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Bi-lateralized Whorfian effect in color perception: Evidence from Chinese Sign Language

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ABSTRACT

Converging behavioral and neural studies have shown a right visual field (RVF) advantage on language's effect on color categorical perception (the Whorfian effect). But little is known about the effect of sign language on deaf people's perception of color categories. To examine whether this lateralized effect also occurs in sign language systems, both behavioral and electrophysiological studies were conducted using visual search and oddball tasks respectively. The visual search results revealed that reaction times to targets were faster when the target and the paired distractor colors were easy to sign than when they were hard to sign, both in RVF and left visual field (LVF), and further, the LVF Whorfian effect was disrupted when participants performed the spatial interference secondary task. In the oddball task, the amplitude of the vMMN component evoked by the within-category deviant was significantly smaller than that evoked by the between-category deviant when displayed in either the RVF or the LVF. Both the behavioral and electrophysiological findings show that the language of the deaf affects their color perception bi-laterally, which suggests that the nature of language decides the pattern of the Whorfian effect.

1. Introduction

1.1. The Whorf hypothesis

The Whorf Hypothesis proposes that language affects users' ways of perceiving the outside world (Subbiondo, 2005; Whorf, 1950; Whorf, Lee, Levinson, & Carroll, 2012). This hypothesis is the focus of a large number of academic researchers, including anthropologists, philosophers, sociologists, linguists and psychologists. Whorf Hypothesis supporters focus on the unique aspects of languages and the cognitive differences associated with language differences. The opponents of the Whorf Hypothesis pay close attention to universal laws and generality across different languages and cultures (Davidoff, 2001; Goldstein, Davidoff, & Roberson, 2009).

Following the introduction of the concept of category perception, an increasing number of studies support the Whorf Hypothesis. Categorical perception is the phenomenon of perceiving distinct categories when there is actually a gradual change in a variable along a continuum. For example, when we look at a rainbow, we tend to see about seven distinct bands of color, even though we know from physics that the dominant wavelength of light that meets the eye changes smoothly from the top to bottom of the rainbow. Our perceptions are warped such that differences between objects that belong in different categories are accentuated, while

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differences between objects that fall into the same category are deemphasized. Categorical perception involves the interplay between humans' higher-level conceptual systems and their lower-level perceptual systems (Goldstone, 1994; Goldstone & Hendrickson, 2010).

Color category perception refers to the fact that color discrimination is faster when the colors belong to different categories than when they belong to the same category, even though the physical differences are of equal size (Harnad, 1987). Given the evidence of color category perception and the assumptions of the Whorf Hypothesis, one can make the argument that if language affects color perception, the words expressing a color category will affect color perception. Indeed, a series of studies has shown that the color lexical category encoded in a language affects the observer's color perception (Berlin & Kay, 1991; Davidoff, 2001; Fonteneau & Davidoff, 2007; Kay & Kempton, 1984; Kay & Regier, 2006; Kwok et al., 2011; Mo, Xu, Kay, & Tan, 2011; Notman, Sowden, & Ozgen, 2005; Roberson, Davies, & Davidoff, 2000; Tan et al., 2008; Whorf et al., 2012; Winawer et al., 2007; Özgen, 2004; Özgen & Davies, 1998; Özgen & Davies, 2002).

1.2. Lateralization patterns and sign language

Because of the contralateral nature of visual projections to the cortex, combined with lexical representation in the left hemisphere (LH), Gilbert, Regier, Kay, and Ivry (2006) proposed that the "Whorfian" effect should be presented asymmetrically; that is, the effect of language on perception in different visual fields should be different. Specifically, the Whorfian effect should be evident in the right visual field (RVF) more than in the left visual field (LVF). Subsequent behavioral, electrophysiological, and neuroimaging studies have verified this view. The general conclusion is that the Whorfian effect is stronger for stimuli displayed in the RVF than in the LVF, and the lateralized pattern is disrupted by the presence of a concurrent demand on verbal memory but not spatial memory. The results indicate that the use of lexical information in the left hemisphere causes the differential visual hemifield responses to color stimuli (Drivonikou et al., 2007; Franklin et al., 2008; Franklin et al., 2008; Gilbert et al., 2006; Gilbert, Regier, Kay, & Ivry, 2008; Kay, Regier, Gilbert, & Ivry, 2009; Liu et al., 2009; Mo et al., 2011; Regier & Kay, 2009; Roberson, Pak, & Hanley, 2008; Siok et al., 2009; Zhou et al., 2010).

Previous studies have widely confirmed the lateralized Whorfian effect based on spoken language systems used by hearing speakers. An important question is how the Whorf Hypothesis applies to sign language systems used by persons who are deaf. Spoken language is an aural-oral language processed by ears and mouth, while sign language is a visual-manual language processed by eyes and hands with abundant visual spatial information (Goldin-Meadow, 2005).

The cerebral activity during sign language comprehension is different from activity during comprehension of spoken language systems. Many studies have shown that besides the activation of classical language areas in the left hemisphere, there is extensive activation of homologous areas in the right hemisphere (RH) (Capek et al., 2008; Capek et al., 2008; Hickok, Pickell, Klima, & Bellugi, 2009; MacSweeney, 2002; MacSweeney et al., 2008; Neville et al., 1997; Neville et al., 1998; Newman, Bavelier, Corina, Jezzard, & Neville, 2002; Newman, Supalla, Hauser, Newport, & Bavelier, 2010; Petitto et al., 2000). For example, one human neuroimaging study investigated the neural substrate of American Sign Language (ASL) processing and found that the RH angular gyrus was active during ASL processing in native signers (hearing, ASL-English bilinguals) but not in those who acquired ASL after puberty (hearing, native English speakers) (Newman et al., 2002).

Another study found that the activation patterns observed during single sign perception were similar to those for sentences. Compared with the baseline condition, deaf and hearing native signers have been shown to recruit an extensive bilateral fronto-temporal network when processing single signs (Macsweeney et al., 2006). A study on Chinese sign language also found that during sign language processing, deaf signers' bilateral brain regions were activated, and the activation in LH usually was stronger than that in RH (Ding & Li, 2012; Fang & He, 2003; Hu et al., 2011; Yu, Xia, Yin, Yuan, & Qi, 2008). The results indicated that the specific processing requirements of sign language partly determined the organization of the language systems of the brain. Given the dominant role of the right hemisphere in spatial processing, it is reasonable to assume that the spatial nature of sign language results in the effect of sign language on color perception being modulated by the RH lateralization.

1.3. Behavioral and electrophysiological evidence

The LH focuses on processing the information involved in abstract-category code, associative co-occurrence values and isolating features, whereas the RH focuses on processing information involving specific-exemplar code, spatial metrics and conjoining features (Dien, 2009). Therefore, for hearing persons, under the restriction of the lateralization of LH in language processing, the Whorfian effect exhibits as color categorical perception with dominant RVF. However, because of the substantial connection between the sign and visual spatial information, the color perception of deaf persons is also restricted by the lateralization of RH in spatial processing. Thus the Whorfian effect is likely to exhibit as a bi-lateralized color categorical effect in left and right visual fields.

