preferred language, after completing an online consent form, with a choice of instructions in written English, BSL or ASL. The test consisted of 108 trials; in each trial, participants viewed 2-second video-clips of individual manual letters or numeral signs, and were instructed to choose a color from a color chart beside the video that best matched their synesthetic perception or to select the first color that came to mind. Testing took around 20 min to complete with 36 stimuli (26 letters, 10 numerals) presented three times in random order. There was an option for selecting "no color". Before starting the test, controls were instructed to avoid this option, and to choose a color, guessing if necessary.

Immediately after testing, participants filled in a brief online questionnaire in written English eliciting information about hearing ability, signing ability (basic, intermediate, or highly fluent) and experience of synesthesia. All participants were asked if they had experienced synesthesia for: sign language; manual alphabet; numeral signs; classical grapheme→color synesthesia, or any other type of synesthesia. For those who indicated that they had grapheme→color synesthesia, this was tested online two months later using the existing test within the Synesthesia Battery (http://www.synesthete.org).

Analysis

Participant data were scored using the consistency formula used by Eagleman et al. (2007). Each participant made three color choices (measured in red green blue (RGB) values) for each of the 36 manual letters or numeral stimuli – (R_1, G_1, B_1), (R_2, G_2, B_2), and (R_3, G_3, B_3). The RGB values were linearly transformed to lie between 0 and 1. The pairwise differences were computed for R, G, and B separately using the following formula:

$$|R_1 - R_2| + |R_2 - R_3| + |R_3 - R_1| + |G_1 - G_2| + |G_2 - G_3| + |G_3 - G_1| + |B_1 - B_2| + |B_2 - B_3| + |B_3 - B_1|$$

This gave consistency scores for each item. A single consistency score was then calculated for each participant which was the mean across the 36 stimuli. A lower score indicates high consistency with less difference between colors. We used the recommended cut-off of <1.43 based on calculations of sensitivity and specificity for diagnosing grapheme-color synesthesia (Rothen, Seth, Witzel, & Ward, 2013).

We conducted observational examination of our ASL data for minimal pairs, as unlike BSL, both fingerspelled letters and numerals are articulated with one hand. We looked for minimal contrasts between ASL letters and ASL numerals with similar forms differing slightly in terms of a single small difference in the articulatory movement or in the position of index finger and thumb (W and 6, F and 9) or the orientation of the hand (V and 2). We were interested to observe whether colors could transfer between types of representation based on shared articulatory features.

Results

Consistency over time

The consistency scores for participants taking the BSL and ASL tests did not differ ($t(48) = 1.08$, $p = .286$) and were collapsed together for subsequent analyses. There was no significant difference in consistency scores between those who reported high fluency in a signed language (*M* 2.16, *SD* .85) and those who reported intermediate fluency (*M* 2.47, *SD* .50; $t(41) = 1.34$, $p = .187$), so these groups were collapsed. The range of participant scores for ASL were .70–3.20 (*M* 2.25, *SD* .88), and for BSL were .76–3.70 (*M* 2.37, *SD* .71). There was no difference between consistency scores for deaf and hard-of-hearing (*M* 2.57, *SD* .57) versus hearing participants (*M* 2.27, *SD* .78; $t(41) = 1.15$, $p = .259$).

Figure 3 shows the distribution of scores for individual participants divided into three groups: those who, when asked after testing, did not self-identify as having manual alphabet/numeral sign→color synesthesia; those who did; and those who were unsure.

Four participants claimed to experience synesthetic colors from signed letters and numerals, and these individuals were significantly more consistent as a group than those people who claimed not to (Mann Whitney $U = 4.0$, $p < .001$). All four of these individuals were below the cut-off (1.43) used to identify other types of synesthesia (Rothen et al., 2013). Applying this cut-off in the present task results in a sensitivity of 100% (4/4 self-reported synesthetes identified) and a specificity of 95% (41/43 self-reported controls classified as controls, with one borderline and two controls scoring in the synesthetic range). Of the 7 people who self-reported having another type of synesthesia, only the 4 who described grapheme→color synesthesia also showed synesthesia for fingerspelling and numeral signs.

