ARTICLE IN PRESS

Consciousness and Cognition xxx (2012) xxx–xxx

Contents lists available at SciVerse ScienceDirect

Consciousness and Cognition

journal homepage: www.elsevier.com/locate/concog

Short Communication

# Grapheme-color synaesthesia benefits rule-based Category learning

Marcus R. Watson[a,*], Mark R. Blair[b], Pavel Kozik[a], Kathleen A. Akins[c], James T. Enns[a]

[a] Department of Psychology, University of British Columbia, 2136 West Mall, Vancouver, BC, Canada V6T 1Z4
[b] Cognitive Science Program and Department of Psychology, Simon Fraser University, 8888 University Drive, Burnaby, BC, Canada V5A 1S6
[c] Department of Philosophy, Simon Fraser University, 8888 University Drive, Burnaby, BC, Canada V5A 1S6

ARTICLE INFO

*Article history:*
Received 4 December 2011
Available online xxxx

*Keywords:*
Synaesthesia
Rule-based category
Category learning
Perceptual development
Color category

ABSTRACT

Researchers have long suspected that grapheme-color synaesthesia is useful, but research on its utility has so far focused primarily on episodic memory and perceptual discrimination. Here we ask whether it can be harnessed during rule-based Category learning. Participants learned through trial and error to classify grapheme pairs that were organized into categories on the basis of their associated synaesthetic colors. The performance of synaesthetes was similar to non-synaesthetes viewing graphemes that were physically colored in the same way. Specifically, synaesthetes learned to categorize stimuli effectively, they were able to transfer this learning to novel stimuli, and they falsely recognized grapheme-pair foils, all like non-synaesthetes viewing colored graphemes. These findings demonstrate that synaesthesia can be exploited when learning the kind of material taught in many classroom settings.



## 1. Introduction

Is *synaesthesia* good for anything? The suggestion that it has some utility goes back well over a century (e.g. Calkins, 1893, 1895) and recent work has begun to confirm this. *Grapheme-color synaesthetes*, who experience letters and numerals as having specific colors, have episodic memory advantages for letters and words (Radvansky, Gibson, & McNerney, 2011; Rothen & Meier, 2010; Yaro & Ward, 2007), *calendar-form synaesthetes*, who experience dates as located in peripersonal space, have advantages for remembering events and dates (Simner, Mayo, & Spiller, 2009), and several varieties of synaesthesia are associated with enhanced perceptual discrimination (Banissy, Walsh, & Ward, 2009; Saenz & Koch, 2008). However it remains an open question whether synaesthesia can be exploited for more sophisticated and abstract forms of learning (cf. Brang & Ramachandran, 2011). Here we answer this question in the affirmative for rule-based Category learning.

We investigated whether grapheme-color synaesthetes are able to use synaesthetic colors on a difficult Category learning task. We show that synaesthetes viewing black letters use their internally-generated colors during this task in much the same way as non-synaesthetes viewing genuinely colored stimuli. Thus synaesthesia can be a tool used in learning novel abstractions.

Participants learned to classify stimuli according to a rule-based category structure. Such learning is hypothesized to involve an explicit reasoning process in which hypotheses are maintained in working memory, individual stimuli are attended to and categorized according to the currently active hypothesis, and this hypothesis is either strengthened or modified on the basis of subsequent feedback (Ashby & Maddox, 2005). The particular 4-category structure we created was structurally similar to one used by Maddox, Filoteo, Hejl, and Ing (2004), in that the category rules conjoin two distinct pieces of information. Such conjunctive rules are frequently taught in primary school, for example when learning English phonetics (e.g. a vowel

* Corresponding author.
*E-mail address:* marcusw@psych.ubc.ca (M.R. Watson).

1053-8100/$ - see front matter © 2012 Elsevier Inc. All rights reserved.
http://dx.doi.org/10.1016/j.concog.2012.06.004

followed by a consonant has a short pronunciation, unless the consonant is immediately followed by the letter 'e', in which case the first vowel has a long pronunciation), in mathematics (e.g. a number is prime if it can be divided by 1 and not by any other number), or in the sciences (e.g. a mammal is an animal with warm blood that gives birth to live young).

Stimuli were pairs of graphemes (see Fig. 1a) whose category membership could be determined by simple rules involving the order and associated colors of graphemes, e.g. "Members of Category 1 contain a green followed by a pink grapheme". As synaesthetes' colors are idiosyncratic, a different stimulus set was generated for each synaesthetic participant. Participants who discovered the color rules were expected to be more accurate on the initial Category learning task than those who did not. Other participants would have to resort to more complex rules based on all possible combinations of the eight graphemes in the stimulus set, to use explicit memorization of 16 stimulus-category pairs, or to resort to more idiosyncratic strategies – e.g. treating letter pairs as acronyms for words or phrases with personal meaning.