In addition, a lateralization pattern might not be the only form of the Whorfian effect. Categorical perception is not necessarily left-hemisphere dominant, as has been shown, for example, in the greater right superior temporal sulcus activation in categorical perception of musical chords (Klein & Zatorre, 2011). Importantly, these studies on the change in symmetry from infancy to adulthood provide empirical evidence suggesting that color categorical perception does not always have an RVF advantage (Franklin, 2009; Franklin, Catherwood, Alvarez, & Axelsson, 2010, 2008; Paluy, Gilbert, Baldo, Dronkers, & Ivry, 2011). Franklin and associates found that the LVF advantage of color categorical perception in infants reversed after the acquisition of a color word (Franklin, 2009; Franklin et al., 2008; Franklin et al., 2010).

These studies on the compensatory processes and plasticity in the brain also suggested that the form of the Whorfian effect was changeable. Paluy et al. (2011) found that patients with right hemisphere lesions showed the RVF advantage of color categorical perception, as did healthy controls, while patients with left hemisphere lesions showed the LVF advantage. The researchers proposed that the reverse pattern of the lateralization of color categorical perception was related to the reorganization or the greater sensitivity of color lexical category in right hemisphere after the lesion of left hemisphere (Paluy et al., 2011). Thus, it is quite reasonable to expect that the Whorfian effect on prelingual deaf signers might be bi-lateralized because of brain plasticity and the developed reverse pattern from infancy to adulthood.

Recent studies also found that this lateralized effect occurred at early, preattentive perceptual processing stages rather than at postperceptual decision/response phases. Thierry, Athanasopoulos, Wiggett, Dering, and Kuipers (2009) assessed visual mismatch negativity (vMMN) in an ERP study and verified that the effect of language on color perception occurred at early perceptual processing stages. This result was replicated in other studies (Athanasopoulos, Dering, Wiggett, Kuipers, & Thierry, 2010; Clifford, Holmes, Davies, & Franklin, 2010).

The vMMN is widely held to reflect the brain's early and automatic change in event-related potentials (ERPs) in response to a novel stimulus (Czigler, 2007; Czigler, Balazs, & Pato, 2004, 2002; Winkler, Czigler, Sussman, Horvath, & Balazs, 2005). The vMMN emerges as the difference between the ERPs elicited by infrequent (deviant) stimuli within a sequence of repetitive (standard) stimuli and the ERPs elicited by the standard (Czigler et al., 2004). It usually peaks at 100–250 ms from change onset, reflecting automatic, preattentive perceptual processing in the brain for the changed stimulus (Näätänen, Paavilainen, Rinne, & Alho, 2007).

The vMMN rests on the relation between the present and the previous stimulus, rather than on the stimulus alone. Hence, the MMN may depend on a memory trace formed by preceding stimuli; i.e., during the presentation of the standard events. If the deviant, or the new event, occurs while this memory trace is still active, the automatic change-detection is activated, giving rise to an MMN response (Garrido, Kilner, Stephan, & Friston, 2009). Therefore, the vMMN can provide an effective tool to identify the time course of the influence of sign language on color perception.

1.4. The current study

In the current study we conducted three experiments to investigate two questions. One question is whether the left lateralized Whorfian effect in color perception occurs in prelingual deaf native signers who were exposed early to sign language once they were found to be deaf, and then used sign language as their primary language. The other question is whether this lateralized effect in prelingual deaf native signers occurs preattentively at an early stage of processing. The Ethics Committee of the School of Psychology at South China Normal University approved all the experiments.

Experiments 1 and 2 used a visual search task to investigate the pattern of sign language's effect on deaf signers' color perception. Previous studies found that the reaction times to targets were faster when target and distractor colors fell into different categories only (or predominantly) in the RVF for the hearing participants (Drivonikou et al., 2007; Franklin et al., 2008; Gilbert et al., 2008, 2006; Kay et al., 2009). Here, Experiment 1 adopted the visual search task used by Gilbert and colleagues to compare the Whorfian effect of deaf and hearing participants. In addition, Gilbert et al. (2006) found that the RVF advantage of color categorical perception was disrupted by an interference task that involved verbal working memory, but not by a spatial interference task requiring comparable demands on spatial working memory (Gilbert et al., 2006, 2008). However, Macsweeney et al., 2006 found that the activation patterns observed during single sign perception included the inferior and middle frontal gyri, which were deemed to be related to spatial information processing in previous studies (Leung, Gore, & Goldmanrakic, 2002; McCarthy et al., 1996). A reasonable assumption is that, for the signers, the spatial interference task would affect the process of their spatial information, so their LVF advantage in categorical perception would be disrupted in the visual search task. However, because the Whorfian effect might show a different manifestation in different languages, the pattern of disruption should be different in hearing speakers. The LH is important for hearing speakers to process lexical information, so a linguistic interference task should disrupt the lateralized pattern. We suggest that spatial processing is important in sign language, and spatial interference could hinder the visual search in the LVF of deaf signers. Hence, Experiment 2 further investigated how the spatial interference task would affect the visual search performance in different visual fields in deaf participants.

Experiment 3 used vMMN as an electrophysiological index of an automatic preattentive detector of change to a novel visual stimulus (Czigler, 2007; Czigler, Balazs, & Winkler, 2002; Czigler et al., 2004; Winkler et al., 2005), to further investigate the time course of sign language's effect on deaf signers' color perception. For hearing speakers, previous research on early ERP evidence of categorical color perception showed that perception varies predictably according to language-specific terms and that it is likely automatic and preattentive. This research showed that between-category color deviants elicit a greater vMMN response than within-category deviants, revealing a Whorfian effect at the early preattentive stage of color processing (Athanasopoulos et al., 2010; Clifford, Franklin, Davies, & Holmes, 2009; Clifford et al., 2010; Holmes, Franklin, Clifford, & Davies, 2009; Thierry et al., 2009). A recent study showed that the categorical modulation of the vMMN by color differences is lateralized to the RVF, which suggests that lateralized Whorfian effects on early color processing appear to be automatic and preattentive (Mo et al., 2011). If the bi-lateralized Whorfian effect was confirmed in Experiment 1 and 2, we predicted that in Experiment 3 the vMMN effect evoked by the between-category deviant would be larger than the vMMN effect evoked by the within-category deviant when the deviant was presented in either the RVF or LVF.