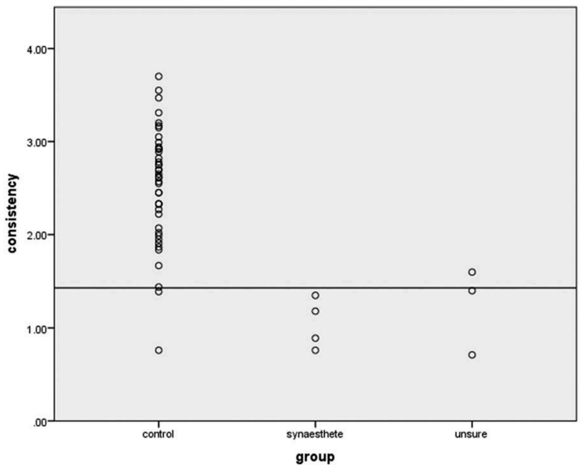


Figure 3. Consistency scores for manual self-reported manual alphabet synesthetes and controls. The line shows the cut-off recommended by Rothen et al. (2013).

Further details of the four cases are summarized in Table 1. All had other types of synesthesia, notably grapheme→color. None had any known relatives with synesthesia. Three had normal hearing, and one was hard-of-hearing and had progressive deafness that had started postlingually in childhood. Two reported projection of colors onto the hands and/or fingers; two stated that they experienced the colors "in the mind's eye" as visual imagery and one reported "just knowing" what the colors were.

The best performing participant was unsure whether she had true manual letter/numeral sign→color synesthesia. This person was recruited from a synesthesia mailing list and took the test because she has grapheme→color synesthesia (consistency = 0.70) and is also proficient in ASL. She reported that when doing the test, she felt that she was not experiencing colors directly from the signed numerals or fingerspelled letters but through association to their corresponding written graphemes. This may constitute a transition stage toward the more autonomous fingerspelled synaesthesia reported by others.

The other two people who were unsure whether they were synesthetes chose consistent colors for only 4/36 and 9/36 signed stimuli. One control participant, who did not self-identify as having synesthesia, obtained an unusually high score but reported using a verbal association memory strategy, which he applied to a limited number of stimuli (he chose colors for only 20/36 items).

Color comparisons between written graphemes and signed counterparts

Figure 4 shows color responses and consistency scores for each of the four synesthetes for graphemes and ASL or BSL letters and numerals. An averaged color was computed for each grapheme (across three trials) and is presented side by side with the averaged color for each corresponding manual letter and numeral. If no color was reported on one or more trials then no average was calculated and this is denoted by "NC". Note that comparisons are made for numerals 1–9 as only the grapheme test included "zero" and only the manual test included "ten". One participant (AC) did not show color associations for number graphemes but consistently responded to BSL numeral signs. Two participants took both the BSL and ASL tests (EJ and KS). Both produced more "no color" responses in their weaker sign language. KS was strongly synesthetic for graphemes but produced fewer sign to color responses, although those that she did produce were consistent. Interestingly, of her 18 color responses to either BSL or ASL stimuli, 4 were similar to the color reported for the corresponding grapheme. The other three synesthetes showed a consistent pattern of color transfer between types of orthographic representation, so color responses to graphemes were similar to those for manual letters and numeral signs, even though these were tested two months apart.

Evidence for transfer of color was examined between three formationally similar pairs of ASL manual letters and ASL signed numerals (W and 6; F and 9; V and 2). The two ASL synesthetes (IM and EJ) responded to both W and 6 with colors that share close correspondence (see Figure 4). For IM, a deep red shade is shared by the W grapheme, its ASL fingerspelled counterpart and the ASL numeral 6, but the written numeral is colored turquoise, suggesting that the color may have transferred from:

Table 1. Demographics for participants with synesthesia.

Case	Gender	Age	Age of sign language acquisition	Hearing status	Types of synesthesia	Color location
IM	M	18	8	Hearing	BSL-color Grapheme-color Weekday-color Month-color Pain-color Musical instruments-color	Hands & fingers In mind's eye
AC	F	24	16	Hearing	ASL-color Grapheme-color	"Knows" color
EJ	F	34	12	Hard-of-hearing	ASL-color Grapheme-color Pain-color Touch-color Orgasm-color Year-spatial form	Hands & fingers
KS	F	34	8	Hearing	ASL-color Grapheme-color Musical pitch-color Musical chords-color	In mind's eye

