Bidirectionality in synesthesia:

Evidence from a multiplication verification task

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Abstract

Color-grapheme synesthetes automatically perceive achromatic numbers as colored (e.g., 7 is turquoise). Up until recently, synesthesia was believed to be unidirectional. For instance, the number 7 gives rise to the percept of turquoise but the perception of turquoise does not trigger the number 7. However, some recent studies argue for bidirectional connections (Cohen Kadosh et al., 2005; Johnson et al., 2007; Knoch et al., 2005). In the present study, a multiplication verification task (e.g., 7 x 2 = 14, true/false?) was used to test bidirectionality. In agreement with previous studies we observed that the presentation of colors evokes numerical magnitudes. The current findings add two important notions to previous studies: 1) The influence of color on the processing of numerical information can be extended to multiplication verification tasks, and 2) The perception of color can both facilitate and interfere with the processing of digit-related information.

Key words: synesthesia, mental arithmetic, bidirectionality

Introduction

In synesthesia, certain types of stimuli give rise to experiences in modalities that are normally not associated with such stimuli. For example, some synesthetes experience tastes when hearing sounds (Ward & Simner, 2003), others feel tactile stimulation while seeing others being touched (e.g., Banissy & Ward, 2007; Baron-Cohen et al., 1996). In the more common type of synesthesia, letters or digits evoke colors (Day, 2005). In all types of synesthesia, an inducer (e.g., digit) gives rise to a concurrent (e.g., color). Although models differ with respect to the precise underlying neural mechanisms, there is consensus that synesthesia results from atypical interactions between brain regions (Hubbard & Ramachandran, 2005; Rich & Mattingley, 2002).

In grapheme-color synesthesia graphemes, digits or letters evoke colors. In a seminal study, Dixon, Smilek, Cudahy and Merikle (2000) demonstrated that the physical presentation of a stimulus is not necessary for the synesthetic experience to occur. An addition problem was presented to a synesthete (e.g. 5 + 2) followed by a colored square that was either congruent or incongruent with the solution of the problem, and the synesthete named the color of this square as quickly as possible. Although the correct solution (e.g., 7) was never shown, the synesthete responded faster to congruent trials (e.g., when a yellow square was presented in the case where the number 7 induces a yellow color) than to incongruent trials (e.g., when a color different to the correct solution was presented). This Stroop-like phenomenon has been replicated (Smilek, Dixon, Cudahy, & Merikle, 2002) and was also extended to the auditory modality (Jansari, Spiller, & Redfern, 2006).

The results of the described studies demonstrate that digits may evoke colors. For instance, the addition problem presented to the synesthete activates a certain numerical solution which in turn activates a color and this color interferes with naming the color of the presented square. It can be asked whether this interference also works in the opposite direction. Does the presentation of a color activate a number that in turn interferes with the correct solution? Although synesthetes can voluntarily retrieve numbers that are usually evoked by a certain color; this process does not appear to be automatic and the numbers are not experienced vividly. As such, this question refers to the issue of directionality. Some authors have claimed that synesthesia is unidirectional so that an inducer gives rise to a concurrent but not vice versa (e.g., Mills, Boteler, & Oliver, 1999).

However, a few recent studies have reported evidence for bidirectionality in synesthesia. Most of these studies used tasks which explicitly required magnitude processing. For instance, in the study of Cohen Kadosh et al. (2005), synesthetes had to explicitly judge the magnitude of two colored digits (e.g, which of the two presented digit is the largest). The researchers based their paradigm on the distance effect (Moyer & Landauer, 1967): The larger the numerical distance between two digits the easier it is to determine which number is largest. Magnitude judgments were performed faster if the synesthetic colors of the digits referred to digits that were more distant from each other than the digits that were actually presented. For instance, the digits 4 and 5 were compared faster if they were presented in the colors of the more distant digits 2 and 7. Apparently, the colors activated numerical values, and since 2 and 7 are compared more easily than 4 and 5, the activated numbers facilitated the comparison. However, no interference was observed in the situation where the digits 2 and 7 were presented in the synesthetic colors of 4 and 5. The absence of interference could have resulted from the fact that the magnitude judgment task was too easy with the larger numerical distance (indicated by faster reaction times) so that interference could not be observed. Therefore, the question whether synesthetic colors can also interfere with the processing of digit information is yet unresolved.

