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Synesthesia Affects Verification of Simple Arithmetic Equations

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ABSTRACT. To investigate the effects of color–digit synesthesia on numerical representation, we presented a synesthete, called SE, in the present study, and controls with mathematical equations for verification. In Experiment 1, SE verified addition equations made up of digits that either matched or mismatched her color–digit photisms or were in black. In Experiment 2A, the addends were presented in the different color conditions and the solution was presented in black, whereas in Experiment 2B the addends were presented in black and the solutions were presented in the different color conditions. In Experiment 3, multiplication and division equations were presented in the same color conditions as in Experiment 1. SE responded significantly faster to equations that matched her photisms than to those that did not; controls did not show this effect. These results suggest that photisms influence the processing of digits in arithmetic verification, replicating and extending previous findings.

Keywords: arithmetic verification, numerical representation, synesthesia

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SYNESTHESIA REFERS TO A CONDITION in which stimulation in one sensory modality causes an experience in a different sensory modality (e.g., hearing a particular musical note results in the visual perception of a particular color), or when stimulation in one dimension within a sensory modality results in a perceptual experience within that same modality (e.g., viewing digits elicits specific colors). *Color–digit synesthesia* refers to the automatic and involuntary perception of a specific color percept (e.g., red) when viewing a digit (e.g., 3). These synesthetic experiences are referred to as *photisms*. While this phenomenon is a fascinating topic of study on its own, results from the study of synesthesia can also be used to inform theories of cognition and perception (Cohen Kadosh & Henik, 2007).

Previous research has examined the effect of color–digit photisms on a variety of cognitive and perceptual tasks. These studies consistently show that synesthetic photisms affect processing of digits. For example, Mills, Boteler, and Oliver (1999) presented a synesthete with matrices of digits and asked her to name the color of the print in a modified Stroop task. In two experiments, digits were presented in colors that matched her photisms, in colors that mismatched her photisms, or in black. The synesthete took longer to name the color of the print when the color did not match her photism for that digit than when it did. The fact that the mismatched condition was slower than the matched when naming the color of the print suggests that interference occurs in the processing of incongruent color–digit combinations.

Dixon, Smilek, Cudahy, and Merikle (2000) also found that photisms interfered with the cognitive processing of digits. They replicated the Stroop effect found by Mills et al. (1999) and in a second experiment presented a synesthete and nonsynesthete controls with a series of items in each trial: a fixation cross, a digit, an arithmetic operator, a second digit, and a color patch. Participants had to name the color patch as quickly as possible and then report the solution to the equation. The color patch was either congruent or incongruent with the synesthete's photism for the correct solution. The synesthete was significantly slower naming the color patch when it was incongruent with the correct solution. The controls showed no effect of color on naming times. This study suggests that the abstract numerical representation of the solution is sufficient to elicit a photism even in the absence of a physical digit stimulus and that incongruence between photisms and color patches slowed color naming times.

Mills, Metzger, Foster, Valentine-Gresko, and Ricketts (2009) showed that coloring the digits themselves in addition equations affected the time required to produce the solution to those equations for a color–digit synesthete. When the color of the digits matched the synesthete's photisms, she produced the solution faster than when the digits mismatched the photisms. This was true even though the color of the digits was completely irrelevant to the production of the solution. In contrast, the color of the digits had no effect on the time required to produce the solutions for six nonsynesthete controls. Taken together, all of these studies support the notion that color–digit photisms influence how synesthetes perceive, represent, and perform operations on digits.

In the current experiments, we extended previous research by examining the effects of synesthesia in a different type of math task: a verification task. Unlike the production task used by Mills et al. (2009), where participants were asked to generate and state the solutions to the arithmetic equations, we had participants determine whether or not a simple arithmetic equation was true or false (e.g., $2 + 2 = 4$). In addition to replicating and extending the findings of Mills et al., we hope our study will improve on the experimental control and precision of Mills et al. Unlike Mills et al., who manually recorded response time (RT) and accuracy for a sheet of 8 equations, we recorded RT and accuracy for each individual equation using a computer. The verification task is also advantageous because it allows for the independent manipulation of the color of the addends and the solutions. This enables us to study the effects of the photisms on different parts of the equations in order to test for the independence of effects and assumptions about how mathematical verification is carried out.

