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Immediate transfer of synesthesia to a novel inducer

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In synesthesia, a certain stimulus (e.g. grapheme) is associated automatically and consistently with a stable perceptual-like experience (e.g. color). These associations are acquired in early childhood and remain robust throughout the lifetime. Synesthetic associations can transfer to novel inducers in adulthood as one learns a second language that uses another writing system. However, it is not known how long this transfer takes. We found that grapheme-color associations can transfer to novel graphemes after only a 10-minute writing exercise. Most subjects experienced synesthetic associations immediately after learning a new Glagolitic grapheme. Using a Stroop task, we provide objective evidence for the creation of novel associations between the newly learned graphemes and synesthetic colors. Also, these associations generalized to graphemes handwritten by another person. The fast learning process and the generalization suggest that synesthesia begins at the semantic level of representation with the activation of a certain concept (the inducer), which then, uniquely for the synesthetes, activates representations at the perceptual level (the concurrent). Thus, the results imply that synesthesia is a much more flexible and plastic phenomenon than has been believed until now.

Keywords: synesthesia, learning, Glagolitsa, Stroop test

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Introduction

Grapheme-color synesthesia, one of the most common variants of the phenomenon, is triggered by linguistic entities like letters and numerals (inducers) and generates perceptions of colors (concurrents) (Cytowic & Wood, 1982). These associations are acquired in early childhood and remain highly consistent over time (Baron-Cohen, Wyke, & Binnie, 1987). Evidence suggests that the neural representations of phenomenal colors experienced in synesthesia (synesthetic colors) resemble those during conscious color vision under standard perceptual conditions (ink colors): fMRI studies indicated activation in areas V4/V8 during synesthetic experiences (Nunn et al., 2002) and psychophysics indicated that these experiences have color opponent properties (Nikolić, Lichti, & Singer, 2007), suggesting the involvement of neurons responsible for color perception. However, the neuronal representations of the inducers are less clear. Neuronal activations during synesthesia involve a variety of striate and extra striate areas, including left dorso-lateral pre-frontal cortex, left intraparietal, and inferior temporal areas (Aleman, Rutten, Sitskoorn, Dautzenberg, & Ramsey, 2001; Sperling, Prvulovic, Linden, Singer, & Stirn, 2006). Some of these areas are likely to be directly involved in the generation of the perceptual associations (binding) between the grapheme and the respective color, such as those in parietal and temporal regions (Robertson, 2003). Others may be dealing with the incongruencies

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between the ink color of the inducer and its synesthetic color, such as the pre-frontal areas (Cohen Kadosh, Cohen Kadosh, & Henik, 2007). The common understanding of the nature of the inducer is consistent with the name of the phenomenon—*syn* + *esthesia* meaning 'union of senses'—, suggesting that the associations occur at the 'lower' perceptual level of representation (Cytowic & Wood, 1982; Harrison & Baron-Cohen, 1997; Ramachandran & Hubbard, 2001a). However, more recent studies suggested the possibility that this, commonly accepted, view does not describe accurately the nature of synesthesia. Several results suggest that the meaning of the inducers plays an important role in the process (Dixon, Smilek, Duffy, Zanna, & Merikle, 2006; Rich & Mattingley, 2003; Ward, Tsakanikos, & Bray, 2006; see also Ramachandran & Hubbard, 2001b). Thus, concurrents may be activated only after semantic decoding is completed at 'higher' processing levels. Synesthesia may not occur due to unification of senses.

In the present study we test the semantic hypothesis of the nature of inducers in the following way: Evidence exists that synesthetic associations can transfer to linguistic symbols learned later, even in adulthood. Here, novel inducers are adopted for old associations as one learns a second language that uses another writing system (Rich, Bradshaw, & Mattingley, 2005; Witthoft & Winawer, 2006). For example, if the Latin letter 'D' was initially associated with a green color and the person later learned the Russian language, the Cyrillic 'D' (Д) may also become associated with the same green color (Witthoft & Winawer, 2006). It is currently unknown how long the formation of these new synesthetic associations takes and how much practice such a transfer requires. If synesthesia originates at the semantic level of representation, the transfer could occur fast, even within minutes, as it would require only the time needed to learn the meaning of a new grapheme (e.g., by a simple writing exercise). In contrast, if the synesthetic association occurs at the perceptual level, one would expect longer transfer times, as are characteristic for perceptual learning (Goldstone, 1998; Kami & Sagi, 1993). In addition, the semantic hypothesis predicts a greater ability to generalize the transferred synesthetic associations than the perceptual hypothesis. Thus, the newly formed associations should generalize to graphemes that have not been seen previously (e.g., those written by another person).

