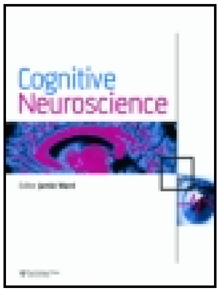

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Synesthetic experiences enhance unconscious learning

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Synesthesia is characterized by consistent extra perceptual experiences in response to normal sensory input. Recent studies provide evidence for a specific profile of enhanced memory performance in synesthesia, but focus exclusively on explicit memory paradigms for which the learned content is consciously accessible. In this study, for the first time, we demonstrate with an implicit memory paradigm that synesthetic experiences also enhance memory performance relating to unconscious knowledge.

Keywords: Synesthesia; Implicit memory; Artificial grammar learning.

Synesthesia is associated with fundamental differences in the perceptual system functionally and structurally (e.g., Hubbard & Ramachandran, 2005; Rouw & Scholte, 2007; but see, Hupé, Bordier, & Dojat, 2012). For people with grapheme-color synesthesia, the neurological condition leads to color experiences for letters and numbers printed in black on a white background (Ward, 2013). Recent group studies provide compelling evidence for a specific profile of enhanced memory performance in grapheme-color synesthetes tested by the means of explicit memory tasks (Gibson, Radvansky, Johnson, & McNerney, 2012; Radvansky, Gibson, & McNerney, 2011; Rothen & Meier, 2010; Yaro & Ward, 2007). Similarly, enhanced "explicit" memory abilities have been reported for both visuo-spatial working memory and for real-life events in groups of sequence-space synesthetes who experience sequence-based concepts such as the days of the week in spatial arrangements (Brang, Teuscher, Ramachandran, & Coulson, 2010; Simner, Mayo, & Spiller, 2009; but see, Brang, Miller, McQuire, Ramachandran, & Coulson, in press). Crucially, empirical evidence for synesthesia to aid mnemonic abilities is entirely limited to performance for *conscious* knowledge accessible via conscious phenomenological report (Rothen, Meier, & Ward, 2012). In this study we demonstrate by the means of an implicit learning paradigm that synesthetic experiences can also enhance performance for *unconscious* knowledge not accessible via conscious phenomenological report.

We developed a new "bilingual" artificial grammar learning (bAGL) paradigm (cf. Reber, 1967). Bilingual because, during the learning phase, two distinct sets of rules (i.e., grammars) were used to create letter and symbol strings that were presented one at a time in random order. Participants were instructed to try to memorize the strings. In the subsequent testing phase, participants were presented with new letter and symbol strings of which each

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category followed either the same grammar as in the learning phase or one of two new distinct grammars. Participants had to judge if the letter and symbol strings were "grammatical" (i.e., followed their respective grammar from the learning phase) or "ungrammatical" (i.e., followed the new grammars). After every grammaticality judgment, participants indicated if their response was based on guessing, familiarity, intuition, rules, or memory; the first three categories operationalize unconscious structural knowledge and the last two operationalize conscious structural knowledge (Scott & Dienes, 2008). Reliable discrimination indicates the presence of structural knowledge (e.g., whether X can or cannot follow T) while the conscious-unconscious distinction indicates whether such knowledge is consciously accessible or remains implicit as, for instance, in intuitive judgments.

We conducted two experiments. Experiment 1 was to assess the impact of the perceptual profile associated with grapheme-color synesthesia on structural knowledge acquisition when the stimuli elicit (i.e., letters) and when the stimuli do not elicit (i.e., symbols) synesthetic color experiences. Employing the same paradigm as in the first experiment, Experiment 2 assessed the impact of the perceptual profile associated with sequence-space synesthesia, because the consistent experience of spatial arrangements in response to sequence-based concepts may provide a performance advantage for structural knowledge about letters or symbols in a string.

EXPERIMENT 1: GRAPHEME-COLOUR SYNESTHESIA

METHODS

Participants

We tested 52 participants. Twenty-six participants were grapheme-color synesthetes: 21 females and five males, mean age = 25.92 (*SD* = 8.50), range 18–50 years. Genuineness of synesthetic experiences was verified by the means of a test of consistency (Eagleman, Kagan, Nelson, Sagaram, & Sarma, 2007) and the according cut-off score of 1.43 (from Rothen, Seth, Witzel, & Ward, 2013). The grapheme-color synesthetes had an average consistency score of.74 (*SD* = .25), range .30–1.33. Synesthetes also provided additional phenomenological reports of their experiences to confirm their genuineness. Twenty-six controls were individually matched in terms of sex, age, and achieved level of education (+/- one level): 21 females and five males, mean age = 26.31 (*SD* = 9.17), range 19–56 years. A pre-test interview confirmed that none of the controls had synesthetic experiences. The study was approved by the local ethics committee of the University of Sussex.