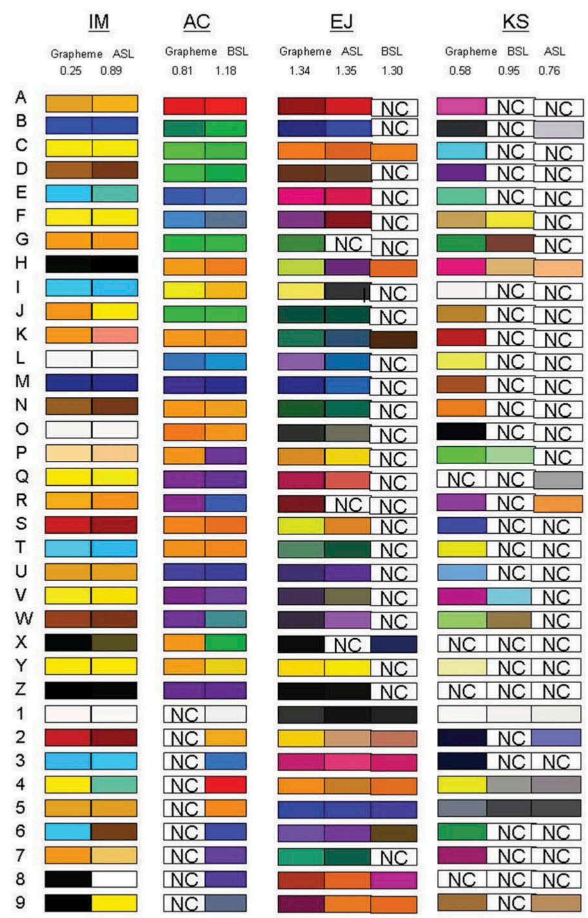


Figure 4. Summary of color choices (average RGB across 3 trials) for four synesthetes. Numbers in the top legend indicate consistency scores for each test taken. NC = no color chosen on at least one trial.

L1[1] grapheme W → L2 manual letter W → (shared handshape) → L2 numeral sign 6, with handshape playing a mediating role in the transfer. For the other participant, EJ, we see similar transfer, with shared handshape phonology from:

L1 grapheme 6→ L2 numeral sign 6 → (shared handshape) → L2 manual letter W, which are all associated with varying shades of purple.

A similar pattern of transfer was found between F and 9. For IM, the written numeral 9 is black but the ASL sign for 9 is colored yellow, signifying possible transfer from:

L1 grapheme F → L2 manual letter F → (shared handshape) → L2 numeral sign 9.

For EJ, although the ASL F and 9 are colored differently (brown and orange, respectively) there is possible transfer from the numeral grapheme 9 to the ASL letter F because both are a similar red color, and so in this instance perceptual or phonological similarity may override conceptual identity. No color transfer was observed between ASL signs for V and 2, which share a handshape but have a different orientation.

Discussion

This study provides evidence that manual alphabet/numeral sign → color synesthesia exists within second-language users of two different signed languages, ASL and BSL. Synesthetes subjectively reported experiences of color in response to signed letters and numerals (sometimes seen as projected on to the hand/fingers of the signer) and they pass an objective measure of authenticity, as they are significantly more consistent than controls.

To what extent is this type of synesthesia autonomous from grapheme→color synesthesia?

In all four identified cases, there was evidence for co-occurring grapheme→color synesthesia. For three individuals, synesthetic colors for fingerspelling and numeral signs closely corresponded with those assigned to written graphemes, suggesting that the two types of synesthesia did not develop independently but that there was transfer from grapheme to manual alphabet synesthesia, and that color associations are not derived separately in each modality for second-language learners but are linked. For example, colors may be first associated to written graphemes (L1→color) and then linked to fingerspelled letters (L2→L1→color). Over time, sign-color synesthesia may become functionally autonomous (i.e., L2→color) but retain previous color associations. As none of our participants were congenitally deaf or L1 sign language users, we still do not know how synesthesia would develop in such cases, if it occurs at all. In native signers, letters of the manual alphabet and signs derived from fingerspelling are typically acquired before learning to read and write, so it is plausible that the association could develop in the other direction, with color associations for numeral signs and manual letters preceding those for graphemes.

There was some evidence that fingerspelled letters and numerals could take on colors that were not found in the corresponding graphemes. It was noteworthy that for one participant using BSL (AC), both manual letters and numeral signs evoked colors, as did written letters, but not written numbers; so some signed stimuli provoked color associations with no obvious counterpart in written language. This goes against the idea that synesthetic responses in L2 signers are only mediated by experience of a written first language. One signer (KS) also showed a general low correspondence of colors *between* graphemes and their associated manual letters or signed numerals, while showing consistent color associations *within* each system The fact that she rarely reported colors for signs (but nearly always did for graphemes) also suggests that she is not relying on association to graphemic colors.