In three experiments, we presented a color–digit synesthete with a series of verification tasks under three color conditions. In one condition, digits were presented in colors that matched her photisms; in the second condition, digits were presented in the same colors but they were not matched with the appropriate digit, thus creating a conflict; and in the third condition, digits were presented in black. The three experiments differed either in the type of math operation required in the task (addition vs. multiplication and division) or in whether the addends, solutions, or both were colored. In all experiments, we measured RT and accuracy. We hypothesized that the synesthete's RT to verify equations would be significantly faster for conditions where the digits were presented in colors that matched her color–digit photisms. Unlike the synesthete, we predicted that there would be no effect of the color manipulation on the verification times for nonsynesthete controls.

EXPERIMENT 1

Several different theories of arithmetic performance (e.g., Ashcraft, Fierman, & Bartolotta, 1984; Parkman & Groen, 1971) propose that verification involves the same process as production, namely encoding the equation and then retrieving or deriving the response to the equation, plus an additional stage of comparing the solution produced to the solution presented, deciding whether or not the two solutions match, and generating the true or false response. However, Campbell (1987) showed that the answer presented in a verification task affects performance, suggesting that the production and comparison stages may not be discrete. Zbrodoff and Logan (1990) have proposed that verification is not just production plus comparison, but instead involves comparing the equation as a whole against information in memory. All of these accounts suggest that the tasks and the cognitive processes underlying verification tasks and production tasks are different. For this reason, we conducted Experiment 1 to determine if manipulating the colors of the digits would have the same effect in a verification task as in the production task of Mills et al. (2009). To investigate this, we compared verification times and accuracy for math equations presented in the same three color conditions used by Mills et al.

Method

Participants

Participants were a synesthete, called SE in the present study, and 15 non-synesthete controls. At the time of testing SE was a 21-year-old college student. The controls were also undergraduate college students. SE experiences photisms for digits as well as for English and Hebrew letters. She has experienced synesthesia for as long as she could remember and experiences her strongest synesthesia colors for digits on a "screen inside her head." Her digit–color correspondences are: 0 = white, 1 = gray, 2 = blue, 3 = green, 4 = pink, 5 = purple, 6 = red, 7 = orange, 8 = yellow, and 9 = black.[1] For additional background on SE, including a more complete description of her photisms, see Mills et al. (2009). All participants in the experiments reported here were screened for normal or corrected-to-normal visual acuity (defined as 20/40 or better) and normal color vision prior to participation. As part of a standardized debriefing procedure, we described color–digit synesthesia to the participants but none reported ever experiencing color–digit photisms or any other type of synesthesia.

Apparatus and Stimuli

Stimuli were presented via a Windows-based computer with a 19-inch cathode-ray tube monitor. Stimulus presentation was controlled and participant responses (RT and accuracy for each trial) were collected using a program written using the E-Prime experimental presentation software version 1.1 (Schneider, Eschman, & Zuccolotto, 2002) and a response box (SR Box-Deluxe, Psychology Software Tools, Inc., Pittsburgh, PA). A chin rest (Model #14302, Lafayette Instruments, Lafayette, IN) was used to maintain a fixed viewing distance of 57 cm. The experiment took place in a dimly lit experimental room.

Equations were presented in the middle of the screen and subtended 8°. Each digit was presented in 36-point Arial type and measured $1.0^\circ \times 1.6^\circ$. Each trial began with the presentation of a black fixation cross that measured $1.4^\circ \times 1.4^\circ$ for 1000 ms. This was replaced by the equation which remained on the screen until the participant responded.

Equations were made up of all possible pairs of the single digits 1–8 in the form $A + B = C$ whose true solution equaled 9 or less. Each equation was presented with a true solution and with a false solution an equal number of times. For half of the trials presented with a false solution, the solution was one less than the true solution. On the other half of the trials, the false solution was one more than the true solution. (An exception was made for the true solution of 9, for which the false solution of 7 was substituted for 10 to avoid a two-digit solution.) On one-third of both the true and false trials the digits were presented in black, one-third were presented in color–digit combinations that matched SE's photisms, and one-third were presented in those same colors but in combinations that did not match her photisms. All stimuli were presented on a white background, with the addition sign and the equals sign presented in black.