This initial task was followed by a Transfer Test and Recognition Test, both designed to verify if participants were using color rules. Immediately following the Category learning task, participants completed 10 Transfer Test trials, in which novel stimuli that followed the same color rules were presented (Fig. 1b). Participants who had used color rules previously ought to be able to apply them to these novel stimuli, whereas those who used other strategies should be at chance. This Transfer Test was followed by a Recognition Test, on which the opposite pattern of results was expected. Here participants were presented with grapheme pairs and asked if they had been presented previously in the experiment. These stimuli included all 16 stimuli from the Category learning task (Fig. 1a), 10 novel Foil Stimuli that also followed the color rules (Fig. 1c), and six additional stimuli with no colors or identities in common with any others used during the experiment (Fig. 1d). Subjects who had used color rules would be expected to confuse the 10 Foil Stimuli with those previously presented in the Category learning task and Transfer Test. However those using alternative rules would be expected to correctly reject more of them.

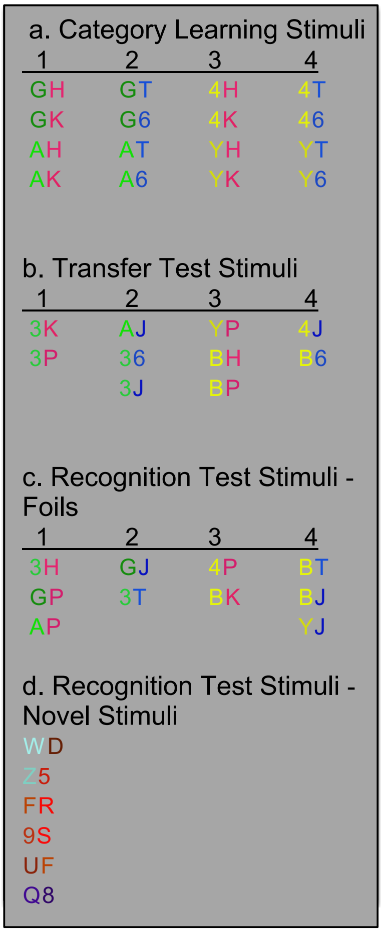


**Fig. 1.** One of the stimulus sets, based on the color assignments of one of the synaesthetes, for the various measures in the experiment. Synaesthetes and members of the Control-Achromatic group would have been presented with these stimuli in black. (a) Stimuli used during the Category learning task and Recognition Test, arranged so that the color rules are obvious. (b) The 10 stimuli used during the Transfer Test. (c) The 10 Foil Stimuli used during the Recognition Test. (d) The six completely novel stimuli used during the Recognition Test.

Please cite this article in press as: Watson, M. R., et al. Grapheme-color synaesthesia benefits rule-based Category learning. *Consciousness and Cognition* (2012), http://dx.doi.org/10.1016/j.concog.2012.06.004

Three groups participated in the study. A Synaesthete group viewing achromatic stimuli was compared with non-synaesthetes viewing either the same achromatic stimuli (Control-Achromatic) or stimuli that were colored according to synaesthetic color assignments (Control-Color). Thus if synaesthetic colors can be used in rule-based categorization tasks, we expect the Synaesthete group to perform better than the Control-Achromatic group on the Category learning task and the Transfer Test, but worse on the Recognition Test. Comparing the Synaesthete and Control-Color groups allows us to infer further similarities and differences between synaesthetic and normal color perception.

## 2. Experiment 1

### 2.1. Participants

Ten grapheme-color synaesthetes participated in the study and were rewarded with $10 (CAN). All synaesthetes' grapheme-color associations were verified as consistent by the online Synaesthesia Battery (Eagleman, Kagan, Nelson, Sagaram, & Sarma, 2007), with a mean consistency score of .70, and a mean accuracy score of 89% on the Speed-Congruency Test. Eighty-six non-synaesthetes were recruited from undergraduate psychology classes at the University of British Columbia. Six of these participants were removed from all analyses for performing at chance, leaving 80 non-synaesthetic participants. Eight of these participants were randomly assigned to each synaesthete's stimulus set, 4 to the Achromatic and 4 to the Color condition.

