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Research report

Implicit versus explicit interference effects in a number-color synesthete

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ABSTRACT

A fundamental question in the study of consciousness is the connection between subjective report and objective measures. We explored this question by testing NM, a grapheme-color synesthete, who experiences colors when viewing digits but not dot patterns. Synesthesia research has traditionally used variants of the Stroop paradigm as an objective correlate of these subjective synesthetic reports. We used both a classical synesthetic Digit Stroop task and a novel Numerosity Stroop task, in which random dot patterns were colored either congruently or incongruently with the colors NM reported for digits. We observed longer response times in the incongruent condition for both tasks, despite the fact that NM denied experiencing colors for random dot patterns, constituting a clear dissociation between subjective and objective measures of synesthetic experience. We argue that distinguishing synesthesia from learned synesthesia-like associations (pseudosynesthesia) should depend primarily on the presence of subjective reports, validated by objective measures. More generally, we suggest that consciously and unconsciously mediated interference may arise from qualitatively different mechanisms.

1. Introduction

Synesthesia is a neurological condition in which sensory and cognitive processing automatically evokes additional experiences (concurrents) in the same or a different sensory modality (Galton, 1880). Although the exact mechanisms remain unclear, it is generally agreed that synesthesia is a consequence of unusual cerebral communication (Baron-Cohen et al., 1996; Grossenbacher and Lovelace, 2001; Hubbard and Ramachandran, 2005). Modified versions of the Stroop paradigm have been widely used to demonstrate the genuineness of synesthesia. In the traditional Stroop paradigm, a color name is presented in different ink colors (e.g., the word RED in red or green ink). Naming the ink color takes longer when it is different from the color word, demonstrating that reading is automatic and interferes with color naming (Stroop, 1935; for a review see MacLeod, 1991). The same logic has been adapted to test grapheme-color synesthetes who report perceiving colors (photisms) when viewing or thinking about letters and numbers (Wollen and Ruggiero, 1983). When the graphemes are incongruently colored relative to the synesthete's reported colors, reaction times (RTs) are slower for

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naming the ink color than when they are congruently colored (e.g., Mills et al., 1999; Dixon et al., 2000; Mattingley et al., 2001, 2006; Elias et al., 2003; Nikolic et al., 2007). This result is generally considered one of the strongest pieces of evidence for the authenticity of synesthesia, suggesting that synesthesia is an automatic and involuntary process (see e.g., Dixon et al., 2004; Mattingley et al., 2001) although this conclusion should be tempered given that some studies have demonstrated that Stroop-like interference is not limited to cases of explicit synesthetic experiences (Elias et al., 2003; Hancock, 2006).

However, synesthesia is not a unitary phenomenon, and may vary depending on whether the synesthetic concurrents are evoked at a perceptual or a conceptual level (Ramachandran and Hubbard, 2001; Hubbard and Ramachandran, 2005). The authors suggest two forms of synesthesia: ‘‘higher’’ synesthesia in which different stimuli sharing the same semantic meaning induce the same synesthetic experience, and ‘‘lower’’ synesthesia in which lower-level stimulus properties are essential for eliciting the experience. Ward and Sagiv (2007) tested a number-color synesthete, TD, who in addition to seeing colors for Arabic numerals reported colors when counting on his fingers and viewing dice patterns, which likely makes him a case of higher synesthesia. Using Stroop-like paradigms, the authors showed that TD’s synesthetic colors interfered with naming incongruently colored stimuli for digits, fingers and dice patterns. Incongruent colors also interfered when TD was asked to estimate the number of finger raised (the reverse of the standard task), suggesting that colors convey numerical information for TD. Based on these results, the authors conclude not only that TD’s synesthesia is elicited at a semantic level but also that it is a result of bi-directional links between colors and numbers. However, dice patterns and hand configurations of numerosities are not strictly comparable to random dot patterns given that they may be overlearned and accordingly be treated as familiar images rather than as pure numerosity stimuli.