The experiment consisted of one block of 72 practice trials representing the overall trial parameters, and four experimental blocks with 216 trials in each block. Each experimental block contained 108 true trials and 108 false trials, with 36 trials in each of the three color conditions for each type of solution. The order of presentation of the trials was randomly mixed within each block. Data from the practice trials were not included in the analysis.

Procedure

After providing informed consent, participants were given instructions for the verification task that emphasized responding as quickly as possible while maintaining accuracy. Participants responded by pressing the corresponding buttons on the response box with the index finger of the right hand to indicate the equation was true or the index finger of the left hand to indicate that it was false.

Results

Because false verification trials can be affected by qualities of the false answers (Campbell, 1987), in this and all experiments reported here, we analyzed data only from the true verification trials. In addition, throughout the experiments reported here we analyzed RT only for the trials in which the participant responded correctly. Table 1 shows mean correct RT for SE and the controls as a function of color–digit condition in all experiments. To analyze the effect of the color condition on SE's verification performance, we calculated mean RT and accuracy in each of the color conditions for each block separately and conducted an analysis of variance (ANOVA) on color condition with Block (1–4) as a random factor. The analysis of SE's RTs revealed a significant effect of color condition, $F(2, 6) = 15.08$, $p < .01$, $\eta^2 = .83$. Planned comparisons (with $\alpha = .05$) revealed that SE responded significantly faster to equations presented in colors that matched her photisms than to equations presented in black or in mismatched colors. RTs for equations in black and mismatched colors were not statistically distinguishable.

To examine the effect of color–digit condition on RT for the control participants, we calculated mean RT and accuracy for each participant in each color condition (collapsed across Block) and ran a standard within-participants ANOVA on the data from each experiment. We found a significant effect of color–digit condition $F(2, 28) = 6.42$, $p < .01$, $\eta^2 = .31$. Planned comparisons revealed that

TABLE 1. Mean Correct Reaction Time (in ms) and Standard Deviations as a Function of Color–Digit Condition in all Experiments

	Color-digit condition					
	Match		Black		Mismatch	
	M	*SD*	*M*	*SD*	*M*	*SD*
Experiment 1						
SE	846_{a}	60	1039_{b}	90	998_{b}	61
Controls	863_{b}	160	838_{a}	168	868_{b}	179
Experiment 2A						
SE	736_{a}	25	$805_{a,b}$	38	843_{b}	22
Controls	874_{a}	141	872_{a}	151	884_{a}	130
Experiment 2B						
SE	$692_{a,b}$	33	686_{a}	26	763_{b}	27
Controls	909_{a}	129	885_{a}	109	922_{a}	155
Experiment 3						
SE	886_{a}	105	1114_{b}	179	1216_{b}	140
Controls	1217_{b}	232	1132_{a}	181	1211_{b}	212

Note. The data for the synesthete (SE) was analyzed with Block as a random factor; data for the controls was analyzed using a standard analysis of variance collapsed across Block. Within each row, subscripts that differ indicate statistically significant differences ($p < .05$) between conditions based on planned comparisons. Comparisons were not made between experiments.

control participants were significantly faster to respond to equations presented in black than to equations presented in the matched or mismatched color conditions. The two color conditions were not significantly different.[2]

SE's overall accuracy was 98%. Accuracy was 99% in the matched color condition and in the black color condition, and 96% in the mismatched condition. SE's accuracy was identical in all four blocks within each color condition, making it impossible to conduct an ANOVA on her data. The control participants' overall accuracy was also 98%. The same ANOVA that was run on the controls' RT data showed no effect of color condition on accuracy for the controls, $F(2, 28) < 1$.