Methods

To test these hypotheses, we trained 16 synesthetes in laboratory conditions to use parts of the Glagolitic alphabet, an ancient Slavic writing system (Franolić & Zagar, 2008), with which none of the subjects had previous experience and which is orthographically largely unrelated to either Latin, Greek, Cyrillic, Arabic or Hebrew (Figure 1A). Each synesthete learned three Glagolitic graphemes corresponding to those Latin and Arabic graphemes that initially produced the strongest grapheme-color associations. We always used two Latin letters and one Arabic digit. The training was implemented as a short writing exercise with paper and pencil, conducted separately for each grapheme, and consisting of two phases: In the first phase the subjects learned grapheme's orthography by handwriting it six times (Figure 1B). In the second phase, subjects acquired the meaning of the grapheme by writing 20 German words or number sequences and substituting one Latin/Arabic grapheme with its Glagolitic equivalent (Figure 1C). The entire exercise for each grapheme lasted always less than 10 minutes. Also, for each grapheme, we applied a Stroop task twice adapted for studying synesthesia (Nikolić et al., 2007; Odgaard, Flowers, & Bradman, 1999) once before the subject has been introduced to the Glagolitic letters, and the second time following the training of a grapheme. In the Stroop task, synesthetic colors interfere with or facilitate the process of naming the ink color of the graphemes, indicating that synesthetic associations occur automatically, without voluntary control. We used the same test to investigate a possible transfer of synesthetic associations to Glagolitic graphemes.

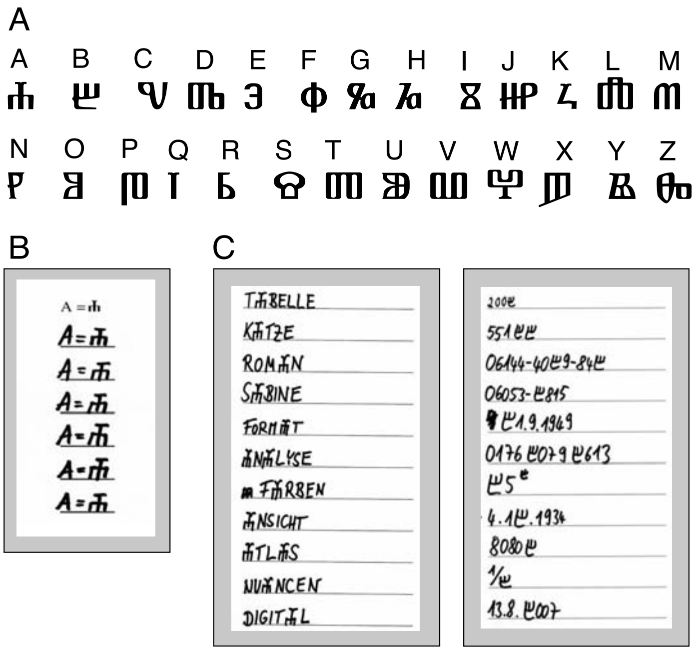

Figure 1. The procedure for acquiring individual graphemes of the Glagolitic alphabet. (A) The correspondence between the graphemes of Latin and square Glagolitic alphabets. (B) Example worksheet used in the first phase during which a subject learned grapheme's orthography by handwriting it six times. (C) Two excerpts from worksheets used in the second phase during which subject J.G. acquired the Glagolitic equivalent either to Latin 'A' or to Arabic digit '2.' Each grapheme was trained with a total of 20 German words or number sequences.

In the Stroop task, synesthetic subjects name the ink color of a grapheme faster when this color is the same as the synesthetic color (congruent condition) than when the two colors are different (incongruent condition), opponent colors producing strongest effects (Nikolić et al., 2007). Figure 2A illustrates the procedure to select grapheme colors and Figure 2B shows the actual stimuli in their congruent colors. The letters were presented in a handwritten form but written by a person other than the subject.