In this study, we present a synesthete (NM) who reports colors for digits 1–9. Unlike TD, NM reports that he does not experience synesthetic colors when shown dice patterns or random dot configurations. Despite his reports that he did not experience subjective colors for these stimuli, we tested NM on two Stroop-like tasks. We used a Digit Stroop task to replicate previous findings and a novel variant of Ward and Sagiv’s (2007) Numerosity Stroop task where canonical (dice patterns) and non-canonical dot configurations were colored either congruently or incongruently with the color of the corresponding digit. Since digits elicit conscious experiences of color for NM, we predicted the same interference effects reported in previous studies. For the dice and non-canonical patterns, however, whether interference would be observed depends on the locus at which his synesthesia is elicited. If NM’s synesthesia depends on the perceptual configuration of the inducer, we would not predict any interference with dot patterns. However, if NM’s synesthesia is elicited at a semantic level, we would expect interference for the dot patterns. Moreover, since the dot patterns are not overtly associated with colors, we would predict that the interference will be smaller in this task than in the Digit Stroop task. The presence of such interference despite the absence of conscious synesthetic reports would also suggest that the connection between semantic stimuli and synesthetic experiences is triggered automatically.

2. Methods

2.1. *Participant*

At the time of testing, NM was a 29 year-old male finishing a PhD program. He reported grapheme-color synesthesia and number-forms for digits and week days. We assessed NM’s synesthesia with a broad self-report questionnaire and assessed the genuineness of his number-color associations for digits 0–9 with a test-retest procedure. Color selections for each number were recorded as RGB triplets (0–255 on each dimension). Five non-synesthetic controls also participated, and were instructed that they would be retested one week later, whereas NM was retested two months later without notice. We then calculated the mean city block distance between the two RGB triplets of each number chosen by each participant, and found that NM was less variable than the controls, scoring nearly two standard deviations (SDs) below the mean of the non-synesthetes [mean distance = .095 for NM and .533, SD = .247, for the controls; $t(4) = -1.62$, $p = .09$ one-tailed; corrected for single sample against a population; Crawford and Garthwaite, 2002]. Although this falls short of conventional significance levels, with only five controls we probably lack the statistical power to fully demonstrate NM’s superior performance. However, the fact that NM was nearly two SDs less variable than controls is certainly indicative of the consistency of his experiences. In order to further validate the consistency of NM’s experiences, we performed a second test by randomly presenting color pairs to external judges and asking them to rate the similarity (1 = completely different to 5 = completely similar) of the colors chosen at Time 1 and Time 2. The judges rated the colors NM selected across the two sessions as significantly more similar than those of control participants [NM mean = 4.57, controls mean = 3.05 and SD = .59; $t(4) = -2.343$, $p < .05$ one-tailed; Crawford and Garthwaite, 2002].

2.2. *Experimental procedures*

NM participated in two different tasks, a Digit Stroop and a Numerosity Stroop task in three experimental sessions. Each session began by asking NM to pick colors for the numbers 1–6 (NM’s associations: 1 – blue, 2 – red, 3 – green, 4 – brown, 5 – yellow and 6 – grey) to ensure that the stimulus colors closely matched NM’s photisms. In order to eliminate the possibility of carry-over effects from the Digit Stroop task, the Numerosity Stroop was run first although we describe the tasks in the opposite order for clarity.

2.2.1. *Digit Stroop task*

In order to replicate previous studies demonstrating synesthetic Stroop effects when Arabic digits are presented in colors inconsistent with those reported by the synesthetes (Wollen and Ruggiero, 1983; Mills et al., 1999; Odgaard et al., 1999; Dixon et al., 2000; Paulsen and Laeng, 2006; Hancock,

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2006), we presented NM with Arabic digits colored either congruently or incongruently with his reported photisms and asked him to verbally name the ink color as quickly and accurately as possible, while ignoring the identity of the digit (Fig. 1).

2.2.2. *Numerosity Stroop task*

To determine whether synesthetic Stroop effects generalize from Arabic numerals to semantic representations of number, we presented NM with dot patterns colored either congruently or incongruently with the photisms that he reported for the corresponding Arabic digit. These dot patterns were either canonical (dice) or non-canonical patterns (numerosities 1–6; Fig. 1). In order to minimize any potential learning effects for the non-canonical configurations, we constructed two different sets, non-canonical 1 (NC1) and non-canonical 2 (NC2) with the same surface area as the dice patterns.