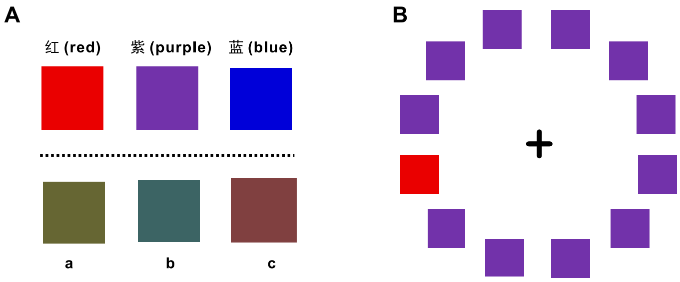

Fig. 1. Experimental materials and experimental paradigm in Experiment 1a. The RGB values of the six colors were as follows: red = 235, 0, 0; purple = 114, 50, 171; blue = 0, 0, 218; a = 102, 102, 51; b = 60, 100, 100; c = 112, 56, 56. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

2. Experiment 1

2.1. Method

2.1.1. Participants

Participants included 15 individuals with typical hearing (8 male; mean age = 18.90 years, *SD* = 0.66) and 15 individuals who were deaf (8 male; mean age = 18.71 years, *SD* = 1.77). All participants who were deaf were severely-to-profoundly deaf (i.e., at least 70 dB loss in both ears), were native Chinese Sign Language (CSL) signers, and knew written Chinese. Eleven were deaf from birth and learned CSL as their first language from their parents, who were also deaf. The remaining four were born with hearing parents and became deaf before 3 years of age due to diseases or medication, at which point they were exposed to sign language by communities of other people who were deaf. These four participants attended boarding schools for children who were deaf, beginning in kindergarten. All etiologies and onset of deafness were self-reported. All 15 participants with typical hearing were native speakers of Chinese who did not know sign language. All 30 participants were right-handed and had normal or corrected-to-normal vision. None had any color vision deficiency (as measured by the Ishihara Color Test (Ishihara, 1918)), history of neurological impairment, or psychoactive medication use. All provided written informed consent and received a small payment as compensation for their participation.

2.1.2. Materials

Two types of colors were used in this study: easy-to-sign colors (ESC; red, purple, and blue) and hard-to-sign colors (HSC; a, b, and c; see Fig. 1). The RGB values of the six colors were as follows: red = 235, 0, 0; purple = 114, 50, 171; blue = 0, 0, 218; a = 102, 102, 51; b = 60, 100, 100; and c = 112, 56, 56. In a pilot test, hearing and deaf adults, who did not take part in the formal experiments, helped to select these colors from 30 possible colors. Firstly, two hearing speakers who were fluent in CSL and worked in a school for deaf children were shown the 30 colors. They consistently selected (1) eight colors that were easy to sign in CSL and (2) six colors that were hard to sign in CSL. Next, eight participants who were deaf and knew sign language were asked to label the 14 selected colors in a preliminary task. Following the 1500 ms display of a central fixation marker ("+") against a grey background, a 5 × 5 cm square stimulus (one of the 14 colors) with three answer choices under it was centrally presented against the grey background at a viewing distance of 75 cm. The RGB values for the background were 178, 178, 178. Participants were instructed to indicate the stimulus with the correct Mandarin Chinese color word from the answer choices as accurately and quickly as possible. One of the three choice options was "don't know." The stimulus did not disappear until the participants made a response. Each color square stimulus was presented three times in 42 randomized trials. The results of the pilot study are reported below.

2.1.3. Design and procedure

A 2 (visual field: left vs. right) × 2 (pair type: ESC vs. HSC) × 2 (group: deaf vs. hearing) mixed experimental design was used. Visual field and pair type were within-subjects factors, and group was a between-subjects factor. Each trial began with a central fixation marker presented against a grey background for 1000 ms. The stimulus (a ring of 12 squares surrounding the fixation marker) then appeared for 200 ms, followed again by the grey screen with the central fixation marker. Participants were instructed to use their left or right index finger to press the "F" or "J" key on the keyboard to indicate as accurately and quickly as possible whether the target (the one square with a different color than the rest) was on the left or the right side of the ring of squares. The fixation marker disappeared until a response was made.

After the response, a blank screen appeared for 500–1000 ms to indicate the start of the next trial. The easy-to-sign set of colors formed three color pairs (e.g., red-blue), and the colors in a pair would alternate between target and distractor (e.g., red was the target and blue was the distractor for some trials, and vice versa for other trials), hence the easy-to-sign set of colors altogether formed six possible target-distractor color pairs. Similarly, the hard-to-sign set of colors also formed six pairs, creating a total of 12 possible target-distractor color pairs. The target square could be located in any of the 12 positions in the ring of squares, leaving 144 possible stimulus configurations. Each participant completed three 144-trial blocks, with each stimulus configuration randomly appearing once per block. Participants first completed a 12-trial practice block.

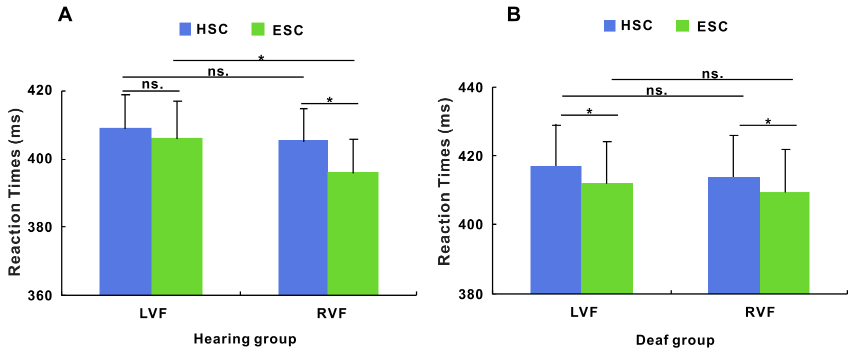

Fig. 2. The results of hearing people and deaf signers in visual search task in Experiment 1a. Keys: ESC = easy-to-sign colors; HSC = hard-to-sign colors; LVF = left visual field; RVF = right visual field; * = $p < .05$; ns. = $p > .05$. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

2.2. Results and discussion

For the material evaluation pilot, each of the eight participants who were deaf made consistent answer choices across the three presentations of a given easy-to-sign color stimulus, and there was no significant difference in the reaction times (RTs) for the three colors ($F_{[2,14]} = 0.024$, $p = 0.957$). As for the hard-to-sign colors, none of the participants made consistent answer choices. Either they consistently chose "don't know" or inconsistently labeled the colors across their respective three trials. There was no significant difference between the RTs for the three hard-to-sign colors ($F_{[2,14]} = 1.686$, $p = 0.234$). The RTs for the three hard-to-sign colors ($M = 2497$ ms, $SD = 495$) were significantly longer than the three easy-to-sign colors ($M = 1366$ ms, $SD = 207$), $t_{[7]} = -6.578$, $p < 0.001$.