Discussion

SE was faster to verify simple addition equations as true or false when the digits were presented in colors that matched her color–digit photisms than when they were presented in mismatched colors or in black. This result replicated the results found in the production task of Mills et al. (2009), and suggests that SE experiences concurrent activation of the numerical representations of digits from both the color and the numerals in the math equation, which ultimately slows verification when the digits do not match her color photisms. Unlike the production task of Mills et al., RT in the black digit condition in the verification task was slower than in the matched condition. The fact that the black condition was slower than the matched condition and that SE's RT in the matched condition are comparable to the controls suggests that interference occurred for SE on black and mismatched trials. Black is the photism color of the digit 9 and seemed to be acting as a mismatched digit.

Control participants also showed an effect of color condition on RT, but a different pattern than SE. Specifically, they were significantly faster to verify equations with black digits compared to the colored digit conditions, and they showed no difference between colors that matched SE's photisms and those that did not.

Accuracy was very high for all participants. We found no evidence of a speed-for-accuracy tradeoff for SE because her accuracy was highest in the same condition that her RT was fastest. The controls showed no effect of color condition on accuracy.

EXPERIMENT 2

In Experiment 1, we found an effect of color–digit photisms in a verification task similar to that found in a production task by Mills et al. (2009). In both of these tasks, all of the digits presented were colored, however in the production task only the two addends were presented. In Experiment 2 we investigated whether coloring only the addends or only the solutions would have the same effect as coloring the whole equation. Given the differences in the tasks and method between Mills et al. and Experiment 1, we wanted to test this directly using the verification task. If verification is production plus comparison (e.g., Ashcraft et al., 1984; Parkman & Groen, 1971) we might expect that coloring the addends might have more of an effect on the performance of a synesthete than coloring the solution. If, however, verification is accomplished by processing the equation as a whole as proposed by Zbrodoff and Logan (1990), we might expect no difference between coloring the addends, or the solution alone.

In Experiment 2A, we presented SE and a new group of controls with the same verification task, but this time only the addends were presented in the three different color conditions and the solution was always presented in black. In Experiment 2B, SE and a third group of controls performed the same task only the addends were presented in black and the solutions were presented in the color conditions. We hypothesized that because similar results were found in both Experiment 1 and the production task used by Mills et al. (2009), we would find effects of color when the addends alone were colored, since the production task only involves addends. It is not clear however whether coloring only the solutions would affect verification times to the same extent if at all, since the solution was already derived based on the addends. However, if the equation is processed as a whole as suggested by Zbrodoff and Logan (1990), or if the solution affects the processing of the equation as a whole as suggested by Campbell (1987), then the effect of color should still occur for the synesthete even if only the solution is colored.

We initially ran SE in both experiments (a and b) in a single session with a 30-min break in between. When we analyzed the RT data we found an effect of color condition in Experiment 2A when the addends were colored but not when the solutions were colored in Experiment 2B. When we looked more carefully at the data, however, we became concerned that the observed differences between the two experiments might not be because of any experimental manipulation, but instead were a ceiling effect due to practice. As a result, we repeated the two experiments with only SE as a participant in the reverse (counterbalanced) order in a second session a few weeks later.

Method

Participants

SE and 19 undergraduate students (different from those in Experiment 1) acting as nonsynesthete controls participated in this experiment. Nine controls participated in Experiment 2A and 10 participated in Experiment 2B.

Apparatus, Stimuli, and Procedure

The apparatus and stimuli were the same as in Experiment 1, except in Experiment 2A, the addends were presented in the same color conditions as in Experiment 1 and the equation solutions were presented in black for all trials. In Experiment 2B, the addends were presented in black for all trials while the solutions were presented in the same color conditions as in the previous experiments. The procedure was the same as in Experiment 1.

Results

The data reported here for SE are for both sessions combined, whereas the results for the controls are based on only one session. Table 2 shows SE's data separated by session.

Experiment 2A

We ran the same ANOVA as in Experiment 1 on SE's RT data and found an effect of color condition, $F(2, 6) = 29.21$, $p < .01$, $\eta^2 = .91$. SE responded significantly faster to equations presented in colors that matched her photisms than to equations presented in colors that did not match her photisms or equations presented in black. Responses to equations presented in black were not statistically

TABLE 2. Synesthete's Mean Correct Reaction Times (in ms) as a Function of Color–Digit Condition and Session in Experiment 2.