Additionally, the results obtained by Cohen Kadosh et al. (2005) show that perception of synesthetic colors can facilitate the processing of magnitude information. An important remaining question is therefore whether colors can activate digit-related information other than numerical magnitude as well. So far, only one study reported that this can indeed be the case in some synesthetes (Johnson, Jepma & de Jong, 2007). In a color-digit Stroop task synesthetes showed a congruency effect. More specifically, in a naming task digits were named faster if they were presented in their synesthetically correct color compared to another color. Note that, also in this case it cannot be concluded whether the congruency effect results from facilitation of congruent colors or from interference from incongruent colors. The facilitation-interference question is an important issue, because if colors only lead to facilitation but not to interference, it might be an indication that color information is actively and strategically employed to optimize performance. Of course, such a possibility seriously questions the automatic nature of the color to digit activations and therefore also true bidirectionality (given that the automatic nature of the digit or color activations is firmly established).

The present study was designed to investigate two issues: 1) Do colors evoke number information other than numerical magnitude? and 2) Does color-induced number information lead to facilitation effects, interference effects, or both? A synesthetic subject, J.Q. performed a multiplication verification task on simple one-digit multiplication problems (e.g. 7x4=28; correct: yes or no?). Such simple multiplication facts are stored in rote verbal memory and are primarily solved by direct retrieval from long-term memory with no or only minimal involvement of quantity manipulation or other elaboration strategies (e.g., Dehaene, Piazza, Pinel, & Cohen, 2003; Ischebeck et al., 2006). More precisely, operands and results are represented in a semantic associative network (e.g., Campbell & Graham, 1985; Verguts & Fias, 2005). A typical characteristic is that a multiplication problem not only activates the correct answer, but also the neighbors of this problem (Galfano, Rusconi, & Umiltà, 2003). For instance, the presentation of two numbers (for instance 7 and 4) activates not only the correct solution 28 but also immediate neighbors such as 21 (7 x 3) and 35 (7 x 5). In the present study we take benefit of this principle of spreading of activation to investigate synesthetic bidirectionality more thoroughly. More specifically, we compare conditions in which the solutions of simple multiplication problems are presented in (a) their correct synesthetic color, (b) the synesthetic color of a table-related solution, (c) the synesthetic color of an unrelated solution or (d) a white background color (see Figure 1).

Insert Figure 1 about here

Comparing conditions in which the semantic relatedness of incorrect synesthetic colors is varied enables us to investigate whether synesthetic colors can facilitate and/or interfere with the processing of digit related information. If the colors activate their associated number (e.g. bidirectionality) then we can predict a specific pattern of results. In the case where a multiplication problem is presented with an incorrect table-related solution, the performance of J.Q. should be improved if the synesthetic color is totally wrong too (e.g. an unrelated incorrect color). This observation would agree with observations of facilitation by the presentation of synesthetic colors (e.g. Cohen Kadosh et al., 2005). Importantly, if synesthesia is truly bidirectional then we should also be able to observe interference by the synesthetic colors. Correct numerical solutions should be judged slower if presented with an incorrect but table-related color.

The synesthetic participant examined in the present study, J.Q. is not an explicit bi-directional synesthete. Digits evoke the conscious experience of colors but not vice versa. The perception of colors does not lead to the conscious experience of digits. Therefore, if effects of bi-directionality are observed with this participant, these effects are of an implicit nature. One unique characteristic of J.Q.'s synesthesia, and the reason why her specific form of synesthesia is highly relevant for the present study, is that her digit-color synesthesia is not restricted to one digit numbers but extends to two-digit numbers. Whereas the large majority of reported digit-color synesthetes who experience color with 2 digit numbers experience one color for each two-digit number (Cohen Kadosh & Henik, 2007), JQ experiences two-digit numbers as two-colored entities. What makes this specific instance of synesthesia even more interesting, is that the color experience depends on the syntactic context of the digit (Simner, 2007) in the sense that J.Q. experiences a different shade of color when the digit expresses a unit, a decade or a hundred digit. For instance, J.Q. experiences the number 28 as a light-pink-to-dark-grey entity (see Figure 1), with light pink being the color of decade 2 and dark grey being the color of unit 8. But when 2 occurs as a unit, it is associated with an even lighter pink color (almost white), and when 2 occurs as a hundred, it is associated with a very dark pink color.