Participants

Our experimental group consisted of sixteen (fifteen females and one male) grapheme-color synesthetes. Their ages ranged from 24 to 73 years old (average 37.7 years). All of the synesthetes reported having vivid color experiences when perceiving graphemes. In addition to grapheme-color associations, eleven subjects reported having other forms of synesthesia. Thirteen of the synesthetes reported seeing colors on the ‘internal screen’ or in their ‘mind’s eye,’ which classified them as associators and the remaining three were projectors as they saw the colors in the external space, projected onto the graphemes (Dixon, Smilek, & Merikle, 2004). In the Stroop effect (i.e., difference between congruent and incongruent) to Latin/Arabic graphemes, projectors were on average only 14.9 ms faster than associators and this difference was not significant (one-tail *t*-test, $t(3) = 0.26$, $p = 0.40$). All subjects reported having synesthesia since early childhood and could not remember the point at which it began. Three subjects reported having direct relatives with synesthesia.

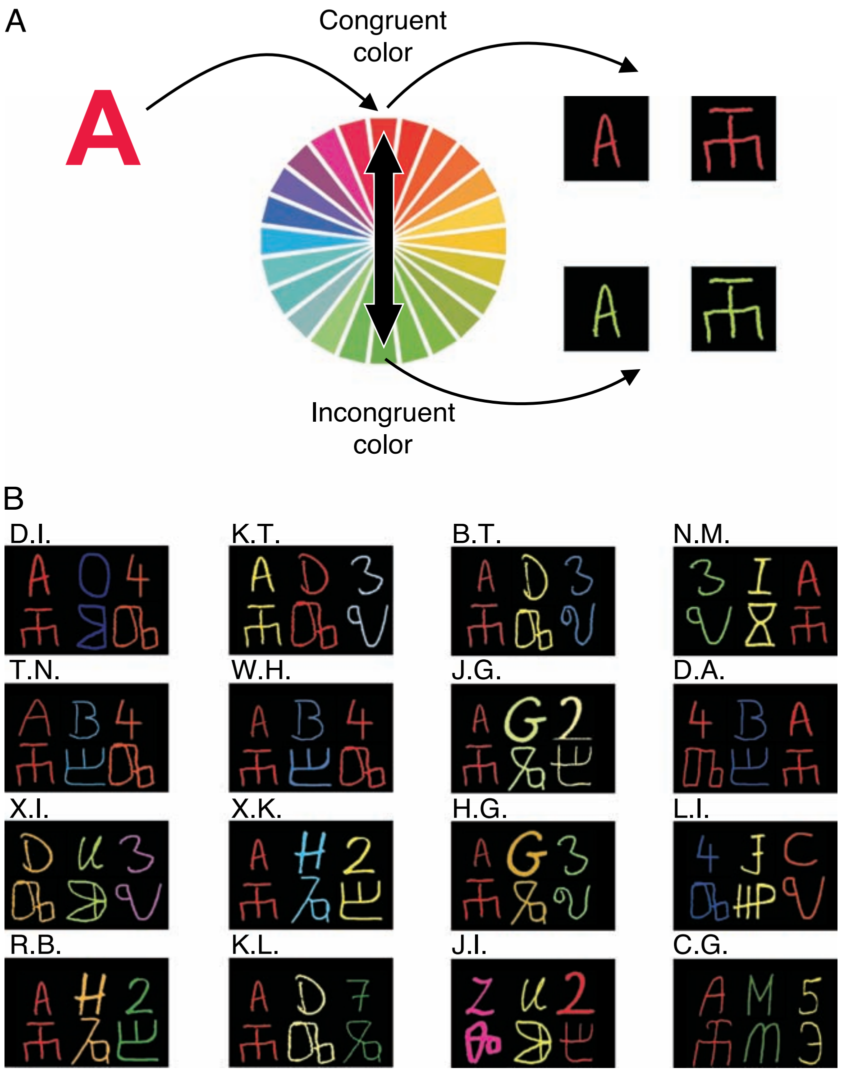

Figure 2. Stimuli used in the Stroop task. (A) Each Latin/Arabic grapheme and its Glagolitic equivalent were shown in two color conditions: the same as the synesthetic color (congruent) or the opponent color (incongruent), as determined from a color wheel. (B) The stimulus colors used in the congruent condition were for all 16 synesthetes customized to match the subjects’ individual synesthetic colors. For identification, individual synesthetes are assigned pseudo-initials.