For the experimental results, the accuracies were above 98% for both the group of participants who could hear and the group of participants who were deaf. A 2 (visual field: left vs. right) × 2 (pair type: ESC vs. HSC) × 2 (group: deaf vs. hearing) ANOVA, with visual field and pair type as within-subjects factors and group as a between-subjects factor, was performed on the RTs (see Fig. 2). Trials with incorrect responses or in which RTs exceeded 2 SD were excluded from the analysis, resulting in 6.42% of trials excluded for the group who were deaf and 6.56% of trials excluded for the group who could hear. The analysis revealed a significant three-way interaction among the three factors ($F_{[1,28]} = 6.25$, $p = 0.019$) and significant main effects of visual field ($F_{[1,28]} = 7.233$, $p = 0.012$) and pair type ($F_{[1,28]} = 25.529$, $p < 0.001$). The visual field × pair type interaction was significant for the hearing group ($F_{[1,14]} = 21.825$, $p < 0.001$) but not for the deaf group ($F_{[1,14]} = 0.002$, $p = 0.969$). Although there had been an overall main effect of pair type, in post hoc analyses on the interaction effect, the main effect of pair type was only significant in the deaf group ($F_{[1,14]} = 20.827$, $p < 0.001$).

We compared the RTs of each group for hard-to-sign and easy-to-sign color pairs within each visual field. For the right visual field (RVF) targets, responses to the easy-to-sign colors were significantly faster than responses to the hard-to-sign colors for both the group who could hear ($t_{[14]} = 4.359$, $p = 0.001$) and the group who were deaf ($t_{[14]} = 3.081$, $p = 0.008$). For the left visual field (LVF) targets, there was no significant difference between the two pair types for the group who could hear ($t_{[14]} = 1.605$, $p = 0.131$), but there was a significant difference for the group who were deaf ($t_{[14]} = 3.588$, $p = 0.003$).

We also compared RTs of each group for RVF and LVF targets within each pair type. For the hard-to-sign pair type, there were no significant differences in the RTs between the visual fields in the group who could hear ($t_{[14]} = 1.107$, $p = 0.287$) or the group who were deaf ($t_{[14]} = 1.614$, $p = 0.129$). For the easy-to-sign pair type, the RTs of the group who could hear were significantly faster when the target appeared in the RVF than when it appeared in the LVF ($t_{[14]} = 3.542$, $p = 0.003$), but this patterns was not apparent in the group who were deaf ($t_{[14]} = 1.17$, $p = 0.261$).

In summary, for the hearing group, the RTs were faster when the target and distractor colors were easy-to-sign, but only when the target appeared in the RVF. This is consistent with the lateralized Whorfian effect. For the deaf group, the RTs were also faster when the target and distracter colors were easy-to-sign, but this was true when the target appeared in either the LVF or the RVF. We labeled this pattern the "bi-lateralized Whorfian effect." This bi-lateralized pattern confirms the RVF Whorfian effect found in previous studies (Athanasopoulos et al., 2010; Clifford et al., 2010; Drivonikou et al., 2007; Fonteneau & Davidoff, 2007; Franklin et al., 2008; Franklin et al., 2008; Gilbert et al., 2008, 2006; Holmes et al., 2009; Kay et al., 2009; Kwok et al., 2011; Liu et al., 2009; Mo et al., 2011; Regier & Kay, 2009; Roberson et al., 2008; Siok et al., 2009; Thierry et al., 2009; Zhou et al., 2010) and suggests that the unique use of spatial information imbedded in sign language in the right hemisphere is the origin of the LVF Whorfian effect.

Some researchers have posited that the activity of the right hemisphere is related to unique properties of sign language, especially its use of space (Capek et al., 2008; MacSweeney et al., 2008; Neville et al., 1998). MacSweeney et al. (2006) found that the activation patterns observed during single sign perception involved brain regions related to spatial information processing. However, Gilbert et al. (2006) found that the RVF advantage of color categorical perception was disrupted with an interference task that involved verbal working memory, but not by a spatial interference task requiring comparable demands on spatial working memory.

Thus, we expected that a spatial interference task would disrupt the LVF Whorfian effect by impeding the activation of spatial information related to the color signs. Experiment 2 tested this hypothesis. Though in sign languages the use of space is necessarily three-dimensional in nature, some studies on sign language processing have used two-dimensional figures (e.g., Hu, et al., 2011), finding that participants could perform sign language recognition based on 2D data. Therefore, we manipulated one spatial task involving two-dimensional figures as the spatial interference task to disrupt the participants' cognitive processing.

3. Experiment 2

3.1. Method

3.1.1. Participants

Participants included 30 people (16 male; mean age = 18.62 years, *SD* = 1.45) who were severely-to-profoundly deaf (i.e., at least 70 dB loss in both ears). All participants were native CSL signers and knew written Chinese. Of the participants, 23 had been deaf from birth and learned CSL as their first language from their parents who were also deaf, and the remaining seven were born with hearing parents and became deaf before 3 years of age due to diseases or medication. The rest of the information about the participants was similar to that in Experiment 1.

3.1.2. Materials and experimental design

The six colors were the same as those used in Experiment 1. Stimuli in the spatial interference task included 15 grids consisting of 12 black squares and 13 white squares. A 2 (visual field: LVF vs. RVF) × 2 (pair type: easy-to-sign colors vs. hard-to-sign colors) × 2 (task group: non-interference vs. spatial interference) mixed experimental design was used. Visual field and pair type were within-subjects factors, and task group was a between-subjects factor.

3.1.3. Procedure

The visual search task was similar to that in Experiment 1, except before each trial participants were shown one of the spatial grids in the spatial interference task or a blank screen in the non-interference task. Participants were randomly assigned to one of the task groups (see Fig. 3A). For the spatial interference task, a fixation marker was presented for 1250 ms, followed by the interference task display for 1250 ms. The fixation screen reappeared for another 1250 ms. Participants were asked to press the space bar with both thumbs if the currently displayed task stimulus was the same as that shown in the previous display (i.e., a one-back match). No response was required if the stimulus was different. Matches occurred in 24 trials (8.33% of all trials). Next, the visual search display appeared for 200 ms, followed by the fixation screen. The procedure of the visual search task was the same as in Experiment 1.

3.2. Results and discussion

The accuracies of the visual search task in the two task groups were both over 98%, and the accuracy of the spatial interference task was 95.8%. In the non-interference task group, 6.85% of trials were excluded from our analysis of the visual search task data because due to incorrect responses or RTs that exceeded 2 SD. For the spatial interference task group, 10.19% of trials occurring after participants gave responses to the task were excluded, and 3.91% of the remaining trials were excluded, either because of incorrect responses or RTs that exceeded 2 SD.