Methods

Participants

J.Q. is a right handed female who was 21 years old at the time of testing. She experiences colors projected at the background of a number. Additionally, she experiences color perception with speech sounds but not with printed letters or words. A group of 10 non-synesthetic controls (8 female, 2 male; first year psychology students) with normal color vision received the same stimuli as the synesthetic participant. Given that J.Q. performed the task 12 times in the course of a year, the comparison with the control participants is based on largely the same amount of trials. Additionally, given that the experiment was spread over such a long period of time, provides with an implicit control for the genuinity and constancy of the synesthetic experience of J.Q. Informed consent was obtained from all participants prior to inclusion in the study.

Stimuli

Out of all possible combinations of multiplication problems with operands ranging from 2 to 9, 40 were selected. Multiplication problems with a correct solution of only one digit (e.g., 2 x 3) were excluded, as were tie problems (e.g., 4 x 4). Each multiplication problem was presented in both ascending (e.g., 4 x 6) and descending (e.g., 6 x 4) order. Additionally, for each stimulus (e.g. 2 x 7) we created four new stimuli (2 table-related and 2 table-unrelated). In half of the cases the presented problem was larger than the stimulus, in the other half it was smaller (e.g. 2 x 6 and 3 x 7).

Within each session, half of the verification trials were presented with a correct solution and half with a false solution. With a false solution, half the trials were assigned a related false answer (e.g., 3 x 7 = 14) and half were assigned a table-unrelated false answer (e.g., 4 x 6 = 22). In order to avoid practice effects, two different sets of related and unrelated solutions were constructed. This resulted in a total of 200 stimuli (i.e., 40 with a correct solution, 2 x 40 with a related solution, and 2 x 40 with an unrelated solution (see appendix 1). Correct stimuli were presented more to match the number of incorrect stimuli.

Problem size was matched across the three number types (correct, table-related and table-unrelated solutions). More specifically, comparisons across these number types resulted in: correct vs. table-related: $t(58) < 1$, $p = .92$; correct vs. table-unrelated: $t(58) < 1$, $p = .98$; table-related vs. table-unrelated: $t(78) < 1$, $p = .92$. Unrelated false answers were approximately 10% larger or smaller than the correct answer and were not multiples of either of the problem's operands. Related false answers were from the same table as the presented problem (e.g., 3 x 7 = 14). Half of the related and unrelated solutions were smaller than the correct solution and half of them were larger than the correct solution.

The even/uneven ratio was equal across correct, related, and unrelated solutions (each $t < 1$). Finally, also problem size was equal across the three conditions (each $t<1$).

We also manipulated the color of the background upon which each solution was presented. More specifically, each solution was presented in colors that were either correct (e.g., 3 x 7 = 21 in the color of 21), unrelated false (e.g., 3 x 7 = 21 in the color of 16) or related false (e.g., 3 x 7 = 21 in the color of 14). Additionally, solutions could be presented with no background at all.

The manipulation of solution types (correct, table related, unrelated) and color types (correct, table related, unrelated, or white) resulted in a 3 x 4 repeated measures design.

Procedure

Each trial started with the presentation of a fixation point. Then, both operands were presented one after the other with a multiplication sign (x) in between. Each presentation lasted 250 ms, and was followed by an empty, white screen for 250 ms. The fixation point, operands, and multiplication sign were presented in black on a white background (no digits evoked the color black or white for J.Q.). After this presentation a solution was presented at the center of the screen and the subjects had to indicate whether the presented solution was correct or false with a left or a right key press (counterbalanced across sessions).

J.Q. performed 12 sessions on different days in the course of one year. Within each session, each multiplication problem was presented 16 times (8 times with a correct solution, 4 times with an unrelated and 4 times with a related false solution, presented once with each background color). Each session consisted of 640 experimental trials. Before each experimental session, 10 practice trials were run. The control participants each performed one session.

Results

The data of the synesthete and the control participants were analyzed separately.

Synesthete

The proportion of incorrect responses was 5.13%. These trials were excluded from all median RT analyses. An analysis of variance (ANOVA) was performed across the 12 sessions and solution types. This resulted in a 3 (number type: correct, unrelated, table related) x 4 (color type: correct, unrelated, table related, white) ANOVA.