Material

We used four finite state grammars to create the letter strings and symbol strings, respectively. Two grammars have been used previously (Reber, 1967) and two were created for the purpose of this experiment (see Figure 1 for the grammar structures). All grammars consisted of the same set of letters (M, T, V, R, X) or symbols (~, >, ?, &, ≠), respectively. However, where necessary, symbols were replaced on an individual basis in order *not* to elicit synesthetic experiences and the same symbols were used for the matched controls. All grammars contained the same set of valid starting bigrams and final letters. The learning phase contained 30 different strings from two different grammars, 15 were letter strings based on one grammar and 15 were symbol strings based on the other grammar. The test phase contained a new set of a total of 120 different strings from all four different grammars. Sixty strings were letter strings of which 30 were based on the grammar that applied to the letter strings during the learning phase, the other 30 letter strings were based on one of the alternative grammars that was not employed during the learning phase. Another sixty strings were symbol strings of which 30 were based on the grammar that applied to the symbol strings during the learning phase, the other 30 symbol strings were based on the remaining alternative grammar that was not employed during the learning phase. All strings were five to nine characters in length. The strings were selected such that number of strings of each length was consistent between the different grammars for each phase of the experiment.

Procedure

Participants were naïve as to the purpose of the experiment, tested individually, and supervised for the duration of the experiment. In the learning phase letter and symbol strings were presented one at a time in random order. They were located at the center of the screen appearing in black against a white background at a viewing distance of approximately 60 cm. Participants were presented with 90 strings, 30 different strings three times each. Strings were presented for 5 s to be memorized and to be written down

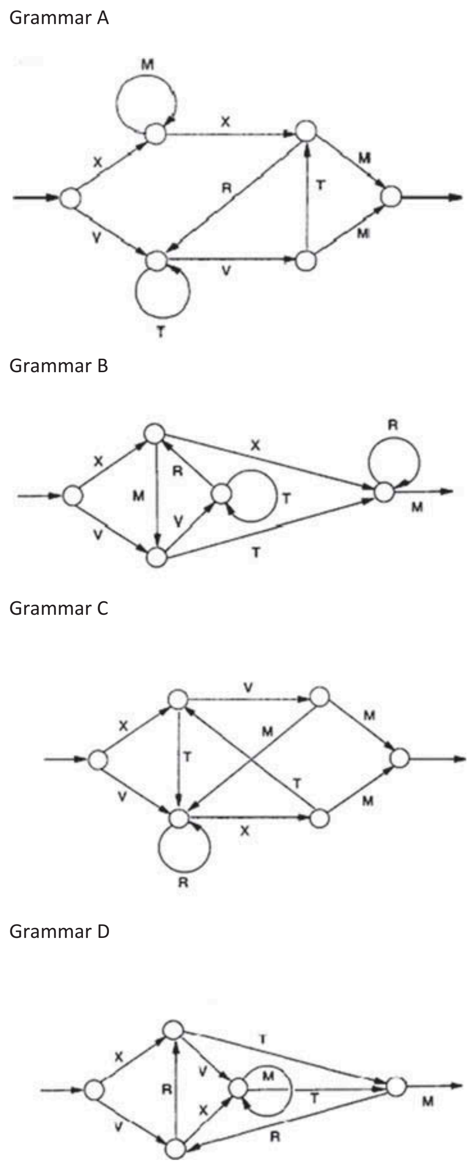

Figure 1. Artificial grammar structures exemplified with letters. For grammar A, VTVTRVM would be a grammatical string, VTVTTVM would be an ungrammatical string.

during the presentation of a blank screen that followed immediately for an additional 5 s. Importantly, participants were only permitted to write whilst the screen was blank. When the learning phase was complete participants were informed that the order of the letters and symbols in the memorized sequences had both independently followed complex sets of rules. They were then notified that they would be required to classify a new set of letter and symbol strings where half of each would conform to the same rules as in the learning phase and half would not. For each test-string participants were required to indicate (1) how familiar the string felt by entering a number from 0–100 (i.e., where 0 indicates not at all familiar and 100 completely familiar); (2) if the string was grammatical or ungrammatical (i.e., whether the string conformed or did not conform to the rules from the learning phase); (3) how confident they were in their grammaticality judgment from 50–100 (i.e., where 50 indicates no confidence and 100 complete certainty); and (4) whether the grammaticality judgment was based on guessing, a feeling of familiarity, intuition, rules, or memory (i.e., knowledge attribution). The response requirements were shown one at a time in the same order as specified above and each string remained on the screen until all responses had been made. Our primary focus relates to the accuracy of grammaticality judgments and the subjective awareness of the knowledge source used to make them (i.e., the knowledge attributions). Hence, we restrict our report to these variables.