A 2 (visual field: LVF vs. RVF) × 2 (pair type: ESC vs. HSC) × 2 (task group: spatial interference vs. non-interference) ANOVA was conducted on the RTs, with visual field and pair type as within-subjects variables and task group as a between-subjects variable (see Fig. 3B). The analysis revealed a marginally significant three-way interaction among the three factors ($F_{[1,28]} = 2.976$, $p = 0.096$) and significant main effects of visual field ($F_{[1,28]} = 5.305$, $p = 0.029$) and pair type ($F_{[1,28]} = 28.082$, $p < 0.001$). The visual field × pair type interaction was also significant ($F_{[1,28]} = 15.838$, $p < 0.001$). For the non-interference task condition, there was only a significant main effect of pair type ($F_{[1,14]} = 8.097$, $p = 0.013$), such that the RTs for ESC were much faster than those for HSC; no significant main effect of visual field or visual field × pair type interaction was found. For the spatial interference task

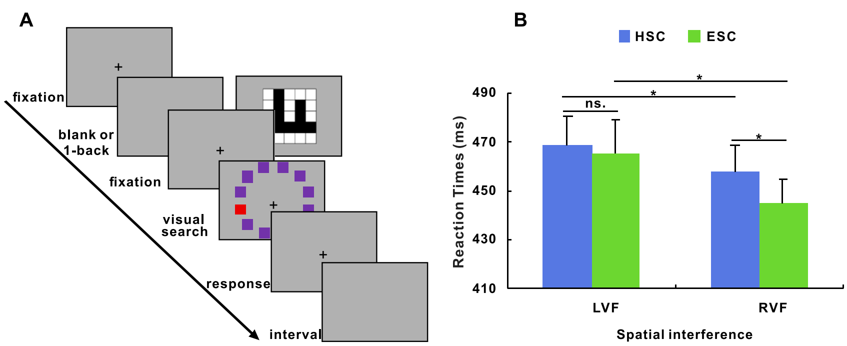

Fig. 3. The experimental procedure and results in Experiment 1b. *A*, the experimental procedure. *B*, the results. Keys: ESC = easy-to-sign colors; HSC = hard-to-sign colors; LVF = left visual field; RVF = right visual field; * = $p < .05$; ns. = $p > .05$. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

condition, no significant visual field × pair type interaction was found ($F_{[1,14]} = 3.032$, $p = 0.104$), but there were significant main effects of both pair type ($F_{[1,14]} = 20.79$, $p < 0.001$) and visual field ($F_{[1,14]} = 20.457$, $p < 0.001$).

Furthermore, we compared the RTs of hard-to-sign and easy-to-sign color pairs within each visual field in the spatial interference condition. For the RVF targets, the responses to the easy-to-sign color pairs were significantly faster than those to the hard-to-sign color pairs ($t_{[14]} = 4.141$, $p = 0.001$). For the LVF targets, there was no significant difference between the two color pairs ($t_{[14]} = 0.963$, $p = 0.352$). We also compared the RTs of the RVF targets with those of the LVF targets for each pair type. For the hard-to-sign pairs, the RTs were significantly faster when the target appeared in the RVF than when it appeared in the LVF (10 ms faster on average; $t_{[14]} = 2.603$, $p = 0.021$). For the easy-to-sign pairs, there was a significant and greater RVF advantage (20 ms faster on average; $t_{[14]} = 4.374$, $p = 0.001$), which indicated that the spatial interference hindered the search for targets in the LVF, especially for the easy-to-sign colors.

In summary, the results of the non-interference condition in Experiment 2 were consistent with the bi-lateralized Whorfian effect seen in Experiment 1 and indicated that the spatial interference only disrupted the Whorfian effect in the LVF. The results suggest a potential relationship between the visual spatial information in sign language and the Whorfian effect in the LVF. However, we did not directly test the relationship between the right visual field advantage and language processing. Though Gilbert et al. (2006) confirmed the relationship between the right visual field advantage and spoken language processing, the current study could not rule out the possibility that there are differences between spoken language and sign language in the effect of a language interference task on color perception in the RVF. Future studies are needed to clarify this question.

Experiments 1 and 2 support the Whorf Hypothesis with new behavioral evidence from speakers of CSL and Chinese, and suggest that the nature of language shapes the pattern of the Whorfian effect. In Experiment 3, we further explored the time course of sign language's effect on categorical color perception in order to investigate whether the Whorfian effect in both the RVF and the LVF occurs at the early preattentive stage of color perception.

4. Experiment 3

4.1. Method

4.1.1. Participants

Participants included 14 young adults (10 male; mean age = 18.84 years, *SD* = 1.69) who were severely-to-profoundly deaf (i.e., at least 70 dB loss in both ears). All participants were deaf from birth and learned CSL as their first language from their parents who were also deaf. The rest of the information about the participants was similar to that in Experiment 1.

4.1.2. Stimuli and experimental design

The stimuli shown in Fig. 4 were presented on a 15-inch CRT monitor with a resolution of 1024 × 768 and a refresh rate of 85 Hz. The RGB values of the four blue-green gradual colors used in the present experiment were as follows: G1 = 0, 171, 129; G2 = 0, 170, 149; B1 = 0, 170, 170; and B2 = 0, 149, 170. The corresponding CIEL*u*v* values were as follows: G1 = 62.2, −52.3, 23.0; G2 = 62.4, −50.4, 6.8; B1 = 63.1, −48.8, −10.5; and B2 = 56.5, −41.5, −27.3. The CIEL*u*v* inter-pair distances were (G1, G2) = 16.3ΔE, (G2, B1) = 17.5ΔE, and (B1, B2) = 19.5ΔE. The RGB values for the background were 210, 210, 210, and the CIEL*u*v* values were 84.2, 0, 0.

Before the ERP experiment, a pilot test was conducted to confirm the bi-lateralized Whorfian effect using the four blue-green gradual colors. An additional eight participants who were prelingually deaf and who did not take part in the ERP experiment participated in the pilot test (5 male; mean age = 18.12 years, *SD* = 1.73). All eight were native CSL signers and had profound hearing loss. Each trial began with a fixation marker ("+") displayed against a grey background for 1000 ms, followed by a 200 ms visual search stimulus. Participants were asked to judge as accurately and quickly as possible whether the target appeared to the left or right of the fixation point.

The target appeared in one of the four positions nearest the fixation marker, in line with Siok et al. (2009). The fixation marker did not disappear until a response was made. After the response, a blank screen appeared for 1000 ms to indicate the beginning of the next trial. There were 240 trials in total, which were evenly divided by pair type (within-category vs. between-category) and visual field (LVF vs. RVF). There was no significant main effect of visual field ($F_{[1,7]} = 0.689$, $p = 0.434$) nor interaction between visual field and pair type ($F_{[1,7]} = 0.023$, $p = 0.884$). A significant main effect of pair type was found ($F_{[1,7]} = 23.349$, $p = 0.002$), which indicated that the RTs were faster when the colors fell into different lexical categories compared to the same category, regardless of which visual field the target appeared in. Thus, the bi-lateralized Whorfian effect was confirmed behaviorally using the four blue-green gradual colors.

A 2 (visual field: LVF vs. RVF) × 2 (deviant type: within-category vs. between-category) within-subjects design was used. Within-category deviant trials were either of type (G1, G2) or (B1, B2), each further distinguished by the side on which the deviant occurred (LVF or RVF). Similarly, between-category deviant trials had colors of two different types (i.e., one considered green and one considered blue), each further distinguished by the side on which the deviant occurred.