### 2.2. Displays and responses

Stimuli consisted of grapheme pairs presented in Arial font, each grapheme occupying approximately 2.5 $cm^2$ (3.6° of visual angle at a distance of 40 cm). Graphemes were either all black (Achromatic condition) or colored as the synaesthete reported them (color condition). Each Category learning and Transfer Test trial began with a fixation cross (approximately 1.5 $cm^2$, or 2.1° v.a.) at the center of the screen for 400–800 ms, followed by a stimulus at the center of the screen and four response boxes near the bottom, labeled with the digits 1–4. Participants selected one box with a mouse click, and were given feedback in the form of the incorrect response boxes disappearing. Participants responded to the feedback by clicking on the correct box, and the next trial began. Recognition Test trials had identical displays, save that there were only two response boxes, labeled "Yes" and "No", and no performance feedback was given.

### 2.3. Category structure

A category structure of 16 letter pair stimuli was created for each of the 10 synaesthetes. These were generated from eight graphemes, which were associated with four distinct colors (see Fig. 1a), organized such that each color appeared only in the left or right position. Stimuli were assigned to one of four categories on the basis of simple conjunctive color rules, as illustrated in Fig. 1a, that can be easily applied in a 2-stage hierarchy. For example, one could begin a trial by looking at the left-hand letter, and narrowing down the possible responses to categories 1 and 2 if the letter is blue or 3 and 4 if it is red. Then the color of the right hand letter could be used to determine which of the two remaining options is correct, since the possible responses are 1 and 3 if this letter is orange or 2 and 4 if it is green. Of course these color rules would be unavailable to non-synaesthetes viewing achromatic letters, and we expected their performance to suffer accordingly.

### 2.4. Foil stimulus sets

In addition to the stimulus sets shown to participants during Category learning, we constructed stimulus sets following the same color rules, but including novel graphemes, for use in the subsequent Transfer and Recognition Tests, illustrated in Fig. 1b and c. Within each set, four additional graphemes were used, each associated with one of the four colors from the learning phase. Combined with the original graphemes, this allowed for the construction of 20 more grapheme pairs (five new stimuli in each category) that followed the same color mapping as in the learning task. Ten of these stimuli were randomly selected to appear in the Transfer Test, and the other 10 appeared during the Recognition Test. Again, participants in the Achromatic condition saw the same letter pairs, but colored black.

### 2.5. Procedure

Category learning consisted of 256 trials in total, divided into eight blocks of 32 trials. Each block contained each of the 16 stimuli presented twice in random order. On each trial participants indicated which category a stimulus belonged to and were given feedback as described above. Immediately following these eight blocks, participants completed 10 Transfer Test trials that were identical in format, except that the stimuli were drawn from the Foil Stimuli. Other than the sudden appearance of novel stimuli, participants were given no indication that anything was different on these trials.

Participants then completed 32 Recognition Test trials, where they were asked to indicate if they had seen a particular stimulus previously during the experiment. They indicated their response by clicking on one of two boxes, labeled "Yes" and "No", and were not given any feedback. The stimuli presented in this phase consisted of all 16 original stimuli, the 10 Foil Stimuli that had not been used in the Transfer Test, and six new grapheme pairs unrelated to any of the other stimuli in the experiment. Thus, half of the stimuli in the Recognition Test had been seen previously and half had not. We were particularly interested in participants' responses for the 10 Foil Stimuli, as someone paying attention to color might be expected to make False Recognition errors on these trials.

Finally, participants were asked to write down any strategies they used during the Category learning phase of the experiment.

### 2.6. Behavioral results

For each participant, we computed four scores. Categorization Accuracy was the mean accuracy over each block of the Category learning task, and response times (RTs) were also recorded during these blocks. Transfer Accuracy was the mean accuracy over the 10 Transfer Test trials. False Recognition was the inverse of the mean accuracy over the 10 Recognition Test trials that used the Foil Stimuli. (Recognition Test accuracy for the other stimuli was over 95% for all groups, and so was not analyzed further.)