The grammars used for symbol and letter strings were counterbalanced; the grammatical strings for half the participants were the ungrammatical strings for the other half. In addition, the pair of grammars used to construct symbol strings for one half was used to construct the letter strings for the other. Thus analysis collapsing across participants was fully counterbalanced.

Analysis

Task performance based on grammaticality judgments was measured as *d'* (i.e., a signal detection measure expressing performance as signal to noise ratio in standard deviation units. In simple words, *d'* indicates the standardized hit rate minus the standardized false alarm rate). Hit rates of 100% and false alarm rates 0% were corrected by subtracting half a hit or adding half a false alarm, respectively (Macmillan & Creelman, 2005). Response criterion on grammaticality judgments was measured as *C*, considering normalized hit rates and normalized false alarm rates, in order to express a participant's tendency to judge strings as grammatical/ungrammatical irrespective of their actual grammaticality. Thereby, negative values indicate a tendency to judge strings as grammatical (i.e., liberal criterion), positive values indicate a tendency to judge strings as ungrammatical (i.e., conservative criterion), and zero indicates the absence of such a response bias. A first analysis considered all responses irrespective of knowledge attribution. In case of a significant effect associated with synesthesia, two follow-up analyses were conducted. The first follow-up analysis focused on *unconscious* structural knowledge (i.e., grammaticality judgments accompanied by guess, familiarity, or intuition attributions). The second follow-up analysis focused on *conscious* structural knowledge (i.e., grammaticality judgments accompanied by rules or memory attributions). For the follow-up analyses, participants with less than four responses in one or several stimulus categories (letter-grammatical, letter-ungrammatical, symbol-grammatical, and symbol-ungrammatical) were excluded. The alpha level was set to .05 for all statistical analyses and *t*-tests were two-tailed.

RESULTS AND DISCUSSION

The results indicating average performance and average response criterion for grapheme-color synesthetes versus controls are shown in Figure 2. Performance was significantly above chance (all ts > 3.75, all ps < .01, all ds > 1.66) in both groups for letter and symbol strings irrespective of the status of structural knowledge (i.e., overall, unconscious, or conscious). The findings demonstrate participants' ability to reliably discriminate between grammatical and ungrammatical strings, even when two different grammars were learned simultaneously in the same learning phase (i.e., bAGL), and furthermore, that discrimination can be achieved in both the presence and absence of conscious structural knowledge. For performance on structural knowledge overall, a mixed two-factorial analysis of variance (ANOVA) with Group (synesthetes vs. controls) as between-subjects factor and String (letter strings vs. symbol strings) as within-subjects factor revealed a significant Group × String interaction ($F(1, 50) = 4.20$, $p < .05$, partial $\eta^2 = .08$), but no significant main effects (all Fs < 1.25, ps > .27, all partial η^2s < .03). The interaction was due to grapheme-color synesthetes significantly outperforming controls on letter strings ($t(50) = 2.21$, $p < .05$, Cohen's $d = .62$), but not on symbol strings ($t(50) = .36$, $p = .72$, Cohen's $d = .10$), consistent with an advantage