Participants' ERPs were recorded while performing a visual oddball task (see Fig. 1B). Each trial presented two colored squares (hereafter "colors") flanking the fixation point. Within each block of trials one of the two colors adjacent to the blue-green boundary (i.e., G2 or B1) served as standard throughout, and each of the four colors served as deviant once (as required). Across blocks, 70% of the trials consisted of two identical standard colors (either G2 or B1) with a "+" fixation point (the "standard" condition), 10% of the trials consisted of the same two identical standard colors with a "○" fixation point (the "target" condition), 10% of the trials consisted

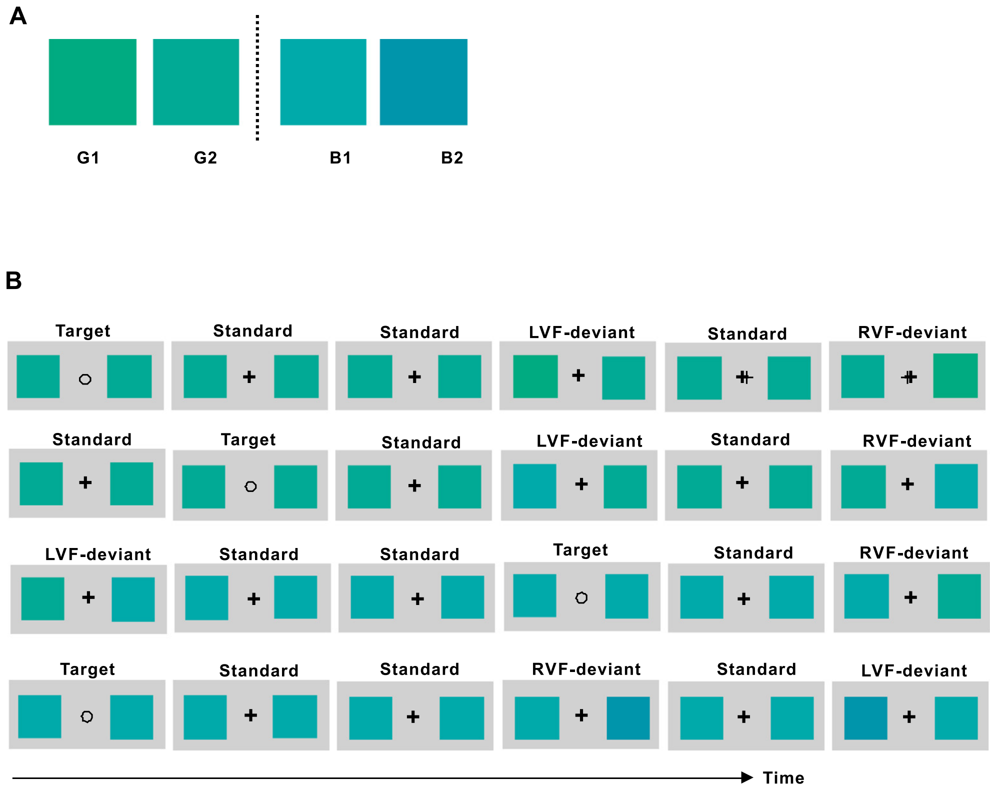

Fig. 4. Experimental materials and experimental paradigm in Experiment 2. The RGB values of the four colors used in the present experiment were as follows: G1 = 0, 171, 129; G2 = 0, 170, 149; B1 = 0, 170, 170; B2 = 0, 149, and 170. Keys: LVF = left visual field; RVF = right visual field. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

of the standard color in the RVF and a deviant in the LVF (the "LVF-deviant" condition), and 10% of the trials consisted of that same standard color instead in the LVF and that same deviant in the RVF (the "RVF-deviant" condition). The two blocks containing the same standard color were distinguished from each other by one having the within-category deviant and the other having the between-category deviant.

4.1.3. Procedure

In the ERP experiment, participants were tested in a dimly lit, sound-attenuated booth and were seated in a comfortable chair. During each trial, two 2 × 2 cm colored squares were presented for 200 ms against a grey background, one to each side of the fixation marker, followed by a blank screen for 900 ms. The distance between the two squares was 8.5 cm, and the inner edge of each square was 3.5° to one side of the fixation mark. The presentation order was pseudo-randomized within each block, such that the first five trials were standard condition trials and two deviants never appeared in succession. Block order was counterbalanced across participants. Participants were asked to press the spacebar with either their left or right index finger when the fixation marker changed from a cross to a circle. There was no mention of color in the instructions. The finger responses were counterbalanced across participants.

After the ERP experiment, all participants were given a blue-green lexical boundary test. On each trial, a 7 × 7 cm square stimulus in one of the four colors (G1, G2, B1, or B2) was presented centrally on a grey background for 500 ms at a viewing distance of 70 cm, followed by a blank grey screen. Participants were instructed to sign the stimulus color with the corresponding sign for "green" or "blue." Each stimulus was presented 15 times in a total of 60 randomized trials. All participants' signing accuracies were above 95%.

4.1.4. EEG recording and analysis

Electrophysiological data were continuously recorded in reference to the tip of the nose, with a sampling frequency of 1000 Hz from 32 Ag/AgCl electrodes mounted on a Quik-cap according to the international 10–20 system. The recordings were amplified with a 40-channel portable NuAmps amplifier from Neuroscan. Data were filtered online with a 0.1–100 Hz band pass and 50 Hz notch filter, and data were re-filtered offline with a zero phase shift digital filter (slope 24 dB/Oct, 0.8–20 Hz band pass for vMMN analysis and 20 Hz low pass for N2 and P3 analysis). Bipolar horizontal and vertical electrooculograms were simultaneously recorded to monitor eye movements.

The Brain Vision Analyzer software package was used to analyze the data. Epochs ranged from −100 to 800 ms after stimulus onset. Baseline correction was performed according to pre-stimulus activity. Ocular artifacts were mathematically corrected by

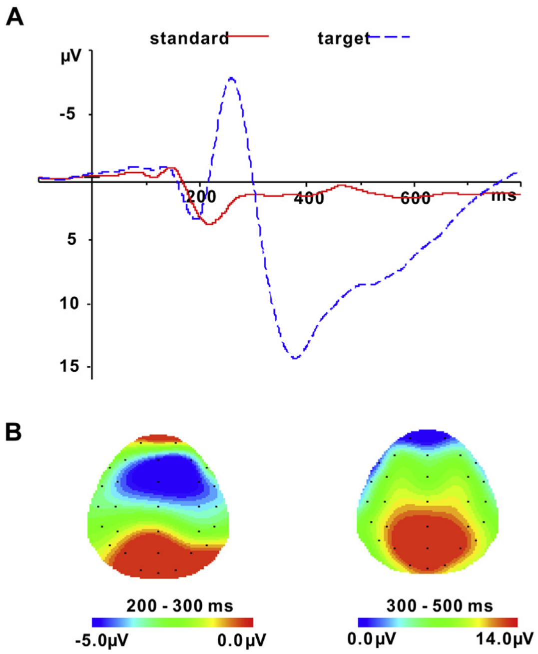

Fig. 5. Grand-averaged ERPs and brain electrical activity mapping. *A*, Grand-averaged ERPs evoked by the frequent and target stimuli in Cz electrode (red solid line represented standard stimuli and blue dotted line represented target stimuli). *B*, the brain electrical activity mapping of N2 and P3 components evoked by the target stimuli. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

subtracting them from the EEG recordings. Epochs with potentials exceeding ± 100 μV at any cap electrode were automatically rejected. Data were segmented and averaged in six ways according to stimulus type: standard, target, between-category deviant in RVF, between-category deviant in LVF, within-category deviant in RVF, and within-category deviant in LVF.