Stimuli

To ensure that the subjects were not familiar with the alphabet prior to the study we worked with the square Glagolitic writing system, because this Eastern European alphabet is little known in Western Europe. The alphabet has the needed exotic appearance, as only few letters bear resemblance to other known graphemes. In the Glagolitic alphabet the letters were also used to indicate numbers, the values being assigned according to the alphabetic order (Franolić & Zagar, 2008), i.e. the sign for letter 'A' was used to indicate number one. All graphemes were presented in handwritten form (Figures 2A and 2B), because, during the first pilot experiment, the subject reported that it was easier to perceive the newly acquired synesthetic colors when the Glagolitic graphemes were presented in handwritten form—as studied—than when presented as a much thicker computer font (Figure 1A), which she did not study.

Procedure

The experiments were made with three graphemes (two Latin letters and one Arabic digit) for which the subjects reported the strongest color experiences. During the training with paper and pencil the synesthetes were first given a sheet of paper on which they had to write one of the Glagolitic graphemes six times. After the orthography of the grapheme was learned, we went immediately to the second phase: to the list of 20 familiar words or 20 number sequences. We asked the subjects to write entire words or number sequences such that they substituted one Latin letter or Arabic digit with the corresponding Glagolitic grapheme. The goal of this phase was to acquire the meaning of the new grapheme. To facilitate the learning process, some of the number sequences were familiar to subjects as they represented important information such as their dates of birth or telephone numbers. The words were read aloud by the experimenter while the number sequences were presented in a written form on a paper. Some words and number sequences contained more than one sample of the trained grapheme and the subjects were instructed to substitute all of them with the Glagolitic equivalent. Subjects substituted only one type of a grapheme at a time, i.e. during the training of later graphemes they no longer used the Glagolitic graphemes learned earlier. After each 20-item list was completed, we asked the subjects to read through the worksheet once again and report whether they saw colors associated with the newly learned grapheme. After that, we presented the subjects with an empty sheet of paper, instructed them to write a single Glagolitic grapheme, and asked again whether they associated any synesthetic experiences. Next, we asked the same question after handing them another sheet of paper with a single Glagolitic grapheme handwritten by the experimenter.

For the three selected graphemes we asked subjects to find the best match to their synesthetic colors, for which we used a color book with a palette of 5.500 colors (Kueppers, 2003) and a computerized procedure implemented online at http://www.synesthete.org (Eagleman, Kagan, Nelson, Sagaram, & Sarma, 2007). The selection of incongruent (opponent) colors for the Stroop task was made on the basis of a color wheel that is close to the psychological color wheel (Figure 2A) and is implemented in a program farbwert.exe, a freeware Windows application downloadable from http://www.AnnaVis.de. During the Stroop task the graphemes were presented in a dimmed room on a black background and on a high-contrast 21 inch CRT computer monitor ViewSonic P227f, with 100 Hz refresh rate. The stimuli were presented and the response times measured with the visual stimulation tool ActiveSTIM (http://www.ActiveSTIM.com). The synesthetes' task was to name the ink color of the grapheme. The initial Stroop task (i.e., before the training) was made collectively for all three graphemes, and consisted of 240 experimental trials (3 graphemes × 2 writing systems × 2 colors × 20 repetitions). In each of the three later tests for each individual grapheme (i.e., after the training) the Stroop task consisted of 80 trials (2 writing systems × 2 colors × 20 repetitions). The inter-trial interval was about one second (<100 ms variability) and all trials were presented within one block, without a break. Prior to the experiment and in order to become familiarized with the color-naming procedure, each subject made between 23 and 51 practice trials (average 36.5). Subjects could freely choose the distance from the monitor, but the typical distance was about 1 m. The sizes of the stimuli on the screen were 2.8–5.0 × 4.5–5.5 cm. The time needed to name the colors of graphemes was measured by the latency of the vocal response. Subjects uttered the name of the grapheme color into a handheld microphone. They were instructed to respond as soon as possible but to keep the response accuracy at high level. All stimulation conditions were presented in a block-randomized way. All synesthete subjects were given the same instructions and were naïve with respect to the purpose of the experiment and the hypothesis. The subjects were paid for participation (15 Euro/hour).