2.2.3. *Baselines*

We also ran three baseline tasks: (1) A color naming baseline, which required naming the color of large disks, to control for any potential differences in color naming times. (2) An enumeration baseline, which required naming the number of black dots, to control for any possible familiarity effects of the dice patterns. Replicating previous work with non-canonical dot patterns, we expected to observe increasing RTs with numerosity (numerical size effect; Wolters et al., 1987) and faster RTs for numerosity 6 compared with numerosity 5 (end-effect) because the largest set has only one competitor whereas all others have two competitors (Van Oeffelen and Vos, 1982; Wolters et al., 1987). For the overlearned dice patterns, a flat RT curve was expected given that the configurations merely need to be recognized rather than enumerated (Wolters et al., 1987). (3) A digit naming baseline, which required naming black Arabic digits. Given that the simple digit naming task can be performed through the non-semantic pathway, we would not expect RTs to be influenced by numerical size, and thus digit naming times should not vary (Dehaene, 1992; Butterworth et al., 2001).

2.2.4. *General procedure*

A total of 240 trials were run for the Digit Stroop (20 trials each of 2 congruities × 6 numbers) and 720 total trials (20 trials each of 3 pattern types × 2 congruity conditions × 6 numerosities) for the Numerosity Stroop, divided into two sessions of 360 trials. Crucially, for the incongruent condition, in both the Numerosity and the Digit Stroop, the colors used were the colors associated with each of the other numbers (e.g., number/numerosity 1 was presented with the synesthetic colors corresponding to all the other numbers: 2, 3, 4, 5 and 6). Therefore, each congruent pairing (e.g., 1 in blue) was also presented with each of the five possible incongruent pairings (1 in red, green, brown, yellow and grey). Congruent stimuli were thus repeated 20 times and each incongruent stimulus was repeated four times, yielding 20 incongruent trials per number. This led to an equal number of presentations for each color in each congruity condition (numbers/numerosities 2, 3, 4, 5 and 6 were presented 4 times in blue). The baseline conditions consisted of 120 trials for color naming (6 colors × 20 presentations), 120 trials for digit naming (6 digits × 20 presentations) and 360 for dot enumeration (3 pattern types × 6 numerosities × 20 presentations).

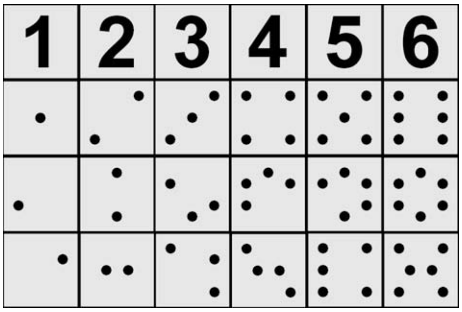

Fig. 1 – Stimuli used for the Digit and Numerosity Stroop tasks. The grey square of 6 cm and the digits or dots fit inside an area of 4.5 cm. The first row represents the digits, the second corresponds to the dice pattern and the following two are the NC1 and NC2 patterns, respectively.

The trial sequence was the same for all tasks: a central fixation cross was presented for 1000 msec after which the stimulus appeared until the voice key detected a response. The experimenter coded the accuracy of the answer and any possible voice key errors. Regular breaks were scheduled and the participant could also choose to rest between trials. The experiment was programmed using E-Prime 1.1 experimental software (Schneider et al., 2002a, 2002b) running on a Windows 2000 desktop computer. Stimuli were presented on a 17-inch screen (1024 × 768 resolution; 75 Hz refresh rate). Digits and dots covered an area of 4.5 cm (2.6°) inside a 6 cm (3.4°) grey square on a black background, with NM being seated 1 meter from the screen. As can be seen in Fig. 1, the digit stimuli and the dot patterns covered roughly the same area, meaning that individual digits were larger than the individual dots.

3. Results

3.1. *Overall Numerosity and Digit Stroop tasks*

Overall accuracy, collapsed across tasks, was 98.3% for congruent trials and 95.4% for incongruent trials. After errors and voice key detection errors were excluded (3.1% of trials), naming latencies exceeding two standard deviations from the mean per condition were eliminated (4.9% of the remaining trials). For the two Stroop tasks, an overall ANOVA was run on mean RTs, with stimulus type (digits, dice pattern, NC1 and NC2), congruency (congruent or incongruent ink color) and numerical value (1–6) as factors. As the NC2 patterns were enumerated more quickly than the NC1 patterns in our baseline enumeration task (see below), we chose to keep these factors separate in all subsequent analyses. All post-hoc comparisons were Bonferroni corrected.