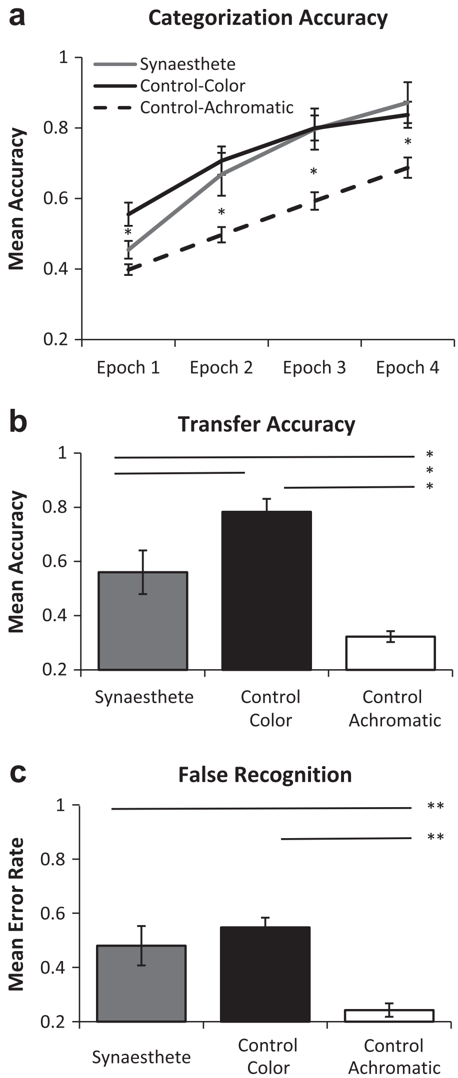


**Fig. 2.** Performance of participants in Experiment 1. (a) Accuracy over the course of the Category learning task (each epoch = 64 trials), (b) accuracy over the 10 Transfer Test trials in which participants categorized foils that follow the same color mapping rules, and (c) error rate over the 10 Recognition Test trials involving novel Foil Stimuli. Error bars indicate plus/minus one standard error of the mean. Asterisks indicate significant group differences. *: $p < .05$, **: $p < .01$.

The results were qualitatively very simple. First, accuracy on the Category learning task was higher for those with access to color information, whether these colors were synaesthetic or real (see Fig. 2a), although synaesthetes learned somewhat more slowly than controls viewing real colors. Second, participants looking at achromatic letters were slower to make decisions, whether they were synaesthetes or controls, and the synaesthetes were generally slowest of all. Third, access to color information also improved participants' ability to generalize to novel stimuli on the Transfer Test, although real colors provided more of an advantage than synaesthetic colors (see Fig. 2b). Finally, participants with access to color information were prone to False Recognition of the Foil Stimuli during the Recognition Test, but those without color were able to correctly reject most of these stimuli (see Fig. 2c).

These qualitative descriptions are supported by analyses of variances (ANOVAs) and post hoc group comparisons. To begin with, Categorization Accuracy and RT were the dependent measures in two-way ANOVAs using Group as a between-subjects factor with three levels (Synaesthete, Control-Achromatic, and Control-Color), and Epoch (1–4, each composed of two experimental blocks) as a within-subjects factor. In both cases, there were significant main effects of Group (Categorization Accuracy: $F_{2,87} = 12.1$, $\eta^2 = .22$, $MSE = .11$, $p < .001$; RT: $F_{2,87} = 11.5$, $\eta^2 = .21$, $MSE = 2.1$, $p < .001$) and Epoch ($F_{3,261} = 146.5$, 31.4, $\eta^2 = .61$, .26, $MSE = .01$, .42, respectively; both $ps < .001$), as well as Block by Epoch interactions ($F_{6,261} = 2.5$, 2.3, $\eta^2 = .02$, .04, $MSE = .01$, .42, respectively; both $ps < .05$). These were followed by tests of the simple main effect of Group at each of the four levels of Epoch, which all indicated group differences ($F_{2,261}$ between 5.0 and 19.3, $\eta^2$ between .04 and .12, $MSE$ for accuracy between .06 and .14, for RT between 2.1 and 8.1, all $ps < .01$; except for RT on epoch 4, where $F_{2,261} = 3.2$, $\eta^2 = .02$, $MSE = 1.3$, $p = .04$). The Tukey–Kramer method was used to determine which groups were significantly different from each other on each of the four epochs, and these results are described below.

In the case of Categorization Accuracy, as shown in Fig. 2a, the interaction stems from the Synaesthete group improving at a faster rate (a rise of over 40% from epochs 1 to 4) than either control group (both of whom improve by approximately 30%). The Control-Color group outperforms the Control-Achromatic group by 15–20% throughout the experiment, while the Synaesthete group begins by performing similarly to the Control-Achromatic group on the first epoch, but on Epochs 2–4 is significantly more accurate than the Control-Achromatic group, and not distinguishable from the Control-Color group.

In the case of RT, the interaction also stems from the Synaesthete group improving at a faster rate (an overall gain of 1.7 s from an initial RT of 4.9 s in Epoch 1) than either control group (the Control-Color and Control-Achromatic groups improve by 0.6 s from 2.1 s and by 0.8 s from 2.8 s, respectively). Despite this greater improvement, the Synaesthete group was slower than both control groups on all epochs save for epoch 4, where it was not distinguishable from the Control-Achromatic group. The Control-Color group was faster than both other groups on all epochs save for epoch 3, where it was not distinguishable from the Control-Achromatic group.