Early deviance-related negativity was defined as the vMMN (Mo et al., 2011), and was parallel to the MMN in auditory stimuli and to the vMMN in other visual stimuli (Holmes et al., 2009; Maekawa et al., 2005; Näätänen et al., 2007). The vMMN was maximal over the lateral parietal-occipital scalp. Thus, electrodes O1, O2, P3, P4, T5, and T6 were chosen for further analysis.

4.2. Results

4.2.1. Target stimuli

Both the behavioral and electrophysiological responses to the target stimuli indicated a high rate of successful target detection. Behaviorally, the mean proportion of correct hits was 98.6% (*SD* = 2), and the mean number of incorrect hits was less than 2. The mean RT was 416 ms (*SD* = 39). Together, these results suggested a high degree of narrowing attention to the fixation point. Grand-averaged ERPs evoked by the standard and target stimuli are shown in Fig. 5A. The target stimuli evoked larger N2 and P3 components. The N2 occurred with a central scalp distribution and the P3 with a parietal-occipital scalp distribution, as shown in Fig. 5B. The mean amplitude of N2 was measured from 200 to 300 ms, and that of P3 was measured from 300 to 500 ms. Paired *t* tests were conducted across all of the electrodes. The mean amplitudes of both the N2 and P3 components evoked by the target stimuli were significantly larger than those evoked by the standard stimuli ($ps < 0.05$).

4.2.2. Deviant stimuli

There was an obvious early negative deflection in all of the deviant stimuli ERPs in relation to the standard stimuli ERPs (green solid line, panels A and C in Fig. 6) except for the within-category RVF deviant stimuli (red dotted line, panel A), beginning at approximately 130 ms post-stimulus, lasting until about 190 ms, and peaking at approximately 160 ms (see Fig. 6).

We found no significant differences in peak latency across all of the deviant and standard stimuli ($F_{[4,52]} = 0.358, p = 0.72$). The mean amplitudes of ERPs in the time window of 130–190 ms evoked by deviant stimuli were compared to those evoked by standard stimuli at these electrodes using paired *t* tests. The between-category deviant stimuli in both visual fields evoked significantly larger vMMN than the standard stimulus did ($t_{[13]} = -3.078, p = 0.009$ and $t_{[13]} = -2.991, p = 0.01$ respectively). The vMMN evoked by the within-category deviant stimuli in the LVF ($t_{[13]} = -0.689$, $p = 0.503$) and the RVF ($t_{[13]} = -0.525$, $p = 0.608$) were numerically larger than that evoked by the standard stimuli, but not significantly so ($t_{[13]} = -0.689$, $p = 0.503$; $t_{[13]} = -0.525$, $p = 0.608$).

Next, we compared the vMMN effects for both types of deviant stimuli and both visual fields in a 2 (pair type: between-category vs. within-category) × 2 (visual field: RVF vs. LVF) repeated-measures ANOVA (see Fig. 7). The vMMN component was measured for

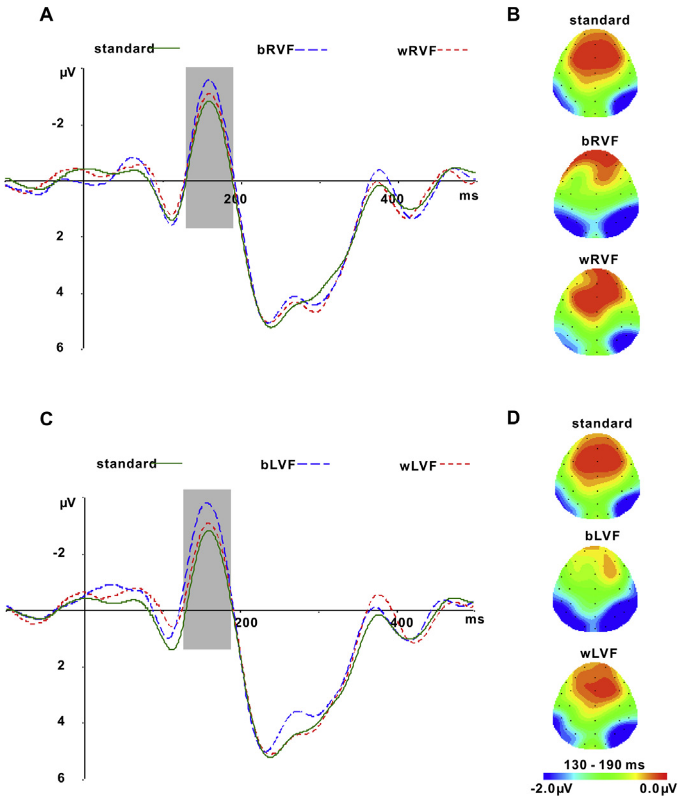

Fig. 6. Grand-averaged ERP wave pattern. *A*, *C*, ERP wave pattern during 100–500 ms. *B*, *D*, EEG topographic map during 130–190 ms. Keys: bLVF = between-category left visual field; bRVF = between-category right visual field; wLVF = within-category left visual field; wRVF = within-category right visual field.

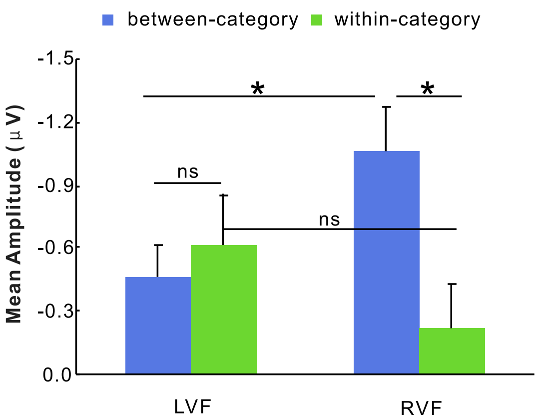

Fig. 7. The average vMMN effects evoked by the deviants. Error bars denote standard error. Keys: * = $p < .05$; ns. = $p > .05$.

each visual field in the time window of 130–190 ms by subtracting the ERPs of the standard stimuli from the ERPs corresponding to each type of deviant stimulus. There was no significant interaction between pair type and visual field ($F_{[1,13]} = 0.068$, $p = 0.79$) nor a main effect of visual field ($F_{[1,13]} = 0.588$, $p = 0.457$), but there was a significant main effect of pair type ($F_{[1,13]} = 10.31$, $p = 0.007$). The results indicated that the vMMN effect of between-category deviants in both visual fields was significantly larger than that of within-category deviants, which provides electrophysiological evidence for bi-lateralized preattentive color categorical perception.