For the latencies, a main effect of number type ($F(2,22) = 36.12$; $p < .001$.) was observed. Planned comparisons showed that correct answers were judged faster than unrelated answers ($F(1,11) = 19.30$; $p < .01$) which in turn were judged faster than table related answers ($F(1,11) = 10.62$; $p < .01$). The main effect of color type was marginally significant ($F(3,33) = 2.73$; $p < .06$). Planned comparisons showed that numbers presented with a white or a unrelated background were judged faster than numbers presented with a correct or a table related background ($F(1,11) = 11.95$; $p < .01$).

Importantly, the interaction between number type and color type was significant, $F(6,66) = 2.95$; $p < .05$ (see Figure 2).

Insert Figure 2 about here

Consequently, planned comparisons are performed to further investigate the predictions outlined in the introduction. These planned comparisons are reported one-sided. Importantly, to avoid identity benefits, conditions where a correct solution was shown in its correct color, where an unrelated solution was shown in its correct unrelated color or where a table related solution was shown in its correct table related color, are omitted from the following planned comparisons. In the case where the presented solution was correct, J.Q. had to indicate that the answer was correct. In this case it was predicted and confirmed that colors referring to the incorrect but table related solution would cause more interference than unrelated and white backgrounds ($F(1,11) = 3.30$; $p < .05$). In the condition where an unrelated solution was presented, J.Q. had to indicate that the outcome was incorrect. In this situation, showing the solution in the synesthetic color referring to the correct solution was predicted to interfere relative to the white background and the table related background because these latter colors point to the correct response (i.e., respond false). This effect was marginally significant ($F(1,11) = 2.81$; $p < .07$). Finally, in the condition where the presented solution was incorrect but table related, J.Q. had to indicate that the outcome was incorrect. In this situation, presenting the number in an incorrect unrelated color should facilitate her responses relative to the white background or the correct color. This prediction was confirmed

($F(1,11) = 6.04$; $p < .05$). Finally, in order to test the consistency of the performance of J.Q., the twelve sessions were divided in 4 time frames. This factor did not interact with any of the effects (all $p > .13$) showing that the performance of J.Q. was consistent over time.

Control Group

The proportion of incorrect responses was 6.39%. For the latencies, a main effect of target number ($F(2,18) = 4.86$; $p < .05$) was observed. Median correct responses to the correct, the table-unrelated and the table-related stimuli were respectively 547, 564 and 631 ms, respectively. Planned comparisons showed no difference between correct and unrelated answers ($F < 1$). Both correct ($F(1,9) = 7.03$; $p < .05$) and unrelated answers ($F(1,9) = 4.59$, $p < .07$) were judged faster than table related answers. Importantly, neither the main effect of color type ($F(3,27) = 1.39$; $p < .27$) nor the interaction with target type approached significance ($F(6,54) = 1.12$; $p < .36$).

In order to enable exactly the same analyses as performed with our synesthetic participant, we tested one additional control participant. Just like J.Q. this subject performed 12 sessions. Replicating the results of the control group, there was a significant effect of number type ($F(2,22) = 28.02$; $p < .0001$) , no effect of color type ($F(3,33) = 0.72$; $p < .55$) nor an interaction between color type and target type ($F(6,66) = 0.93$; $p < .48$). Importantly, the planned comparisons for the conditions showing significant differences with J.Q. were far from significant for the control participant (all $F < 1$).

Discussion

In line with previous observations (Cohen Kadosh et al., 2005; Knoch et al., 2005; Johnson et al., 2007) we observed that the visual experience of color influences the processing of numerical information. The results from the current multiplication verification task with two-digit numbers, which was used for the first time in synesthetic research, gives a strong indication that what is being evoked by the color extends to arithmetical fact knowledge, and hence is not restricted to numerical magnitude. In a multiplication verification task, magnitude information does not need to be manipulated explicitly as multiplication tables can be stored in rote verbal memory placing (Dehaene, Piazza, Pinel, & Cohen, 2003). This result is in line with the work of Johnson and colleagues (2007, see also Knoch et al., 2005) where it is shown that the influence of color experience on the processing of numerical information is not restricted to tasks where magnitude information has to be processed explicitly. Indeed, large consensus exists from both behavioral and imaging studies that simple multiplication verification tasks are performed on the basis of long term memory associations instead of magnitude processing (for review see Dehaene et al., 2003).