The remaining two measures (Transfer Accuracy and False Recognition) were dependent variables in one-way ANOVAs using Group as a between-subjects factor. Levene's test showed a violation of the homogeneity of variance assumption for Transfer Accuracy ($F_{2,87} = 4.5$, $p < .05$) so Welch's statistic was used. Both ANOVAs were significant (Transfer Accuracy: $F_{2,22.2} = 39.4$, $\eta^2 = .46$, $MSE = .06$, $p < .001$; False Recognition: $F_{2,87} = 24.2$, $\eta^2 = .36$, $MSE = .04$, $p < .001$), indicating group differences on each of the measures. Following up with Tukey–Kramer revealed that the Control-Color group had the highest Transfer Accuracy (78%), then the Synaesthete group (56%), followed by the Control-Achromatic group (32%), and all 3 between-group comparisons were significant (all $ps < .05$). Finally, the Synaesthete and Control-Color groups both performed poorly on the Recognition Test trials using Foil Stimuli (False Recognition of 48% and 55%, respectively) whereas the Control-Achromatic group made far fewer errors (24%) than either (both $ps < .01$).

### 2.7. Self-report data

The data from participants' reports of their own strategies also support the notion that group performance differences stemmed from the availability of color-based rules. Reviewing these reports revealed a number of common strategies, including the use of acronyms (mentioned by 14% of participants), memorization (60%), various forms of mathematical reasoning (11%), the use of color information (49%), and explicit descriptions of the formal category structure (22%). Fisher's Exact Test was used to see if the proportions of participants reporting each strategy differed between groups. This was the case for memorization ($p = .002$), the use of color ($p < .001$) and describing the structure ($p < .001$), but not for acronyms ($p > .9$) or math ($p > .25$). The Control-Achromatic group was the source of all three group differences, as removing this group resulted in no significant differences between the Synaesthete and Control-Color groups (all $ps > .5$). Specifically, the Control Achromatic group was more likely to report memorization (80%) than the Synaesthete (50%) or Control-Color (43%) groups, and less likely to report the use of color (0% vs. 80% and 90%, respectively) or to describe the category structure (3% vs. 40% and 38%, respectively).

Finally, we verified whether these strategies were connected to performance using five ANOVAs, each using Group and one of the strategies described above as between-subjects factors, and accuracy on the final Category learning epoch as the dependent measure. There were main effects of describing the category structure ($F = 7.1$, $\eta^2 = .08$, $MSE = .04$, $p < .01$) and mathematical reasoning ($F = 6.8$, $\eta^2 = .05$, $MSE = .04$, $p < .01$), and an interaction between the use of color information and group ($F = 5.2$, $\eta^2 = .05$, $MSE = .04$, $p < .05$). No other main effects of strategy or interactions were significant (all $ps > .05$). The two main effects of strategy were due to participants who described the category structure performing better than those who did not (mean accuracy on Epoch 4 = 94% vs. 73%) and those who used mathematical reasoning performing *worse* than those who did not (60% vs. 80%). The group by color interaction was followed with tests of the simple main effect of color, which was marginally significant for the Control-Color group ($F = 3.8$, $\eta^2 = .04$, $MSE = .15$, $p = .06$), but not for the Synaesthete group ($p > .25$). Among Control-Color participants, Tukey–Kramer revealed that participants who used color had a higher accuracy than those who did not (87% vs. 59%, respectively). As only two synaesthetes did not report using color, the lack of a main effect is likely uninformative for this group.

## 3. Experiment 2

The overall pattern of results from Experiment 1 is consistent with the claim that synaesthetes can exploit their color experiences during Category learning, in much the same manner as non-synaesthetes viewing real colors. Indeed, the only accuracy differences between the Synaesthete and Control-Color groups were that the synaesthetes were slightly slower to learn the category structure, and somewhat less accurate on the Transfer Task. But it was still possible that the superior performance of the Synaesthete and Contol-Color groups was not due to their using color rules *per se*. For instance, it is possible that color by itself makes the categorization task easier to learn, irrespective of any category rules: perhaps it is simply easier to memorize letter pairs when they are colored, and hence easier to apply mnemonic strategies to learn the category structure. To see if this was the case, we ran a second experiment using new subjects, identical to Experiment 1 save that colors were no longer diagnostic of category membership. If the results from Experiment 1 were indeed due to participants in the Synaesthete and Control-Color groups making category decisions on the basis of color rules, then they should not be able to do this in Experiment 2, and we should not find the group differences we found in Experiment 1.