Normalization

As in a previous study (Nikolić et al., 2007), prior to the ANOVA analysis, we normalized the individual naming times relative to each subject's average naming time. This normalization increased the power of statistical analysis because the variability of naming times between subjects was large ($\sigma = 119.3$ ms, $n = 16$) compared to the variability between different stimulation conditions for individual subjects (on average, $\bar{\sigma} = 67.2$ ms, $n = 8$ conditions).

Results

Immediately following the second training phase we first investigated whether the subjects experienced transfer of synesthetic concurrents subjectively. Out of the total of 16 subjects, 14 (88%) stated perceiving synesthetic colors to at least one of the three newly learned graphemes, most of them (n = 8) perceiving the respective colors in association to all three novel graphemes. The perception of color was easier if the grapheme was embedded into a word (number sequence) than if it was presented alone. Nevertheless, 10 subjects experienced colors with at least one of the graphemes when presented alone, irrespectively of whether the grapheme was handwritten by the subject or by another person (the experimenter). In all cases in which synesthetic experiences were reported, the associated colors were identical to those that had already been associated to the corresponding Latin/Arabic graphemes.

The times for naming the colors of the stimuli were subjected to a 2 × 2 × 2 ANOVA with the following factors: *grapheme color* (congruent or incongruent), *grapheme type* (Latin/Arabic or Glagolitic) and *training* (before or after). Consistently with previous reports, when presented in congruent color, Latin/Arabic graphemes were named 114.9 ms faster than when presented in incongruent color. This effect was similar irrespectively of whether the test was made before or after the training with the Glagolitic graphemes (100.6 and 129.2 ms differences, respectively; Figure 3A). As expected, when Glagolitic graphemes were presented prior to the training their congruent and incongruent colors were named at roughly equal speed (only 6.7 ms difference). Importantly, however, after the training, this difference increased to