There are various theoretical models that could explain the data. The cross-activation theory (e.g., Hubbard et al., 2011) explains the data based on the fact that the perception of fingerspelling uses adjacent areas of the brain to the

[1]L1 is used in this context to refer to written English, L2 to refer to fingerspelling or signing.

perception of color; i.e., the same explanation as used for grapheme-color synaesthesia. However, other accounts suggest that synaesthesia arises from indirect feedback from higher-order regions involved in conceptual knowledge (e.g., Chiou & Rich, 2014) or multi-sensory processing (e.g., Grossenbacher and Lovelace, 2001). Another suggestion is that synaesthetic associations are derived from associative learning (Yon & Press, 2014). To distinguish these accounts it would be important for future research to assess whether the same colors are found for Roman numerals (e.g., VI) and written number names (SIX), which would suggest a role of semantic meaning, or whether they are limited to single graphemes and their signed counterparts which would indicate paired learning between these specific codes. The neural substrates of these associations would also differ across theories: the cross-activation theory predicts local, direct connections (between V4 and VWFA), whereas other theories predict top-down connections from anterior temporal lobes (in semantic memory), whereas episodic associative learning would be mediated by the hippocampus.

Do similar handshapes elicit similar colors within the signed modality?

This study produced some observational examples of the transfer of color between ASL letters and numeral signs for minimal pairs that share a similar handshape, in line with other studies that show colors can transfer from one representational system to another. It is not possible to determine from our data whether handshape-induced transfer hinged on articulatory similarity or visual similarity since these are conflated in this exploratory study. Experimental manipulation would be required to explore this further. Caution must be taken in interpreting our findings because we do not know if participants may have simply mistaken ASL numerals for letters; particularly because there were no contextual or English mouthing clues, and ASL fluency was self-reported rather than objectively assessed. However, it should be noted that fluent signers would have no trouble distinguishing between the stimuli, and our synesthetes are unlikely to have maintained any case of mistaken identity across three separate trials.

Future research and limitations

It is important to extend these results to establish: (a) whether color synesthesia exists for lexical signs, and whether they behave differently from fingerspelling and numerals with regard to their independence from written or spoken language; (b) how the pattern may be affected by early deafness or, indeed, whether fingerspelling/sign → color synesthesia exists at all in L1 signers (whether deaf or hearing); and (c) the impact of age of acquisition on manifestation of synesthesia in native signers compared to deaf individuals whose L1 acquisition was delayed, falling outside the normal timeframe for anomalous synaptic pruning in synesthesia. Indeed, given the protracted nature of the development of synesthetic associations during early childhood (Simner, Harrold, Creed, Monro, & Foulkes, 2009), synesthesia may present very differently in native or late L1 signers or not occur at all.

This exploratory study has limitations that should be addressed in future research. Sign fluency should be measured objectively rather than relying on self-rating. Closer attention could be paid to the mediating factors of handshape and other articulatory features within the research design. It is noteworthy that there was a trend for fingerspelling-color to be less consistent than grapheme-color and this would be important to explore in future research.

Conclusion

This study provides further evidence that synesthetic associations may transfer from one symbolic representation to another both *between* and *within* language modalities, and new evidence that this can occur within the visuomotor modality based on perceptual similarity or articulatory features such as handshape. These findings fit with the notion that for most second-language learners the transfer of color into this system is primarily determined by conceptual meaning based on their first language but can also be influenced by perceptual properties. The fact that the brain regions for print and fingerspelling are remarkably similar suggests that no separate causal model needs to be invoked, since existing neurodevelopmental explanations can equally explain phenomena in both modalities. This study underlines the importance of widening research by conducting not only cross-linguistic but also cross-modality studies, because inducing factors for synesthesia are likely to be both language- and modality-specific. Without studies of manual languages, we run the risk of overlooking new and unique inducing factors for synesthesia that relate to differences in the way these languages are phonologically expressed, their lack of written form, their reliance on the perception of biological motion, and the way in which individual signs and utterances are segmented. Broadening our research to include signed languages may cast new light on the mechanisms underpinning synesthesia in general.

Acknowledgements

We would like to thank the participants for their time and Robert Adam for modeling the signed stimuli. This work was supported by the ESRC Deafness Cognition and Language Research Centre under Grant RES-620-28-0002.

Disclosure statement

No potential conflict of interest was reported by the authors.

Funding

This work was supported by the Economic and Social Research Council [RES-620-28-0002].

References

Anderson, L. (1979). Sign Language Number Systems and the Numerical Alphabet. In Selected Papers of the NATO Advanced Studies Institute: Sign Language Research. Special issue of LOGOS. Copenhagen University: Audiologopedic Research Group.