## 4. Methods

The experimental procedure was identical to Experiment 1, save that similarly-colored letters were not grouped in the same categories, so colors were no longer diagnostic of category membership. Eight synaesthetes participated in the experiment, whose grapheme-color associations were verified as consistent by the Synethesia Battery (mean consistency score: .66, mean Speed-Congruency accuracy: 87%), along with 68 non-synaesthetic controls, four of whom were eliminated from the analysis as random responders, leaving 64 non-synaesthetes who were randomly assigned to a particular synaesthete's stimulus set, and to a Color or Achromatic condition, as in Experiment 1. None of the participants were in Experiment 1.

As in Experiment 1, stimuli were composed of pairs of graphemes, made from eight graphemes with four distinct colors. These were organized into four categories of four stimuli each. However graphemes with each of the four colors appeared in at least three of the four categories, and at least once on the left and once on the right-hand side of different stimuli. Thus color was entirely useless for categorization.

### 4.1. Results

In brief, the three groups perform similarly to each other on all tasks, with only one exception. Furthermore, all three groups also perform very similarly to the Control-Achromatic group from Experiment 1. Thus it is clear that the group differences we found in Experiment 1 are not due to color *per se*, but to its use in a system of rules.

To support this conclusion, we performed the same analyses on the same variables as in Experiment 1. No group differences or interactions were found (all $ps > .3$) save for False Recognition ($F = 5.4$, $\eta^2 = .14$, $MSE = .05$, $p < .01$). Tukey's HSD revealed that this group difference was due to the Control-Color group performing significantly worse ($p < .01$) than the Control-Achromatic group (False Recognition of 57% and 28%, respectively). Furthermore, with the exception of the Control-Color group's False Recognition, all groups' mean performance on all measures was within the 95% confidence interval of the performance of the Control-Achromatic group on Experiment 1.

## 5. Discussion

These results demonstrate that synaesthetes can learn rule-based categories using internally-generated synaesthetic colors. Moreover, they do this similarly to non-synaesthetic individuals using physical colors. Both synaesthetes and non-synaesthetic participants viewing colored stimuli learned to categorize more successfully than non-synaesthetes viewing achromatic stimuli, were able to generalize to novel stimuli on the transfer task, and were unable to correctly reject Foil Stimuli in a Recognition Test, indicating that their memory for individual grapheme identities was impaired. Furthermore, these participants were also likely to give explicit reports indicating that they used the color information and understood the category structure, unlike non-synaesthetes viewing achromatic stimuli, and giving these reports was correlated with higher accuracy. Taken together, these findings demonstrate that synaesthetes can exploit their grapheme colors to learn a rule-based category structure similar to those taught in a variety of domains.

More detailed analyses showed some performance differences between synaesthetes and non-synaesthetes viewing physically colored stimuli. First, synaesthetes learned more slowly. Though their performance for most of the experiment was comparable to non-synaesthetes viewing real colors, their accuracy was lower at the start of the experiment. We suggest that this is because experiences of synaesthetic colors may be somewhat less vivid than experiences of real colors, which might delay rule acquisition.

Second, synaesthetes were not as successful in transferring their learning to novel stimuli. This might also be explained by less vivid synaesthetic experiences. Alternatively, a comment made by a synaesthetic participant may shed light on this result. He indicated that when viewing the stimuli, he did not experience two different colors, but saw a single color for the pair as a whole, typically the color of the grapheme that seemed more "dominant" than the other. Indeed, many grapheme-color synaesthetes experience single colors for words, often determined by the color of an individual letter (Simner, Glover, & Mowat, 2006; Ward, Simner, & Auyeung, 2005). This may account for the lower accuracy of synaesthetes on the transfer task, although it does not mitigate the critical finding that their accuracy was almost twice that of non-synaesthetes viewing achromatic grapheme pairs.

Third, synaesthetes were slower to respond than participants viewing real colors. There are at least two ways of accounting for this result. First several researchers argue that synaesthetic colors cannot be induced without the conscious recognition of the grapheme (e.g. Laeng 2009). This would imply that the Synaesthete group ought to respond at least as slowly as the Control-Achromatic group, which is what we find. An alternative is that the process of establishing which letter in a pair is dominant, as described in the previous paragraph, may take some time to resolve itself. The present data does not provide enough evidence to decide whether one or both of these is the true source of the reaction time differences.