Fig. 2 shows the mean RTs for each of the four stimulus types as a function of congruency. RTs were significantly faster in the congruent condition than in the incongruent condition leading to a main effect of congruency across both tasks [$F(1, 834) = 190$, $p < .001$, $\eta^2 = .084$]. This result replicates and extends previous research on digit and dot patterns

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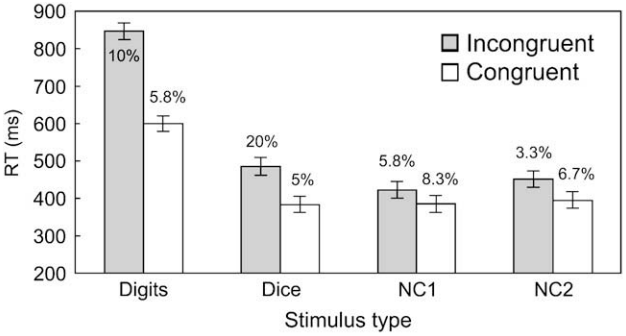

Fig. 2 – Mean RTs, two SDs and percentage of errors as a function of congruency across type of stimuli. Shaded bars represent the incongruent condition, while the white bars represent the congruent condition.

demonstrating a synesthetic Stroop effect when ink colors are incongruent with reported photism colors. Mean RTs were 441 msec (SD = 121 msec) in the congruent condition and 549 msec (SD = 228 msec) in the incongruent condition. In addition, the main effect of stimulus type was significant [F(3, 834) = 358, $p < .001$, $\eta^2 = .474$], with RTs to digits being slower than all three dot patterns (all $ps < .001$, post-hoc) and dice patterns being significantly slower than the NC1 pattern ($p < .05$, post-hoc). Mean RTs (collapsed across congruency) were 718 msec (SD = 197 msec) for digits, 430 msec (SD = 94 msec) for the dice pattern, 404 msec (SD = 105 msec) for the NC1 pattern and 424 msec (SD = 131 msec) for the NC2 pattern.

Our finding of longer RTs for digits than for dot patterns was surprising given that the digits should have been, if anything, more discriminable than the dot patterns, and that digits typically are named faster than dot patterns (e.g., Bourdon, 1908; Roelofs, 2006). Additionally, as the digit condition was run last, any practice effects should have led to shorter RTs for the digits than for the other stimulus types. We suggest, rather, that the overall slowing for digits was due to the fact that NM consciously experienced synesthetic colors for the digits, but not for the dots. This conscious interference may therefore have led NM to exert greater cognitive control while performing the digit task compared with the dot tasks. Increased cognitive control has been consistently shown to increase mean RTs both in non-synesthetes (Gratton et al., 1992; Ridderinkhof, 2002) and in conflict tasks with synesthetes (Gray, 2002; Lupiáñez and Callejas, 2006), although this is rarely remarked on in the synesthesia literature. As congruent and incongruent stimuli were randomly presented in the same block, cognitive control would have affected RTs for both congruent and incongruent stimuli. Consistent with this interpretation NM spontaneously reported that color naming was more difficult for incongruent digits than for the incongruent dots, and that he had to concentrate more to avoid errors with the digits than the other stimulus types (which had been tested prior to the digit condition). Moreover, consistent with our suggestion that slower naming latencies for digits reflect greater cognitive control, error rates were higher for dice patterns than for digits. Previous studies have suggested that cognitive control is only engaged when conflict is conscious (Tsushima et al., 2006), and here in the absence of enhanced cognitive control, NM's responses would be expected to be faster, but error rates would be expected to be correspondingly higher.

We also found a significant stimulus type × congruency interaction with digits and dice patterns showing greater interference than the two non-canonical patterns suggesting that the congruency effect is modulated by stimulus type [F(3, 834) = 35, $p < .001$, $\eta^2 = .05$; digits: 247 msec, dice patterns: 102 msec, NC1: 38 msec and NC2: 58 msec]. Most importantly, the synesthetic Stroop effect was significant for all four stimulus types (all $ps < .01$), demonstrating the presence of a synesthetic Stroop effect for each of the stimulus configurations despite the fact that NM denied experiencing colors for dot patterns. Finally, we found a significant stimulus type × congruency × numerical value interaction [F(15, 834) = 2.09, $p < .01$, $\eta^2 = .014$]. Separate analyses for each stimulus type showed that the congruency × numerosity interaction was significant only for dice and NC2 patterns ($p = .028$ and $p = .015$, respectively).