The control participants did not show a moderating effect of digit color on the processing of digit information showing that the interaction obtained between number type and color type is specific to the synesthetic experience of J.Q. The present results support the notion of bidirectionality in synesthesia, which is reported in few studies so far. The use of a simple multiplication verification task provides with additional theoretical advantages.

Most importantly, because a multiplication verification task was used, it was possible to look for both facilitation and interference effects in situations where the colors of the presented solution were incongruent with the synesthetic colors. Both facilitation and interference effects were indeed observed. These results provide strong evidence that the semantic association network of multiplication facts is activated by the mere presentation of colors. This result resembles those obtained by Cohen Kadosh et al (2005), who observed that colors can activate a magnitude representation if the explicit processing of magnitude information is required. However, the present results differ in one important aspect from those reported by Cohen Kadosh et al. In the explicit magnitude task used by Cohen Kadosh et al., synesthetic colors facilitated performance, in no occasion interference was observed. It was not clear whether this lack of interference was due to the time course (faster responses with larger numerical distance) or whether it is specific to synesthesia. The present results indicate that it is not specific to synesthesia because both facilitation and interference were observed in the present paradigm. In the study of Cohen Kadosh et al. presented numbers needed to be compared with each other but were not inherently correct or incorrect. This was the case in the present study where the numerical solutions presented to J.Q. could be either correct or incorrect. In the case of an incorrect, but table related solution, performance was facilitated by presenting the solution in synesthetic unrelated colors. On the contrary, in the case of a correct solution, synesthetic incorrect but related colors interfered with performance. Future research should help to clarify whether the need to judge the outcome as correct or incorrect is the important characteristic to observe both facilitation and interference. Some might argue that bi-directional synaesthesia is due to a lifetime of experience pairing numbers and colors that affects memory. While this can provide some challenge not only to bi-directional synesthesia, but also to unidirectional synesthesia (Elias et al., 2003), brain imaging challenge this idea. It seems that bi-directional synesthesia occurs at perceptual-related areas in the occipito-temporal cortex, and modulates an ERP component that relates to perceptual (N170) rather than cognitive processes. Additionaly, the finding that not all synesthetes are bi-directional synaesthetes (Johnson et al., 2007), implies that bi-directionality might be due to different underlying brain mechanism rather than simply the result of a lifetime of experience pairing numbers and colors.

In line with previous research, our synesthetic participant J.Q. shows evidence for implicit bi-directionality. Additionally, the results show that this bi-directionality is not restricted to numerical magnitude information but extends to other number related information as well (for instance, table relatedness in multiplication). Finally, subscribing to the idea of the automatic activation of color to digit activation, it is demonstrated that color-induced number information can lead to both facilitation and interference. One possible limitation of this study is that the present conclusions are based on observations made with a single synesthete. Therefore, it would be favorable to further substantiate these conclusions in future studies by searching and investigating a larger group of synesthetes with similar synesthetic experiences.

Author Note

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Figure Caption

Figure 1: A graphical illustration of the stimulus material that was presented to J.Q. In this example, a multiplication problem is presented with a correct numerical solution. However, for J.Q, the background colors refer to a) the correct solution, b) a table-related solution, c) an unrelated solution and d) a white background. The colors were drawn by J.Q.

Figure 2: Response times (in milliseconds) as a function of number type (correct, unrelated, table related) and color type (correct, unrelated, table related, white).