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

Baron-Cohen, S., Harrison, J., Goldstein, L. H., & Wyke, M. (1993). Coloured speech perception: Is synaesthesia what happens when modularity breaks down? *Perception*, *22*, 419–426. doi:10.1068/p220419

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.

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*(February). doi:10.3389/fpsyg.2014.00105

Cohen, L., & Dehaene, S. (2004). Specialization within the ventral stream: The case for the visual word form area. *NeuroImage*, *22*, 466–476. doi:10.1016/j.neuroimage.2003.12.049

Cytowic, R. E., & Eagleman, D. M. (2009). *Wednesday is indigo blue – discovering the brain of synesthesia*. Cambridge, MA: MIT Press. doi:10.1002/ajhb.21039

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*, 139–145. doi:10.1016/j.jneumeth.2006.07.012

Emmorey, K., McCullough, S., & Weisberg, J. (2015). Neural correlates of fingerspelling, text, and sign processing in deaf American sign language–english bilinguals. *Language, Cognition and Neuroscience*, *30*, 749–767. doi:10.1080/23273798.2015.1014924

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

Hubbard, E. M., Brang, D., & Ramachandran, V. S. (2011). The cross-activation theory at 10. *Journal of Neuropsychology*, *5*, 152–177. doi:10.1111/j.1748-6653.2011.02014.x

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

Mills, C. B., Viguers, M. L., Edelson, S. K., Thomas, A. T., Simon-Dack, S. L., & Innis, J. A. (2002). The color of two alphabets for a multilingual synesthete. *Perception*, *31*, 1371–1394. doi:10.1068/p3429

Ramachandran, S., & Hubbard, E. M. (2001a). Synaesthesia — A window into perception, thought and language. *Journal of Consciousness Studies*, 3–34. doi:10.1111/1468-0068.00363

Ramachandran, V. S., & Hubbard, E. M. (2001b). Psychophysical investigations into the neural basis of synaesthesia. *Proceedings. Biological Sciences /The Royal Society*, *268*, 979–983. doi:10.1098/rspb.2001.1576

Reich, L., Szwed, M., Cohen, L., & Amedi, A. (2011). A ventral visual stream reading center independent of visual experience. *Current Biology*, *21*, 363–368. doi:10.1016/j.cub.2011.01.040

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*, 156–160. doi:10.1016/j.jneumeth.2013.02.009

Simner, J., Harrold, J., Creed, H., Monro, L., & Foulkes, L. (2009). Early detection of markers for synaesthesia in childhood populations. *Brain*, *132*(1), 57–64. doi:10.1093/brain/awn292

Simner, J., Mulvenna, C., Sagiv, N., Tsakanikos, E., Witherby, S. A., Fraser, C., & Ward, J. (2006). Synaesthesia: The prevalence of atypical cross-modal experiences. *Perception*, *35*, 1024–1033. doi:10.1068/p5469

Sutton-Spence, R., & Woll, B. (1999). *The linguistics of BSL: An introduction*. Cambridge: Cambridge University Press.

Ward, J., & Mattingley, J. B. (2006). Synaesthesia: An overview of contemporary findings and controversies. *Cortex*, *42*, 129–136. doi:10.1016/S0010-9452(08)70336-8

Ward, J., Tsakanikos, E., & Bray, A. (2006). Synaesthesia for reading and playing musical notes. *Neurocase*, *12*, 27–34. doi:10.1080/13554790500473672

Waters, D., Campbell, R., Capek, C. M., Woll, B., David, A. S., McGuire, P. K., & MacSweeney, M. (2007). Fingerspelling, signed language, text and picture processing in deaf native signers: The role of the mid-fusiform gyrus. *Neuroimage*, *35*, 1287–1302. doi:10.1016/j.neuroimage.2007.01.025

Watson, M. R., Akins, K. A., Spiker, C., Crawford, L., & Enns, J. T. (2014). Synesthesia and learning: A critical review and novel theory. *Frontiers in Human Neuroscience*, *8*(February), 98. doi:10.3389/fnhum.2014.00098

Witthoft, N., & Winawer, J. (2006). Synesthetic colors determined by having colored refrigerator magnets in childhood. *Cortex*, *42*, 175–183. doi:10.1016/S0010-9452(08)70342-3

Yon, D., & Press, C. (2014). Back to the future: Synaesthesia could be due to associative learning. *Frontiers in Psychology*, *5*, 702. doi:10.3389/fpsyg.2014.00702

Zeshan, U., Escobedo Delgado, C., Panda, S., & De Vos, C. (2013). Cardinal numerals in village sign languages: Approaching cross-modal typology. *Linguistic Typology*, *17*, 357–396.