Experiment 3 showed that, for participants who were deaf and used CSL, color patches of an unexpected hue that were exposed briefly in the right or left visual field elicited less of a surprise response in the brain when they fell into the same lexical category as colors that were perceptually equidistant from the expected color but belonging to a different lexical category. This suggests that the Whorfian effect in both the RVF and the LVF is preattentive. The results provide evidence of the important role of the right hemisphere in sign language comprehension (Capek et al., 2008; Hickok et al., 2009; MacSweeney, 2002; MacSweeney et al., 2008; Neville et al., 1997; Neville et al., 1998; Newman et al., 2002; Newman et al., 2010; Petitto et al., 2000) and support the opinion that color categorical perception could be right hemisphere dominant (Dien, 2009; Emmorey & Corina, 1993; Klein & Zatorre, 2011; Paluy et al., 2011; Yovel, Tambini, & Brandman, 2008).

5. General discussion

Three experiments were conducted to investigate the Whorfian effect in participants who were deaf and used CSL, and the behavioral and electrophysiological evidence documented a bi-lateralized Whorfian effect. To our knowledge, this is the first study to test the Whorf hypothesis using both behavioral and electrophysiological measures in a sample of CSL users. Unlike the participants who could hear, those who were deaf and used CSL presented a bi-lateralized Whorfian effect in color perception tasks, and the color categorical effect occurred at early, preattentive perceptual processing stages. These results supported the Whorf Hypothesis well, indicating that the nature of the language decided the specific pattern of language's effect on perception. Hence, in the field of color perception, the Whorfian effect showed different manifestations in different languages. For the hearing speakers, it presented as an RVF advantage on color categorical perception, whereas for the signers, it presented as a bi-lateralized Whorfian effect on color categorical perception.

The lateralization of the visual field reflects the asymmetry of the brain functions. Visual words related to language processing are representative of the lateralization of brain functions, reflecting the lateralization of LH and RH, respectively. The lateralization of RH in facial recognition occurs because RH is involved in spatial information processing. Hence, according to two important identification systems, for persons who hear, under the restriction of the lateralization of LH in language processing, the Whorfian effect exhibits as color categorical perception with dominant RVF. However, because of the substantial connection between the sign and visual spatial information, the color perception of persons who are deaf also is restricted by the lateralization of RH in spatial processing. Thus, in persons who are deaf, the Whorfian effect exhibits as a bi-lateralized color categorical effect in the left and right visual fields. Relevant differences between persons who hear and persons who are deaf and use sign language have also been found in other studies. For example, Emmorey presented ASL signs and non-signs to each visual half field to compare the lexical decision-making of persons who could hear and persons who were deaf and used sign language (Emmorey & Corina, 1993). The results showed that deaf signers and hearing English speakers both showed an RVF advantage for abstract lexical items. In addition, persons who were deaf and used sign language showed a significant LVF advantage for imageable signs, whereas persons who could hear exhibited no visual field effect for imageable words.

On the other hand, categorical perception itself is not necessary to exhibit lateralization in LH. For example, Klein and Zatorre (2011) found stronger activation in right superior temporal sulcus (STS) associated with the categorical perception of chords. It is important that color categorical perception itself is not necessarily always manifest as lateralization in LH (Franklin, 2009; Franklin et al., 2008; Franklin et al., 2010). Whether from the perspective of compensatory processes and plasticity of the brain, or based on studies on varied symmetry of brain function from infancy to adulthood, people who are deaf will likely form the bi-lateral effect of color categorical perception.

Firstly, according to evidence of the compensatory processes and plasticity of the brain, the brain can establish new functional lateralization based on a new environment. For example, after intense language comprehension training, brain injury patients with aphasia significantly improved their performance, which correlated with activations in regions such as the right superior temporal gyrus and the left precuneus (Musso et al., 1999). In addition, Paluy, et al. (2011) found that patients with RH brain injury and the normal control group showed the right visual advantage of categorical effect of color, whereas patients with LH brain injury showed an opposite left visual advantage of categorical effect of color. The researchers suggested that this reversal of asymmetry in the categorical effect was related to a reorganization of the color lexicon in the RH following LH brain injury and/or a strengthened RH sensitivity to color categories.

Secondly, research on the change in symmetry from infancy to adulthood provides empirical evidence. Deruelle and de Schonen (1991) tested 4- to 9-month old infants to investigate pattern processing by the two hemispheres. Researchers presented two different patterns: in one condition the components of the patterns were arranged so as to produce a face-like pattern; in the other condition the same components were arranged into arbitrary patterns that were not “good form” patterns. The results showed that no performance asymmetry was observed with the arbitrary patterns. However, for the face-like patterns, there was an RH disadvantage, implying that the RH advantage for individual face recognition is not due to a general immaturity (Deruelle & de Schonen, 1991). In addition, the research from Franklin and her colleagues also indicated that the infant color categorical perception initially exhibited the LVF advantage, but with the acquisition of a color lexicon, the children shifted to exhibiting the RVF advantage (Franklin, 2009; Franklin et al., 2008; Franklin et al., 2010).

Though the present study could not show clear causal effects between language experience and color perception, studies using language training paradigms may provide some ideas on this issue. For example, Franklin and his colleague found that people could gain the right visual advantage in color category perception through learning a color lexicon (Franklin, 2009; Franklin et al., 2008; Franklin et al., 2010). In their studies, infants showed the left visual field advantage and in contrast, adults showed the right visual field advantage (Franklin, 2009).

Zhou et al. (2010) further found that after learning artificial categories that violate universal tendencies in color naming, categorical perception changed accordingly, and lateralized categorical perception of color could reflect strictly learned color categories. Kwok et al. (2011) found that this training of color lexicon restructuring would result in increased volume of grey matter in V2 and V3 around left visual cortex. One study in our lab also found that short-term trained lexical categories produce lateralized preattentive color categorical perception, and that language enhances sensitivity to the differences among between-category stimuli (Zhong, Li, Li, Xu, & Mo, 2015). Admittedly, the causal effects between language experience and perception of color still need further study. Moreover, persons who are deaf and do not sign, and also native and late hearing signers, should be included in future studies to better reveal the relationships among the bi-lateralized Whorfian effect, sign language, and hearing loss.

6. Conclusion

In conclusion, the current research investigated the Whorfian effect in the color perception of persons who are deaf and use sign language. The study is unique in using behavioral and electrophysiological data to document a bi-lateralized Whorfian effect, and in providing support for the Whorf hypothesis through the study of sign language. Combined with evidence of the lateralized Whorfian effect in spoken language systems, the results suggest that the nature of the language determined the specific pattern of the Whorfian effect on color perception. However, the study here only gained an initial understanding of this issue. Further studies are needed to systematically investigate it.

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Conflicts of interest

No.

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