Figure 1

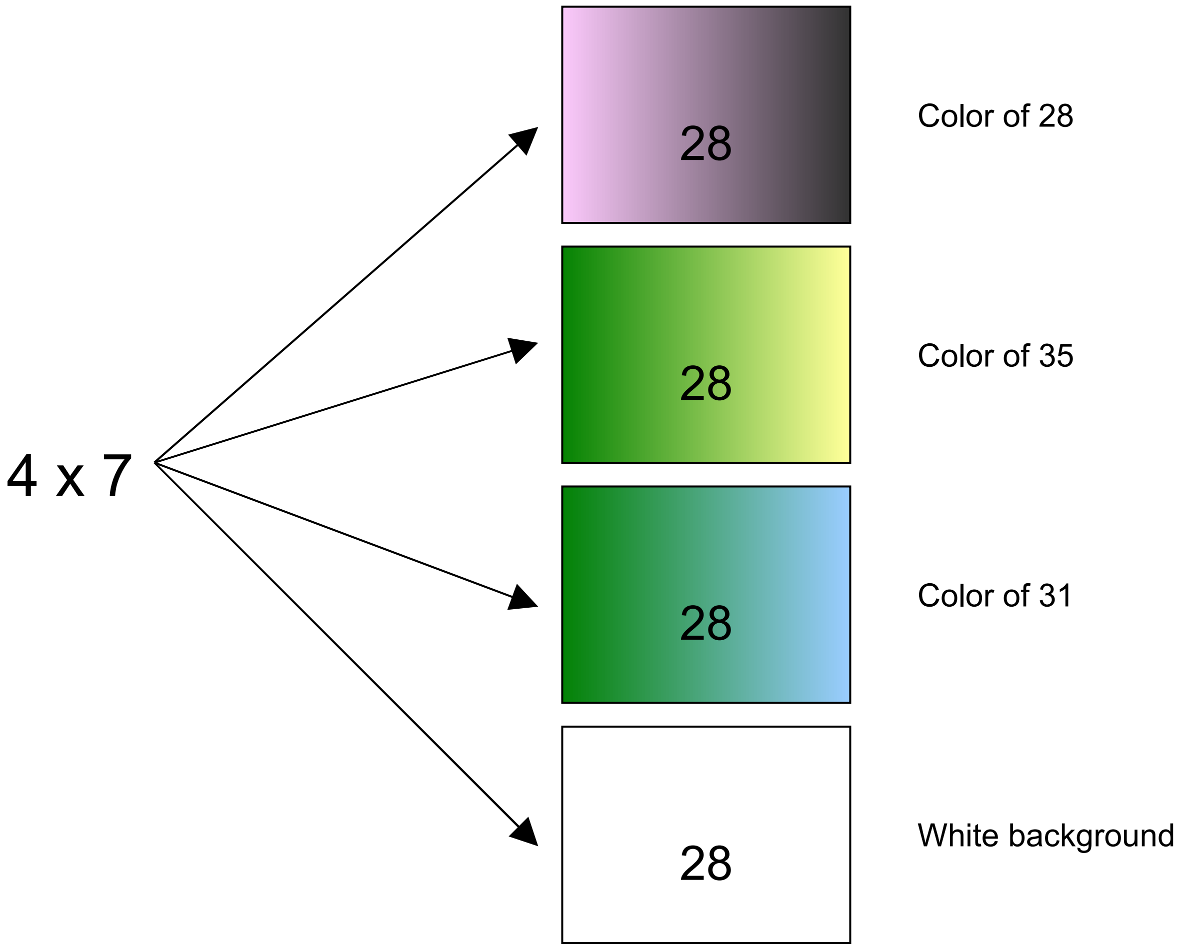
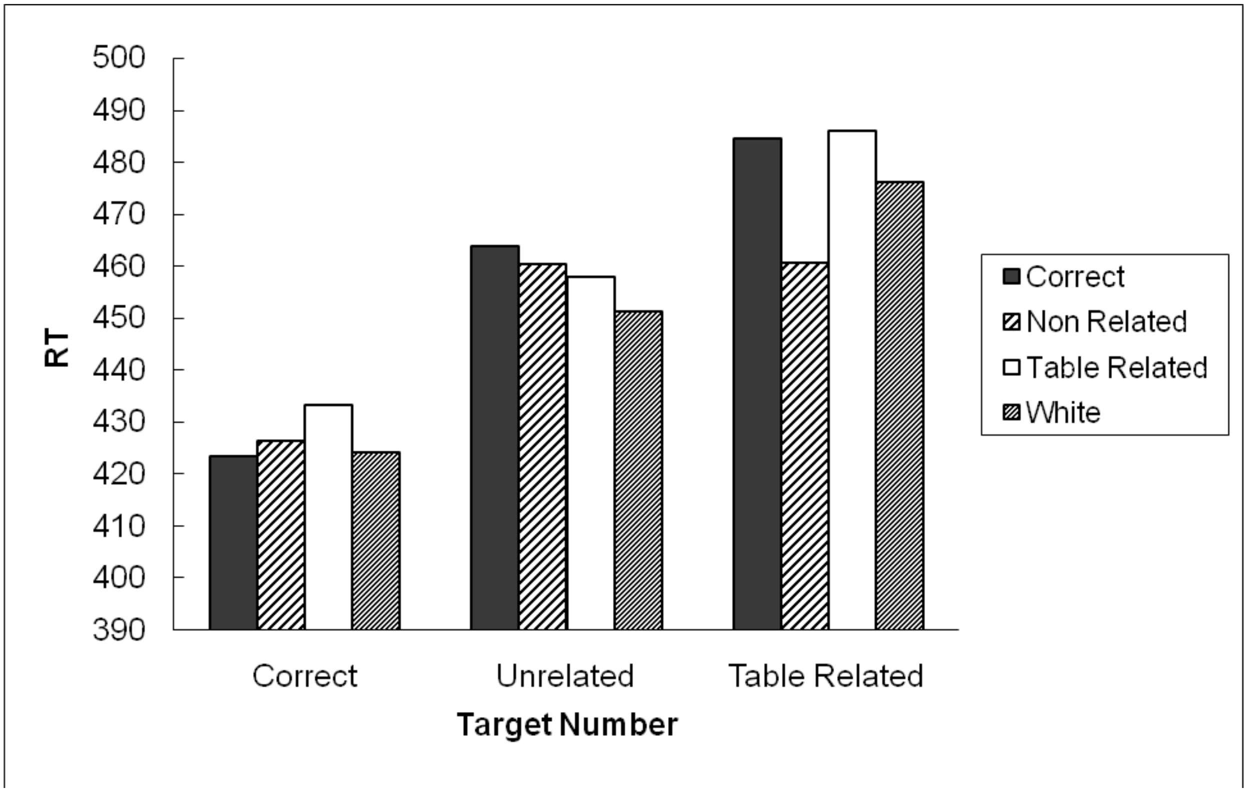