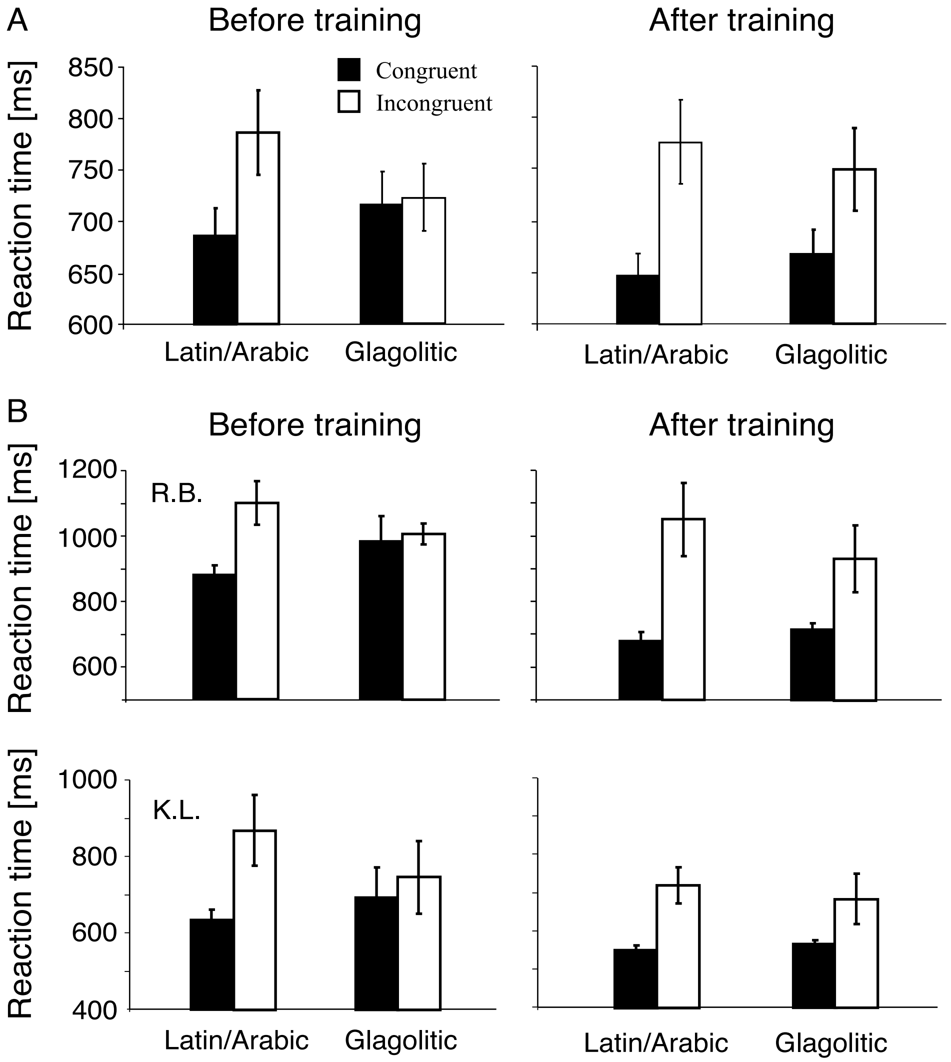

Figure 3. The times needed to name the ink color of the graphemes in the Stroop task. Reaction times in four stimulation conditions: both colors and both alphabet types. (A) Average response (naming) times for the entire group of 16 synesthetes. (B) Individual response (naming) times for the only two subjects who, after the training, reported not experiencing synesthetic associations to Glagolitic graphemes. Vertical lines: standard error of the mean.

81.7 ms, which was a significant Stroop effect as indicated by the significant 2-way interactions between *grapheme color* and *training* [$F(1, 15) = 9.7$, $p = 0.007$, $\eta^2 = 0.393$]—i.e. overall, colors had less effect before than after the training—, and between *grapheme color* and *grapheme type* [$F(1, 15) = 22.7$, $p = 0.000$, $\eta^2 = 0.602$]—i.e. colors had more effect on Latin/Arabic than on Glagolitic graphemes. The lack of interaction between *grapheme type* and *training* [$F(1, 15) = 1.0$, $p = 0.341$, $\eta^2 = 0.061$] indicated that, if color was not considered, Glagolitic and Latin/Arabic graphemes did not differ in naming times. Moreover, supporting the conclusion that *grapheme color* exerted a Stroop effect in all but one combination of *grapheme type* and *training*—namely that in which Glagolitic graphemes were presented prior to the training—the 3-way interaction was also significant [$F(1, 15) = 6.0$, $p = 0.028$, $\eta^2 = 0.284$].

The only significant main effect was that of *grapheme color* [$F(1, 15) = 33.5$, $p = 0.000$, $\eta^2 = 0.691$], response times being thus overall faster to graphemes presented in congruent than in incongruent color. The non-significant main effects of *grapheme type* [$F(1, 15) = 2.9$, $p = 0.108$, $\eta^2 = 0.163$] indicated that the effects of *grapheme colors* shown in Figure 3A tended to average out: The degree to which incongruent colors prolonged the responses approximated the degree to which the congruent colors shortened these responses, a result consistent with previous reports (Nikolić et al., 2007). Furthermore, the non-significant main effect of *training* [$F(1, 15) = 1.1$, $p = 0.319$, $\eta^2 = 0.066$] indicated that, despite the trend that color naming was 16.9 ms faster after than before the training, there was not sufficient evidence of practice-dependent improvement in the naming times.

The two subjects who experienced no synesthetic associations for any of the three new graphemes (subjects R.B. and K.L.) showed nevertheless evidence of a Stroop effect when presented with Glagolitic graphemes after the training. The patterns of their individual naming times (Figure 3B) matched closely those of the entire group (Figure 3A). Consequently, the responses of these two subjects were retained in the group analysis.

Discussion

These results indicate that synesthetic colors associated to graphemes since early childhood can be transferred to a novel grapheme in a very short period of time by only engaging in a small writing exercise. These novel associations immediately induce a significant Stroop effect when subjects attempt to name the colors of the newly learned graphemes and are also sufficiently strong to be consciously experienced by most subjects. Thus, although the grapheme-color associations in synesthesia are remarkably stable during lifetime (Grossenbacher & Lovelace, 2001), new inducers can be added. So, the inducers are in principle flexible. Hence, apparently, one important reason for lifelong stability of synesthetic associations is the stability of the inducers (e.g., the grapheme 'A' always retains the same meaning).