	Color-digit condition					
	Match		Black		Mismatch	
	M	*SD*	*M*	*SD*	*M*	*SD*
Experiment 2A						
Session 1	796_{a}	49	$902_{a,b}$	93	908_{b}	73
Session 2	675_{a}	25	705_{a}	24	778_{b}	66
Experiment 2B						
Session 1	$708_{a,b}$	36	697_{a}	34	762_{b}	37
Session 2	675_{a}	31	$674_{a,b}$	33	765_{b}	47

Note. Within each row, subscripts that differ indicate statistically significant differences ($p <$ .05) between conditions based on planned comparisons. Comparisons were not made between experiments.

distinguishable from mismatched equations. For the controls, the same ANOVA as in Experiment 1 revealed no significant effects in Experiment 2A, $F(2, 16) < 1$.

SE's overall accuracy was 96%. There was no effect of color condition on accuracy $F(2, 6) = 3.0, p = .125$. Control participants' mean overall accuracy was 98% and also showed no significant effect of color condition on accuracy, $F(2, 16) = 2.80, p = .091$.

Experiment 2B

Analysis of SE's RTs showed an effect of color condition, $F(2, 6) = 7.91$, $p < .05, \eta^2 = .73$. SE responded significantly faster to equations presented in black than to equations presented in colors that did not match her photisms. Responses to equations presented in colors that matched her photisms were not statistically distinguishable from black or mismatched equations. Analysis of RTs for the control participants showed no effect of color condition, $F(2, 18) = 1.46, p = .248$.

SE's overall accuracy was 95%. The ANOVA revealed a significant effect of color condition on accuracy, $F(2, 6) = 6.78$, $p < .05$, $\eta^2 = .69$, with SE significantly less accurate on mismatched colored trials (93%) than black trials (97%). The control participants' overall mean accuracy was 96%, with the ANOVA revealing no significant effects of color condition on accuracy, $F(2, 18) < 1$.

Discussion

These results suggest that SE's synesthesia affected her processing of the equations because her RTs to verify equations with matched photism colors were usually faster than for equations in mismatched colors. Overall, the matched condition was significantly faster than mismatched one in Experiment 2A, but the difference did not reach statistical significance in Experiment 2B. However, in Experiment 2B, we also found color condition affected accuracy. Because accuracy was significantly lower in the mismatched condition there is the possibility of a speed-for-accuracy tradeoff. Such a tradeoff may have artificially reduced RT in the mismatched condition and resulted in the difference not reaching statistical significance.

When we analyzed SE's data from each session individually, the matched condition was faster than the mismatched condition and was statistically significant in 3 of the 4 sessions (based on planned comparisons). In all individual sessions in Experiment 2A and 2B, the black condition was statistically equivalent to the matched condition. For SE, it also appears that practice may have reduced the differences between the black condition and the matched condition. Overall, SE shows an effect of practice in Experiment 2 compared to Experiment 1 as revealed by the generally faster RTs. Examination of the data in Table 1 also shows that the size of the effect of the color conditions was reduced in Experiment 2.

We did find a difference in the overall pattern of results between Experiment 2A and Experiment 2B. In Experiment 2B, unlike Experiment 1 and Experiment 2A, we did not find a difference between black colored digits and the matched digits, nor between matched and mismatched digits. The potential presence of practice effects, however, makes comparing the data difficult. Contrary to SE, controls showed no effect of color condition on verification performance.

EXPERIMENT 3

In Experiments 1 and 2, we demonstrated that SE performed better in a standard verification task using simple addition equations when the color of the digits in the equations matched her color digit photisms than when they did not match, whereas control participants did not show a comparable color effect. In Experiment 3 we sought to investigate whether this finding would generalize to a verification task using simple multiplication and division equations. In the previous experiments, we also found that as SE's RT decreased with practice, the differences between the color conditions diminished, possibly due to a ceiling effect, so in addition we hoped to increase the difficulty of the task by using a combination of multiplication and division equations and mixing them within each block. We used the same color conditions as in the previous experiments. We hypothesized that SE's classification of these more difficult equations would be faster when the digits were presented in colors that matched her color–digit photisms, and that control participants would show no color effect, replicating and extending our previous findings. Further, if practice reduced the effect of the color manipulation in Experiment 2, we expected that the size of the color effects would increase in comparison to Experiment 2, because this was a new task for SE.