How well might these results generalize to other tasks? Stimuli in Experiment 1 were specifically tailored to each synaesthete such that their personal color associations would be maximally informative for distinguishing between the four categories. It seems remarkably unlikely that this could happen by chance. Thus one would be justified in asking whether our results have any meaning outside the laboratory. Are the apparently arbitrary associations synaesthetes make between graphemes and colors actually any use in learning or using the rules of, for example, spelling, mathematics or phonetics?

Our data do not directly address this question, but there is reason to think that synaesthetic colors could provide a significant benefit to such rule use. Many of the explicit rules we learn in everyday life – including all the examples given in Section 1 – are single rules that do not require combining with other rules in a hierarchical fashion, as the color rules in this study do. Any rule that involves a specific combination of letters – e.g. "*I* before *E* except after *C*" – is one that involves a specific combination of colors for a grapheme-color synaesthete. Provided the synaesthete's colors for these letters are distinguishable from each other, this could provide a cue to aid in learning and applying the rule. The same is true for any numerical rule in math – e.g. any number ending in 5 is divisible by 5. The present study shows that with less than 30 min training, synaesthetes can flexibly employ their colors to learn and use a complex and abstract set of intertwined rules. We see no reason why they could not do the same for simpler rules in the classroom or in the rest of daily life.

Of course establishing that this is *possible* is one thing, verifying that it occurs under natural conditions is another matter. There are no published studies that test this hypothesis. There are anecdotal reports, and several savants attribute their astounding memory and mathematical skills to synaesthesia (cf. Bor, Billington, & Baron-Cohen, 2007; Luria 1968), but it remains unconfirmed whether the average synaesthete employs their colors in this manner. It appears that synaesthetic photisms influence mathematical processing (Ghirardelli, Mills, Zilioli, Bailey, & Kretschmar, 2010), but the nature of this influence is far from clear. Determining if colors are actually being used to represent rules in mathematics, spelling, or in other domains is a crucial next step.

Finally, the rule-based categorization task used here is generally considered to involve explicitly conscious processes that operate in a fundamentally different manner from the processes used in statistical or implicit learning (e.g. Reber, 1993). Further experiments could more directly test whether the sub-personal mechanisms that underlie implicit learning can also exploit synaesthetic color information. If this is the case, the potential utility of synaesthesia for learning is even wider, given the ubiquity of implicit learning throughout life.

Previous work has demonstrated that the colors synaesthetes associate with letters are influenced by a number of learned properties of these letters (Beeli, Esslen, & Jäncke, 2007; Cohen Kadosh, Henik, & Walsh, 2007; Day, 2005; Rich, Bradshaw, & Mattingley, 2005; Simner & Ward, 2008; Simner et al., 2005; Smilek, Carriere, Dixon, & Merikle, 2007; Watson, Akins & Enns, 2012). Here, we demonstrate the reverse: synaesthetic colors can influence learning about letters. Further exploration of the interactions between synaesthesia and learning is likely to be the source of new understanding about the nature of this fascinating phenomenon.

## Acknowledgments

Funding was provided by a SSHRC Doctoral Fellowship to Marcus R. Watson, a James McDonnell Fellowship Centennial Fellows Award to Kathleen A. Akins, and NSERC Discovery Grants to Mark R. Blair and to James T. Enns. Many thanks to Sean Povill and K.L. Ta for assistance with data collection, and to Beat Meier for suggesting the alternative explanation of our RT results.

## Appendix A. Supplementary material

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.concog.2012.06.004.

## References

Ashby, F. G., & Maddox, W. T. (2005). Human category learning. *Annual Review of Psychology, 56*, 149–178.

Banissy, M. J., Walsh, V., & Ward, J. (2009). Enhanced sensory perception in synaesthesia. *Experimental Brain Research, 196*(4), 565–571.

Beeli, G., Esslen, M., & Jäncke, L. (2007). Frequency correlates in grapheme-color synaesthesia. *Psychological Science, 18*(9), 788–792.

Bor, D., Billington, J., & Baron-Cohen, S. (2007). Savant memory for digits in a case of synaesthesia and Asperger syndrome is related to hyperactivity in the lateral prefrontal cortex. *Neurocase, 13*(5–6), 311–319.

Brang, D., & Ramachandran, V. S. (2011). Survival of the synesthesia gene: why do people hear colors and taste words? *PLoS Biology, 9*(11), e1001205. http://dx.doi.org/10.1371/journal.pbio.1001205.