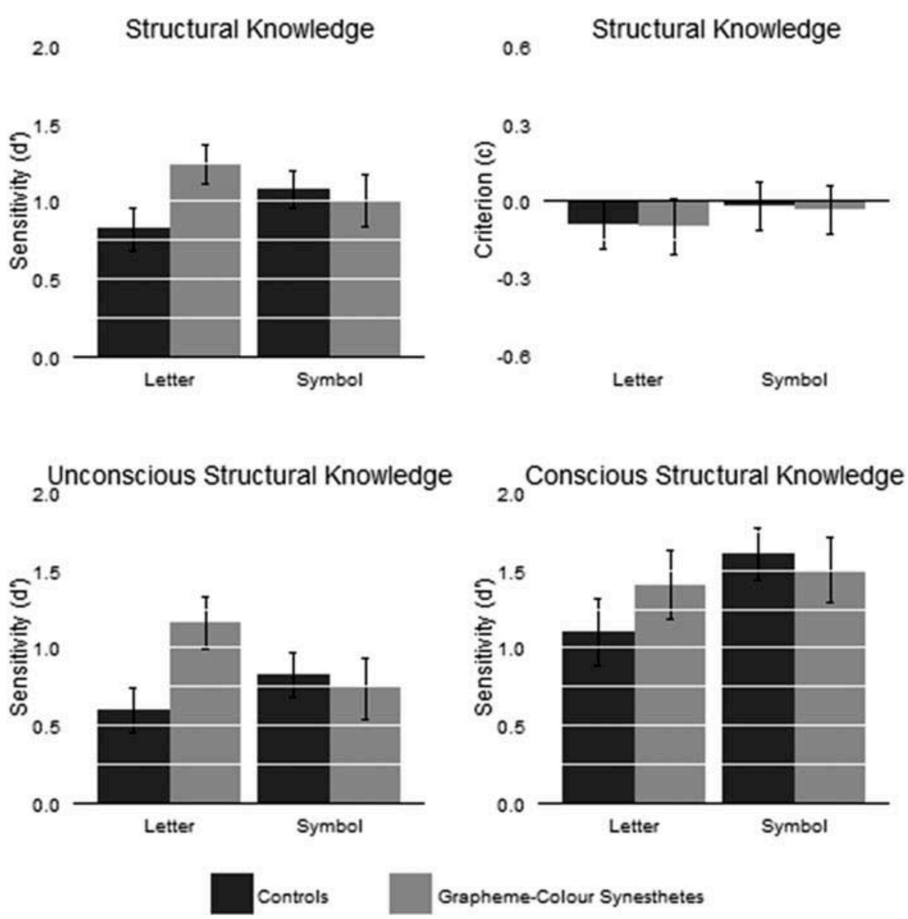

Figure 2. Average performance and average response criterion for grapheme-color synesthetes versus controls. Error bars represent standard errors of the mean.

derived from synesthetic experience. Notably, in both groups for letter and symbol strings the response criterion was not significantly different from zero (all *t*s < .973, all *p*s > .34, all Cohen's *d*s < .29). The same 2 × 2 ANOVA on criterion revealed neither a significant interaction nor any significant main effects (all *F*s < .65, all *p*s > .42, all partial η^2s < .02).

Crucially, the effects on performance were driven by unconscious structural knowledge, conducting the same 2 × 2 ANOVA on performance for unconscious structural knowledge revealed a significant Group (synesthetes *N* = 17; controls *N* = 22) × String interaction ($F(1, 37) = 5.10$, $p < .05$, partial $\eta^2 = .12$), but no significant main effects (all *F*s < 1.84, all *p*s > .18, all partial η^2s = .05). This was again due to grapheme-color synesthetes significantly outperforming controls on letter strings ($t(37) = 2.57$, $p < .05$, $d = .85$), but not symbol strings ($t(37) = .37$, $p = .72$, Cohen's $d = .12$). Although the pattern of the results was the same, repeating the 2 × 2 ANOVA (synesthetes *N* = 19; controls *N* = 18) on performance for conscious structural knowledge revealed neither a significant interaction nor significant main effects (all *F*s < 2.49, all *p*s > .12, all partial η^2s < .07).

EXPERIMENT 2: SEQUENCES-SPACE SYNESTHESIA

METHODS

Participants

We tested 28 participants . Fourteen participants were sequence-space synesthetes: nine female and five male, mean age = 32.64 (*SD* = 16.13), range 18–65 years. Genuineness of synesthetic experiences was verified by the means of an adapted version of the test of consistency (cf. below). The sequence-space synesthetes had an average consistency score of 187 (*SD* = 86) which differed significantly from the average 417 (*SD* = 327) of a previously tested sample of 26 non-synesthetes controls (unpublished; $t(38) = 3.37$, $p < .01$, Cohen's $d = .87$). As measured by the test of consistency, 13 synesthetes experienced spatial forms for days, all experienced spatial forms for months, and 10 experienced spatial forms for numbers. The average number of these spatial forms experienced by any given synesthetes was 2.64 (*SD* = .50). Each of the synesthetes experienced at least two types of spatial forms. Synesthetes also provided additional phenomenological reports of their experiences to confirm their genuineness. Fourteen controls were individually matched in terms of sex, age, and achieved level of education (+/- one level): nine female and five male, mean age = 31.93 (*SD* = 16.46), range 19–63 years. A pre-test interview confirmed that none of the controls had synesthetic experiences. The study was approved by the local ethics committee of the University of Sussex.