Method

Participants

SE and eight undergraduate students (different from those in Experiments 1 and 2) acting as nonsynesthete controls participated in this experiment.

Apparatus, Stimuli, and Procedure

The apparatus and stimuli were the same as in Experiment 1, except that equations were made up of all possible pairs of the single digits 1–9 in the form $A \times B = C$ or $A \div B = C$, whose true solution equaled 9 or less. This yielded a total of 45 unique equations (23 multiplication equations and 22 division equations). Each equation was presented with a true solution and with a false solution an equal number of times. For trials presented with a false solution, the false solutions were chosen in the same manner as in the previous experiments. All digits were presented in the same color conditions as in Experiments 1 and 2. All stimuli were presented on a white background, with the multiplication or division sign and the equals sign presented in black. The experiment consisted of one block of 96 practice trials representing the overall trial parameters, and four experimental blocks with 270 trials in each block. Each experimental block contained 135 true trials and 135 false trials (each of the 45 unique equations presented in each of the three color conditions for each solution type). The order of presentation of the various types of trials was randomly mixed within each block. Data from the practice trials were not included in the analysis. The procedure was the same as in the previous experiments.

Results

The same ANOVA as in the previous experiments run on SE's RTs revealed a significant effect of color condition, $F(2, 6) = 15.76$, $p < .01$, $\eta^2 = .84$. Planned comparisons revealed that SE responded significantly faster to equations presented in colors that matched her photisms than to equations presented in mismatched colors, or in black. RTs for equations in mismatched colors and black were not statistically distinguishable. Analysis of RTs for control participants showed a significant effect of color condition, $F(2, 14) = 4.54$, $p < .05$, $\eta^2 = .39$, with planned comparisons revealing that control participants were faster in the black condition than in either of the color conditions. RT in the matched color condition was again not significantly different from the mismatched color condition. This is the same pattern we observed in the controls in Experiment 1.

SE's overall accuracy was 93%. The same ANOVA run on mean accuracy indicated a significant effect of color condition, $F(2, 6) = 17.81$, $p < .01$, $\eta^2 = .86$. Planned comparisons revealed that SE was significantly more accurate in the matched color condition (98%) than in either the mismatched (89%) or black (91%) conditions. Accuracy did not differ between the mismatched and black conditions. The control participants' overall accuracy was 97%. They showed no effect of color condition on accuracy, $F(2, 14) < 1$.

Discussion

As in Experiments 1 and 2, SE's responses were significantly faster and more accurate to verify equations with digits in matched colors than those with digits in mismatched colors. In addition, for RT the size of the effects were as large as in Experiment 1. Making the equations more difficult seemed to take away the ceiling effect due to practice. Furthermore, in this experiment, RT in the black condition increased relative to the matched condition, indicating that the black color was again interfering for SE. As in Experiment 1, control participants showed an overall effect of color condition on RT—they were significantly faster to verify equations with black digits compared to the colored digit conditions, and they showed no difference between colors that matched SE's photisms and those that did not. Overall accuracy was highest for SE in the matched color condition (where RT was also fastest) showing that there was no speed-for-accuracy tradeoff.

GENERAL DISCUSSION

The results of these three experiments support our hypothesis that synesthesia affects verification performance. In Experiment 1, we demonstrated that SE verified equations as true or false faster when the equations were presented in colors that matched her color–digit photisms as compared to when they were presented in colors that did not match her photisms. Contrary to SE, controls showed no difference between colors that matched SE's photisms and those that did not. We conclude that the color of the digits affects her processing of the equations due to concurrent activation of the numerical representation based on the digit and the color. This is consistent with the results of Dixon et al. (2000) and Mills et al. (1999) and also extends the findings from the production task of Mills et al. (2009) to a verification task.