Although the analysis of variance is a very robust statistical method, running it on a single case violates basic assumptions of data independency (Basso et al., 2006, 2007). We thus compared a simplified ANOVA (with congruency and stimulus type as factors) with a permutation test analysis (10,000 permutations) to provide independent verification of the observed congruency and stimulus type effects. Since only a limited number of factors may be introduced in a permutation analysis we focused our permutation analysis on those factors that yielded the smallest effects in our ANOVA; thus the demonstration of a significant effect in the permutation analysis allows us to conclude that larger effects would also be significant if we were to test them with the permutation analysis. Both the permutation analysis and the ANOVA yielded substantially similar results, with both main effects and the interaction being significant at $p < .005$, confirming the robustness of observed effects.

3.2. *Numerosity influence*

In order to more thoroughly explore the effects of numerosity, we ran a second ANOVA on the Numerosity Stroop task only, with numerosities subdivided in two ranges: small (1–3) and large (4–6). Smaller numerosities (usually up to 3) are processed faster and with greater accuracy compared to larger ones, a process known as subitizing (Mandler, 1982; Trick and Pylyshyn, 1994). Overall mean RTs were faster in the congruent condition (388, SD = 85 msec) than in the incongruent condition (451, SD = 126 msec); [F(1, 649) = 62, $p < .001$, $\eta^2 = .08$]. In addition, mean RTs were faster for the dice patterns than for the two non-canonical patterns [F(2, 649) = 4.74, $p < .01$, $\eta^2 = .013$]. As in the overall ANOVA, the stimulus type × congruency interaction was significant [F(2, 649) = 5.25, $p < .01$, $\eta^2 = .014$] with the synesthetic Stroop effect being stronger in the dice condition than in the other two conditions. Finally the interference was stronger for smaller numerosities than for larger numerosities (90 msec and 36 msec, respectively) yielding a significant congruency × range interaction [F(5, 649) = 9.76, $p < .005$, $\eta^2 = .013$;

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Fig. 3]. In separate analyses for both ranges, congruency remained significant (both *ps* $< .001$).

These results provide two arguments in favor of a semantic interpretation of NM's experiences. First, the slower RTs observed in all four incongruent conditions demonstrate that the interference occurred independently of notation, a hallmark of semantic processing. Second, the finding that smaller numbers elicited stronger effects indicates that the concurrents are elicited at a semantic level, since small numerosities are processed faster and with greater accuracy than larger numbers (Mandler, 1982; Trick and Pylyshyn, 1994) which would thus elicit the synesthetic color faster, and lead to correspondingly greater interference with the physically presented color.

3.3. *Baseline tasks*

3.3.1. *Enumeration baseline*

Since dice patterns are overlearned, and are therefore likely to be processed differently than non-canonical patterns, we asked NM to enumerate black versions of the dice, NC1 and NC2 patterns used in the main experiment. This baseline task also allowed us to test for any possible learning effects on the non-canonical configurations. An ANOVA for the enumeration baseline was run introducing stimulus type (dice, NC1, NC2) and numerosity (1–6) as factors. As expected, RTs were longer for larger numerosities [$F(5, 325) = 108$, $p < .001$, $\eta^2 = .477$; Fig. 4]. We also found a main effect of stimulus type [$F(2, 325) = 83$, $p < .001$, $\eta^2 = .147$], with the dice patterns being enumerated faster than both non-canonical patterns, and the NC2 patterns being enumerated faster than NC1 patterns (all *ps* $< .05$, post-hoc). The increase in RTs as a function of numerosity was only observed for the NC1 and NC2 patterns since RTs for the dice patterns, as expected, were constant for all numerosities, yielding a significant stimulus type × numerosity interaction [$F(10, 325) = 10$, $p < .001$, $\eta^2 = .09$]. This difference indicates that the non-canonical configurations were indeed unfamiliar to NM and could have not been previously associated with colors in long term memory.