Material, procedure, and analysis of the bAGL paradigm were identical to Experiment 1. Notably, none of the participants had been tested in Experiment 1. For the test of consistency numbers (digits 0–9), days (*N* = 7) and month (*N* = 12) stimuli were presented at the center on a laptop screen (with resolution set to 768×1024) in random order three times each. We did not ask about the presence of other kinds of spatial forms. Participants were instructed to use the screen as a reference frame for their mental number lines and to indicate via mouse-click where each presented stimulus would be located. Participants were required to press the space bar for stimuli which did not elicit a synesthetic experience. Consistency was assessed as the mean Euclidean distance in 2D space (as it was done in 3D color-space in Rothen, Seth, et al., 2013).

RESULTS AND DISCUSSION

The results indicating average performance and average response criterion for sequence-space synesthetes versus controls are shown in Figure 3. Performance was significantly above chance in both groups for letter and symbol strings (all *t*s > 3.67, all *p*s < .01, all Cohen's *d*s > 1.43). This finding is consistent with Experiment 1, demonstrating reliable "bilingual" AGL. Conducting the same 2 × 2 ANOVAs as for Experiment 1, the results indicated similar performance between groups and for letter and symbol strings by the absence of any effects (all *F*s < .34, all *p*s > .57, all partial η^2s < .02). Similarly unbiased responses (one-sample *t*-test against zero; all *t*s < 1.96, all *p*s > .07, all Cohen's *d*s < .78) were found for the different groups and strings (all *F*s < 2.47, all *p*s > .12, all partial η^2s = .09). Hence, Experiment 2 is not indicative of a performance advantage for sequence-space synesthesia on implicit learning.

GENERAL DISCUSSION

In this study, we introduced a "bilingual" AGL paradigm and demonstrated for the first time by the means of an implicit learning paradigm that synesthetic

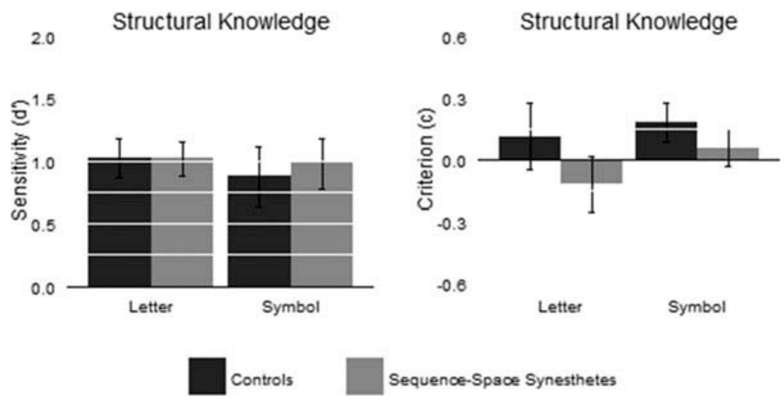

Figure 3. Average performance and average response criterion for sequence-space synesthetes versus controls. Error bars represent standard errors of the mean.

experiences can also enhance unconsciously acquired knowledge. Specifically, we showed that grapheme-color synesthesia provides for a memory advantage relating to unconscious structural knowledge for stimuli which elicit synesthetic experiences (i.e., letters), but not for stimuli which do not elicit synesthetic experiences (i.e., symbols). Although, we were not able to show that sequence-space synesthesia provides for a memory advantage in bAGL, both experiments demonstrate that two distinct artificial grammars can be learned simultaneously during the same learning phase when presented randomly intermixed.