4 x 7
28
Color of 28
28
Color of 35
28
Color of 31
28
White background

Figure 2


500
490
480
470
460
450
440
430
420
410
400
390
RT
Correct
Unrelated
Table Related
Target Number
Correct
Non Related
Table Related
White

Appendix 1: List of all stimuli used in this study.

The targets were divided into two sets. Set 1 was used in half of the sessions and Set 2 was used in the other half. The allocation of sets was counterbalanced with the response modus (right/left key press).

Operand 1	Operand 2	Target (set 1)	Target (set 2)	Relation
2	7	14	14	Correct
2	7	21	12	Table related
2	7	19	13	Unrelated
2	8	16	16	Correct
2	8	14	24	Table related
2	8	15	21	Unrelated
2	9	18	18	Correct
2	9	27	16	Table related
2	9	23	17	Unrelated
3	5	15	15	Correct
3	5	12	18	Table related
3	5	13	16	Unrelated
3	6	18	18	Correct
3	6	21	12	Table related
3	6	22	14	Unrelated
3	7	21	21	Correct
3	7	14	24	Table related
3	7	16	22	Unrelated
3	8	24	24	Correct
3	8	27	16	Table related
3	8	26	19	Unrelated
3	9	27	27	Correct
3	9	24	36	Table related
3	9	25	32	Unrelated
4	6	24	24	Correct
4	6	28	18	Table related
4	6	26	22	Unrelated
4	7	28	28	Correct
4	7	24	35	Table related
4	7	26	31	Unrelated
4	8	32	32	Correct
4	8	36	24	Table related
4	8	34	26	Unrelated
4	9	36	36	Correct
4	9	32	45	Table related
4	9	34	42	Unrelated
5	3	15	15	Correct
5	3	12	18	Table related
5	3	13	16	Unrelated
5	7	35	35	Correct
5	7	42	28	Table related
5	7	38	31	Unrelated
5	9	45	45	Correct
5	9	36	54	Table related
5	9	41	49	Unrelated
6	3	18	18	Correct
6	3	21	12	Table related
6	3	22	14	Unrelated
6	4	24	24	Correct
6	4	28	18	Table related