Calkins, M. W. (1893). A statistical study of pseudo-chromesthesia and of mental-forms. *American Journal of Psychology, 5*, 439–464.

Calkins, M. W. (1895). Synaesthesia. *American Journal of Psychology, 7*, 90–107.

Cohen Kadosh, R., Henik, A., & Walsh, V. (2007). Small is bright and big is dark in synaesthesia. *Current Biology, 17*(19), R834–R835.

Day, S. A. (2005). Some demographic and socio-cultural aspects of synesthesia. In L. C. Robertson & N. Sagiv (Eds.), *Synesthesia: perspectives from cognitive neuroscience* (pp. 11–33). Oxford: Oxford University Press.

Eagleman, D. M., Kagan, A. D., Nelson, S. S., Sagaram, D., & Sarma, A. K. (2007). A standardized test battery for the study of synesthesia. *Journal of Neuroscience Methods, 159*(1), 139–145.

Ghirardelli, T. G., Mills, C. B., Zilioli, M. K. C., Bailey, L. P., & Kretschmar, P. K. (2010). Synesthesia affects verification of simple arithmetic equations. *Journal of General Psychology, 137*(2), 175–189.

Laeng, B. (2009). Searching through synaesthetic colors. *Attention, Perception, and Psychophysics, 71*(7), 1461–1467.

Luria, A. R. (1968). *The mind of a mnemonist*. New York: Basic Books.

Maddox, W. T., Filoteo, J. V., Heil, K. D., & Ing, A. D. (2004). Category number impacts rule-based but not information-integration category learning: Further evidence for dissociable category-learning systems. *Journal of Experimental Psychology: Learning, Memory and Cognition, 30*(1), 227–245.

Radvansky, G. A., Gibson, B. S., & McNerney, M. W. (2011). Synesthesia and memory: Color congruency, von restorff, and false memory effects. *Journal of Experimental Psychology: Learning, Memory, and Cognition, 37*(1), 219–229.

Reber, A. S. (1993). *Implicit learning and tacit knowledge: An essay on the cognitive unconscious*. Oxford: Oxford University Press.

Rich, A. N., Bradshaw, J. L., & Mattingley, J. B. (2005). A systematic, large-scale study of synaesthesia: Implications for the role of early experience in lexical-color associations. *Cognition, 98*, 53–84.

Rothen, N., & Meier, B. (2010). Grapheme-color synaesthesia yields an ordinary rather than extraordinary memory advantage: Evidence from a group study. *Memory, 18*(3), 258–264.

Saenz, M., & Koch, C. (2008). The sound of change: visually-induced auditory synesthesia. *Current Biology, 18*(15), R650–R651. http://dx.doi.org/10.1016/j.cub.2008.06.014.

Simner, J., Glover, L., & Mowat, A. (2006). Linguistic determinants of word coloring in grapheme-color synaesthesia. *Cortex, 42*(2), 281–289.

Simner, J., Mayo, N., & Spiller, M. J. (2009). A foundation for savantism? Visuo-spatial synaesthetes present with cognitive benefits. *Cortex, 45*(10), 1246–1260.

Simner, J., & Ward, J. (2008). Synaesthesia, color terms, and color space – Color claims came from color names in Beeli, Esslen, and Jancke (2007). *Psychological Science, 19*(4), 412–414.

Simner, J., Ward, J., Lanz, M., Jansari, A., Noonan, K., Glover, L., et al (2005). Non-random associations of graphemes to colors in synaesthetic and non-synaesthetic populations. *Cognitive Neuropsychology, 22*, 1069–1085.

Smilek, D., Carriere, J. S. A., Dixon, M. J., & Merikle, P. M. (2007). Grapheme frequency and color luminance in grapheme-color synaesthesia. *Psychological Science, 18*(9), 793–795.

Ward, J., Simner, J., & Auyeung, V. (2005). A comparison of lexical-gustatory and grapheme-color synaesthesia. *Cognitive Neuropsychology, 22*, 28–41.

Watson, M. R., Akins, K. A., & Enns, J. T. (2012). Second-order mappings in grapheme-color synaesthesia. *Psychonomic Bulletin & Review, 19*, 211–217.

Yaro, C., & Ward, J. (2007). Searching for shereshevskii: What is superior about the memory of synaesthetes? *Quarterly Journal of Experimental Psychology, 60*(5), 681–695.

Please cite this article in press as: Watson, M. R., et al. Grapheme-color synaesthesia benefits rule-based Category learning. *Consciousness and Cognition* (2012), http://dx.doi.org/10.1016/j.concog.2012.06.004