To control for repeated exposure to the dot patterns during the experiment, a second ANOVA on enumeration RTs was run including session (first or second) as a factor. In addition to the previous main effects, the main effect of session was significant [$F(1, 307) = 10$, $p < .01$, $\eta^2 = .008$] indicating that NM was faster during the second session [session 1: 346 (98) msec; session 2: 331 (98) msec]. However, none of the interactions with session as a factor approached significance ($p > .1$). Separate analyses confirmed the presence of a significant stimulus type × numerosity interaction in both sessions (both *ps* $< .001$, $\eta^2 = .09$ and .11). Taken together, the findings that enumeration of both non-canonical patterns was significantly slower than for dice patterns and that they did not become overlearned during the experimental sessions strengthens the argument that our results are not simply due to an association between particular patterns and colors. Rather these results suggest that synesthetic interference generalizes to other numerically based stimuli (at least for NM), including novel dot patterns, further arguing for a semantic locus for the observed effects.

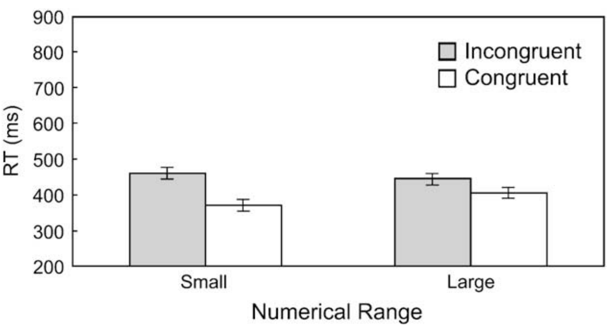

Fig. 3 – Mean RTs and two SDs as a function of congruency across the numerical range. The shaded bars represent the incongruent condition, while the white bars represent the congruent condition.

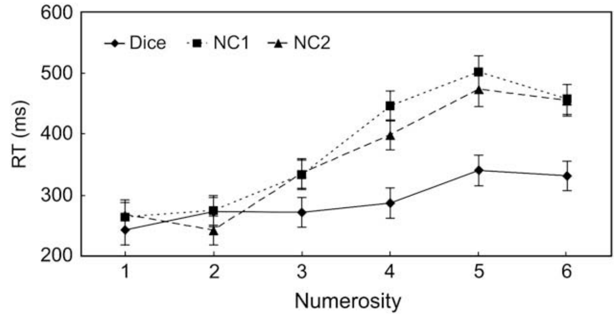

Fig. 4 – Mean RTs and two SDs for the six numerosities for each of the three dot configurations (dice, NC1 and NC2). Diamonds represent the dice patterns, squares represent the NC1 patterns, and triangles the NC2 patterns. Error bars represent two SDs from the mean.

3.3.2. *Color naming baseline*

To test for the presence of differences in naming times for each color, we tested NM in a color naming baseline. We found a significant main effect of color [$F(5, 223) = 6.934$, $p < .01$, $\eta^2 = .134$], with brown and grey being slower to name than the other colors (all *ps* $< .05$, post-hoc). It seems unlikely that the interference effects obtained in the Stroop tasks were mediated by the slower RTs to these colors, given that we presented all of the stimuli in every other color. However, to rule out this possibility, we performed an ANOVA with mean naming time for each color (according to each experimental session) as a covariate. The covariate did not reach significance ($p = .623$) whereas the congruency and stimulus type effects were still significant [$F(1, 833) = 190$, $p < .001$, $\eta^2 = .10$ and $F(3, 833) = 266$, $p < .001$, $\eta^2 = .40$]. Moreover, the interactions also remained significant: congruency × stimulus type [$F(3, 833) = 35$, $p < .001, \eta^2 = .05$] and congruency × stimulus type × number [$F(15, 833) = 2.09$, $p < .01$, $\eta^2 = .02$]. These results rule out the possibility that the interference effects were contaminated by differences in color naming times.

4. Discussion

We tested a grapheme-color synesthete for whom digits, but not dot patterns, elicited the subjective experience of colors.