In Experiment 2, we repeated the task and the color manipulation but only colored some of the digits. The results of Experiments 2A and 2B were consistent with Experiment 1. We initially thought that whether the colored digits were addends or the solution might affect SE's response and therefore differences between Experiments 2A and 2B would allow us to distinguish between competing accounts of mathematical verification. We did not find the expected differences, but it appears that SE's results were affected by practice. This practice effect was revealed in two ways. First, SE's responses became faster across Experiments 1 and 2 (and across sessions in Experiment 2), and second, the RT to black digits decreased relative to the other color conditions. We have proposed that the color black interferes because it corresponds to SE's photism for 9. With practice, the color black became less interfering. This interpretation is suggested by the findings of Experiment 1, in which the matched condition for SE is faster than the black condition, but about equivalent to the control participants' RT in each color condition (see Table 1). Previous research with SE also found that her responses to black digits decreased across trials (Mills et al., 2009).

In Experiment 3, we generalized the findings from the earlier addition experiments to multiplication and division. By using a combination of simple multiplication and division equations in a single experiment, we were also able to eliminate the practice effect observed for SE in the earlier experiments. As expected, the effects of practice with addition equations and the resulting ceiling effects disappeared in Experiment 3, when the equations were switched to multiplication and division. In Experiment 3 the effects were again large for SE between the color conditions and the RT for black digits increased relative to the matched digits. Note that ceiling effects were not present for the controls because they had no prior experience with the verification task. The fact that there were new control subjects in each experiment also makes it impossible to compare the RTs directly for SE and the controls, particularly in Experiments 2 and 3.

These results contribute to the growing literature that demonstrates that synesthetic photisms can influence the processing of digits. Our three experiments suggest that the color of the digits affected SE's processing of the equations. This view is consistent with Zbrodoff and Logan's (1990) dual macroprocess model of production and verification. Zbrodoff and Logan propose an associative network model where digits and mathematical operators are associated with their solutions. According to this model, activation flows along these connections between individual digits and their associated solutions. Macroprocesses operate on these patterns of activation. Different tasks may involve different macroprocesses operating on the same patterns of activations. For example, in the production task the macroprocess might select the most highly activated node, presumable corresponding to the correct answer, but in the verification task, the macroprocess may need to select between a set of activated nodes associated with the false answer and the ones associated with a true answer. We propose that for SE, synesthesia affects the representations of digits, altering the activation of each digit. When the color of the digits is consistent with the digit identity, this increases the activation leading to a quicker (and more accurate) response. When the color is inconsistent, as in the mismatched and black color conditions, there is some activation in the unrelated digits. Because this activation due to the photism occurring at the level of the representation of the digits, the model predicts similar effects in both production and verification tasks.

These results are also consistent with production plus comparison accounts (e.g., Ashcraft et al., 1984; Parkman & Groen, 1971). According to this view, the color of the addends might influence the speed and accuracy of the initial production stage and the color of the solution might influence the comparison stage similarly. If the colors of the digits were consistent with SE's photisms, we would expect faster and more accurate responses than when they were inconsistent. We expected the results of Experiment 2 to help differentiate between the dual macroprocess model and production plus comparison accounts; the obtained results, however, are consistent with both these two models.

The number of digits colored also may have affected SE's performance. Our results—showing more of an effect of color in Experiments 1 and 3, where all of the digits were colored, than when only 2 digits (Experiment 2A) or only 1 digit (Experiment 2B) were colored—are consistent with this claim. Given that these may be subtle effects and given the large practice effect observed, however, it is difficult to disentangle this in the current research. Additional studies are planned to investigate this question.

In any event, we can conclude from this study that synesthesia affects arithmetic verification performance, and that these effects are similar to effects seen in arithmetic production and other mathematical tasks. This study also serves to remind us how dynamic synesthesia can be with high levels of practice (see Mills et al., 2002 for a similar finding) and therefore how much caution is needed in working with a synesthete (or other single cases) due to the potential effects of practice on task performance.

NOTES

1. We used black as a standard condition encountered in real life. However, because SE's photism for 9 is black, the black digit condition may not be entirely neutral.
2. We also ran the same ANOVA that we ran on SE's data with Block as a random factor on data from the control participants and found no effect of color condition on RT or accuracy in any experiments.

AUTHOR NOTES

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