The findings are consistent with the notion that grapheme-color synesthesia is associated with a specific profile of enhanced memory performance as compared to demographically matched controls (e.g., Rothen & Meier, 2010; Yaro & Ward, 2007). A well-established finding is that grapheme-color synesthesia provides a performance advantage for word-stimuli in explicit memory tasks (Gibson et al., 2012; Gross, Neargarder, Caldwell-Harris, & Cronin-Golomb, 2011; Radvansky et al., 2011; Rothen & Meier, 2010; Yaro & Ward, 2007). Notably, word-stimuli elicit synesthetic experiences in grapheme-color synesthesia and there is a systematic relationship between the colors of words and those of the letters within the words (Ward, Simner, & Auyeung, 2005). Given the consistency of synesthetic experiences over time (e.g., Baron-Cohen, Wyke, & Binnie, 1987; Rothen, Seth, et al., 2013), the most intuitive explanation for enhanced memory for word-stimuli is based on dual coding. That is, memory performance for verbal material can be enhanced when additionally encoded as mental image (cf. Paivio, 1969). In line with this notion, synesthesia provides additional features at encoding which may act as additional cues at retrieval. However, enhanced memory abilities in grapheme-color synesthesia were also demonstrated for material that does not elicit synesthetic color experiences such as color (Yaro & Ward, 2007), color-shape pairs, and simple abstract figures (Rothen & Meier, 2010). Crucially, memory is not globally enhanced in grapheme-color synesthesia. Studies failed to demonstrate enhanced memory performance for complex abstract figures (Yaro & Ward, 2007), for the location of digits randomly assigned to the cells of a matrix (Rothen & Meier, 2009; Yaro & Ward, 2007), and for the digit span task (Gross et al., 2011; Rothen & Meier, 2010) of the Wechsler Memory Scale (Wechsler, 1987). Hence, the specific performance profile in grapheme-color synesthesia suggests enhanced memory for color and item identity, but not item location. That is, enhanced memory in grapheme-color synesthesia may be linked to enhanced visual processes within the parvocellular (or ventral) stream affecting color and form more than location (Rothen et al., 2012).

In AGL reliable discrimination indicates the presence of structural knowledge (e.g., whether X can or cannot follow T). Hence, performance in AGL can be based on associative memory rather than memory for item location (Pothos, 2007). However, it is less clear whether the suggested early visual processing differences in grapheme-color synesthesia could fully account for the findings here as the letters and symbols do not differ in terms of basic visual appearance but do so, primarily, in terms of the propensity to elicit color experiences. Moreover, our findings indicate that also dual coding mechanism may play an important role under specific circumstances. For instance, dual coding might interact with different levels of complexity such that it reveals a memory advantage where the stimulus material is too complex to profit from enhanced visual processing alone.

The lack of evidence for sequence-space synesthesia to reliably enhance memory in bAGL is somewhat difficult to interpret as previous studies provided mixed results. Two studies provided evidence for enhanced spatial working memory in sequence-space synesthetes (Brang et al., 2010; Simner et al., 2009). In contrast, two other studies were not able to confirm this finding. Instead, evidence was found for self-reported visual but not spatial imagery (Rizza & Price, 2012) and for a behavioral advantage in a visuo-spatial imagery task (Brang et al., in press). In line with the notion that sequence-space synesthesia is a form of visuo-spatial imagery (Rizza & Price, 2012) it seems more likely that sequence-space synesthetes show primarily enhanced visualization abilities which may occasionally moderate their memory abilities depending on the specific demands of the memory task. However, this does not seem to be the case for the associative nature of structural knowledge in AGL.

Nevertheless, the absence of a memory advantage in sequence-space synesthetes has other important implications. That is, the null findings of Experiment 2 suggest that the memory advantage for grapheme-color synesthetes in Experiment 1 cannot simply be explained by motivational differences between synesthetes and controls (for a discussion on motivational aspects see also, Rothen, Nikolić, et al., 2013).

More generally, given the ubiquity and universality of implicit learning throughout life (e.g., acquisition of one's first language), our findings have important implications which are consistent with—but go beyond—previous findings demonstrating that synesthetic experiences affect higher cognitive functions whose contents are consciously accessible (Rothen et al., 2012; Ward, 2013). Furthermore, our findings imply that conscious experiences are functionally relevant, even for unconscious cognitive processes, rather than being purely epiphenomenal.

To conclude, in a substantial sample of synesthetes we demonstrated, for the first time, that synesthesia can enhance memory performance relating to unconscious knowledge. Our findings support the idea that synesthesia is linked to wider changes in the cognitive system at the interface of perception and memory in the ventral visual pathway. Moreover, our findings suggest that dual coding mechanism may play an important role under specific circumstances.

Author contributions

N.R. and J.W. developed the concept of the study. N.R., R. B.S, A.D.M, and D.J.C contributed to the study design. N. R. and A.D.M. programmed the experimental tasks. D.J.C and V.B. tested the participants and collected the data. N.R. performed the data analysis and interpretation. J.W., R.B.S., and A.D.M provided critical comments to the interpretation of the data. N.R. drafted the paper and J.W. and R.B.S. provided critical revisions.

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