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Our results demonstrate Stroop-like interference for incongruently colored stimuli both when NM performed a Digit Stroop task and when he performed a Numerosity Stroop task with dice and non-canonical patterns, despite the fact that he denies any conscious experiences of color for dot patterns. Moreover, both interference and facilitation were stronger for the smaller numerosities than for larger ones. These results suggest that NM may be a "higher" synesthete for whom the associations are explicit for digits but implicit for other numerical stimuli. These results differ from those of Ward and Sagiv (2007) even though both studies suggest the same synesthetic locus of induction. Their synesthetic participant, TD, explicitly reported colors for digits, fingers and dice patterns, but not for random dot patterns. Consistent with his reported experiences, TD demonstrated interference for digits, fingers and dice patterns, but not for random dot patterns, resulting in a tight correspondence between subjective experience and objective measures. In contrast, we find a synesthetic Stroop effect even with non-canonical dot patterns, demonstrating a dissociation between these measures in the case of dot patterns.

Cohen Kadosh and colleagues have argued that the interference due to higher synesthesia can be bi-directional, even though conscious reports of synesthetic experiences are almost universally uni-directional (Cohen Kadosh et al., 2005, 2008; Cohen Kadosh and Henik, 2006a, 2006b). They showed that when their synesthetes, MM and AD, made judgments on which of two numbers was larger, the magnitude of the distance effect was influenced by the ink colors (Cohen Kadosh et al., 2005). They subsequently showed that color can influence the judgment of physical magnitudes when geometrical shapes were presented with the colors of the photisms associated with numbers (Cohen Kadosh and Henik, 2006a, 2006b). In an attempt to rule out a possible learning-based account of their findings, Cohen Kadosh et al. (2005) trained non-synesthetic participants in five one-hour sessions to associate numbers with colors. However, it is clear that 5 h of training cannot mimic a lifetime of synesthetic experiences.

Although these results have been taken as evidence for an implicit bi-directional association between colors and digits, we argue that such conclusions are premature. Based on our own results in a uni-directional paradigm, we have shown that, despite the absence of overt color report for dice and non-canonical patterns, NM was slower for those stimuli when they were colored incongruently with his corresponding digit photisms.

Given the presence of both implicit uni- and bi-directional interference effects in synesthesia, some account of how such interference arises must be given. One possibility is that such implicit effects in synesthesia are due to neural connections between color and numerical representations, which are strong enough to lead to behavioral interference, but not strong enough to elicit a conscious experience (Hubbard and Ramachandran, 2005; Cohen Kadosh and Henik, 2007). This view therefore suggests that bi-directional and implicit effects are intrinsic to the synesthetic phenomena. However, another possibility, which has not been sufficiently considered, is that these interference effects are secondary cognitive consequences of the primary synesthetic connections, which do lead to conscious experiences (see Fig. 5). That is, implicit effects are not a direct consequence of synesthesia *per se* (implicit synesthesia), but rather are secondary consequences of a lifetime of associations between digits, colors and numerical magnitudes (pseudosynesthesia). We suggest that the latter name should be used to refer to these secondary associative consequences as pseudosynesthesia emphasizes that these effects mimic synesthesia, without being actual synesthesia, and retains the use of synesthesia as an unusual conscious experience, unlike implicit synesthesia which is, in fact, a contradiction in terms. That is, pseudosynesthesia would be instantiated by neural connections appearing long after the onset of the primary synesthetic associations, and through different associations than those resulting from primary synesthesia.

Neuroimaging and neuroanatomical methods suggest that the primary linkage in grapheme-color synesthesia is due to cross-activation between graphemic representations and color representations in the fusiform gyrus (Hubbard and Ramachandran, 2005; Rouw and Scholte, 2007). Accordingly, each time a number-color synesthete looks at a digit, he or she also automatically experiences a color and simultaneously activates the numerical magnitude associated with that digit. Because of the constant association between magnitudes and colors, the two may become associated within a broader cognitive system, despite the absence of conscious links between them (for a similar line of reasoning, see Simner and Hubbard, 2006). Both functional magnetic resonance imaging (fMRI) adataptation in humans (Piazza et al., 2007) and single-unit recordings in monkeys (Diester and Nieder, 2007) have demonstrated that numerosity stimuli (dot patterns) and Arabic digits map onto the same neurons in parietal and prefrontal cortices. In this manner, spreading activation