The short learning process and the fact that synesthesia has transferred also to handwriting of another person suggest that subjects learned a category of stimuli rather than only individual exemplars and hence, that the nature of this learning was semantic, rather than perceptual. Thus, the reported synesthetic associations to Glagolitic letters must have been induced indirectly through the newly created associations between the Glagolitic graphemes and their Latin/Arabic equivalents, the activation of perceptual experiences being exerted through the pre-existing synesthetic association between the Latin/Arabic grapheme and the corresponding color. Therefore, we propose the following chain of associations: 1) semantic representation of the Glagolitic grapheme, leading to 2) semantic representation of the Latin/Arabic grapheme, leading to 3) perceptual (sensory) representation of the color. Only the association between 2 and 3 is unique for the synesthete subjects while the one between 1 and 2—created in the present study during the training—reflects the formation of novel associations between symbols and meaning, which everyone can achieve. These conclusions are in disagreement with hypotheses that emphasize hard-wired cross-associations between low-level perceptual representations of graphemes and colors, but agree with the reports that synethetes require focused attention to detect individual graphemes and only following grapheme detection, can perceive the associated colors (Laeng, Svartdal, & Oelmann, 2004). These latter findings suggest that the grapheme's meaning had to be extracted before color association could occur.

There is evidence that IT cortex plays a role in processing multi-modal categorical information necessary for semantic representations (Fiebach, Friederici, Smith, & Swinney, 2007) and also that the same region is activated during synesthesia (Paulescu et al., 1995). Thus, the representations in IT cortex may provide some or all of the semantic associations responsible for inducing synesthetic experiences and hence, cause activations in color areas V4/V8. An anatomical study reported increased connectivity between right IT and the neighboring areas V4/V8 in grapheme-color synesthetes (Rouw & Scholte, 2007; see also McKeefry & Zeki, 1997). However, this result alone does not prove that synesthesia originates in IT cortex because increased connectivity can be either the result or the cause of a frequent co-activation between two brain areas. Superior temporal cortex is also involved in the processing of semantic information (Zahn et al., 2007) and hence, may also play a role in inducing synesthesia, especially for inducers strongly associated with linguistic representations. Our results suggest that research on the neuronal mechanisms supporting synesthesia should focus on the top-down effects exerted on early sensory processing stages by 'high' level areas that are capable of semantic processing and category formation.

We relied on synesthetes' subjective reports as indicative of synesthetic color experiences. Previous studies demonstrated that synesthetes, as a group, provide reliable subjective reports about their life-long synesthesias (Aleman et al., 2001; Baron-Cohen et al., 1987; Dixon, Smilek, Cudahy, & Merikle, 2000; Eagleman et al., 2007; Meier & Rothen, 2007; Nunn et al., 2002; Rouw & Scholte, 2007; Sperling et al., 2006). Thus, we assumed that the same holds for newly transferred synesthesias. A simple Stroop task, used as in the present study, cannot be taken as a sufficient proof of new synesthesia. Non-synesthetes are also slower in naming colors unusual for a presented object (e.g. a blue lemon) (Elias, Saucier, Hardie, & Sarty, 2003; MacLeod & Dunbar, 1988; Nikolić et al., 2007). Thus, in synesthesia, a Stroop task contains two components of competition (or facilitation), one that occurs at the level of perception (due to synesthesia) and the other at the level of the semantic representation (due to non-synesthetic associations) (Nikolić et al., 2007). In the present study, we did not make this distinction. Therefore, it is unknown whether, for Glagolitic letters, the Stroop effect occurs due to synesthesia proper or due to semantic expectations. The finding that the subjects who did not report a subjective transfer exhibited a Stroop effect suggests that, as a minimum, a competition/facilitation at the semantic level occurs.

Direct evidence of transferred synesthesias from a third-person perspective would require additional experiments but proofs may be more difficult to obtain than is the case for the life-long synesthesias. The newly transferred associations are relatively weak and may thus require especially sensitive methods.

In the present study, we did not create novel synesthetic associations. Instead, only the existing ones were transferred. For creation of a truly new synesthesia, a new concurrent should be introduced, one not associated previously to another inducer. It is not known whether (or how) this would be possible to achieve in laboratory settings. For example, simple consistent shape–color pairings are not likely to create new synesthesias. Such pairings are frequent in everyday lives (e.g., a shape of a heart is associated only with red color) and synesthetes do not report such consistent matches to convert into synesthetic associations (at least not in the adulthood). The only possible exceptions are the temporary effects of hypnotic suggestions (Cohen Kadosh, Henik, Catena, Walsh, & Fuentes, 2009).

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