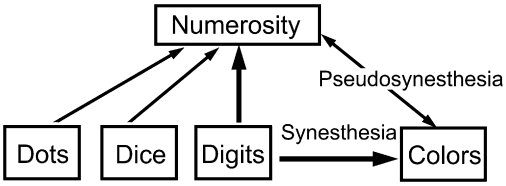

Fig. 5 – Schematic representation of synesthetic and pseudosynesthetic connections between areas for NM. Bold arrows indicate the direct pathway between Arabic numerals and numerosity processing and primary synesthetic links between Arabic numerals and colors. Thinner arrows from dice and dot patterns to numerosity indicate other pathways to access numerosity information that do not directly elicit synesthesia, while the double-headed arrow indicates secondary pseudosynesthetic associations between numerical information and colors. The latter arrow corresponds to the secondary link caused by a lifetime of repeated simultaneous activations of digits and colors. This connection is responsible for the Stroop effect when NM processes numerical information in different formats than digits although it does not yield an explicit synesthetic perception. Moreover, the connection also goes from color to numerosity indicating the possibility that color activates the corresponding number (bi-directional effects).

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within the semantic network may account for the presence of color interference for dot patterns, and similarly, for the findings of implicit bi-directionality reported in previous studies.

In order to distinguish between conscious synesthetic reports and non-conscious associations that may develop with repeated associative learning (i.e., bi-directional or implicit effects), we suggest that the latter be referred to as pseudosynesthesia, indicating the fact that they mimic synesthesia without giving rise to conscious experiences, one of the defining features of synesthesia (see Fig. 5). It is therefore important to differentiate between primary synesthetic connections, which through some combination of genetic factors and learning lead to additional conscious experiences, from secondary semantic links that arise due to the consistent experience of color each time a digit is seen. Higher synesthesia would therefore be distinguished from pseudosynesthesia because it would generate an explicit secondary perception and would be the consequence of primary connections between brain areas.

Consistent with this distinction, Elias et al. (2003) compared a single synesthete with a non-synesthete with eight years of experience in cross-stitching, for whom colored threads were associated to digits. Despite the fact that the cross-stitcher denied any conscious color experience in response to digits, he demonstrated as much interference as the synesthete. This suggests that individuals who learn number-color associations over a sufficiently long period of time may be subject to synesthetic Stroop-like interference, despite the fact that they are not synesthetic. Similarly, 5 h of training on a task that required naming geometric shapes using color words was sufficient to create an interference effect while performing a Stroop type task with colored shapes (MacLeod and Dunbar, 1988). After 20 h of practice, one participant even claimed that the white shapes began to take on the colors of their associated color names, suggesting that very extensive training may mimic synesthetic associations in particular individuals.

A similar associative learning explanation could account for findings of a mathematical Stroop effect in synesthetes (Dixon et al., 2000; Jansari et al., 2006). Models of arithmetic fact retrieval suggest that performing simple arithmetic problems activates a rich network of associations that includes preferential links between numbers that are consistently paired (Campbell, 1994; Campbell et al., 2004). We suggest that every time a synesthete retrieves a given arithmetic problem, viewing or thinking of digits will also elicit the relevant colors, creating a link not only between the operands and the results, but also for the appropriate sequence of colors, which would then prime the naming of the color appropriate for the answer to the problem, even if the color was not consciously experienced. This suggestion is supported by the finding of a mathematical Stroop effect in Elias et al.'s cross-stitcher (Elias et al., 2003).

These considerations highlight that Stroop tasks, when used as objective markers for synesthesia *in the absence of corresponding subjective reports*, must be treated with caution (for a related argument see Smilek and Dixon, 2002). Stroop-like paradigms have been highly useful as a method of validating subjective reports, but we question their application in the absence of subjective reports, given that the entire cognitive system will be modified by synesthetic experience. In the absence of developmental studies of synesthesia, it is difficult to disentangle primary, direct consequences of synesthesia, from secondary adaptations to a lifetime of altered sensory experience. Results obtained with Stroop paradigms only demonstrate the presence of an association, which could be either synesthetic or pseudosynesthetic.

In sum, we stress that identifying synesthesia traditionally depends on a conscious experience in the second non-stimulated modality. We suggest that in the quest for understanding synesthesia, reports of additional sensations should be explicit, since it is only then that we can distinguish between synesthetic phenomena and overlearned associations. More generally, we argue that studies of unusual experiences should depend on not only objective measures, but also on subjective report, especially given that explicit and implicit processing may yield qualitatively different effects (Cheesman and Merikle, 1986) and may even arise from qualitatively different mechanisms.

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