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Executive functions in synesthesia

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ABSTRACT

In grapheme-color synesthesia, a number or letter can evoke two different and possibly conflicting (real and synesthetic) color sensations at the same time. In this study, we investigate the relationship between synesthesia and executive control functions. First, no general skill differences were obtained between synesthetes and non-synesthetes in classic executive control paradigms. Furthermore, classic executive control effects did not interact with synesthetic behavioral effects. Third, we found support for our hypothesis that inhibition of a synesthetic color takes effort and time. Finally, individual differences analyses showed no relationship between the two skills; performance on a 'normal' Stroop task does not predict performance on a synesthetic Stroop task. Across four studies, the current results consistently show no clear relationship between executive control functions and synesthetic behavioral effects. This raises the question of which mechanisms are at play in synesthetic 'management' during the presence of two conflicting (real and synesthetic) sensations.

1. Introduction

In synesthesia, certain sensations will evoke additional, seemingly unrelated, sensations. One of the most common and well-studied types of synesthesia is grapheme-color synesthesia, where letters or numbers evoke colors (e.g. Baron-Cohen, Wyke, & Binnie, 1987; Ramachandran & Hubbard, 2001b; Simner et al., 2005; Smilek, Dixon, Cudahy, & Merikle, 2001). For example, for a certain synesthete the letter 'R' might evoke a bright-blue color. There are many different types of synesthesia, for example, moving patterns that evoke sounds (Saenz & Koch, 2008) or words that elicit a taste (Ward & Simner, 2003). Different from 'normal' (memory) associations, synesthetic experiences have a truly perceptual nature (Dixon, Smilek, Cudahy, & Merikle, 2000; Palmeri, Blake, Marois, Flanery, & Whetsell, 2002; Ramachandran & Hubbard, 2001a; Smilek et al., 2001). Furthermore, synesthetic experiences are consistent (the same associations persist from early childhood), idiosyncratic, highly specific, and are evoked rapidly and seemingly effortlessly. Synesthesia runs in families, and genetic association studies support the idea of a genetic predisposition (Asher et al., 2009; Barnett et al., 2008; Tomson et al., 2011). The estimated prevalence is about 4%, and the grapheme-color subtype has an estimated prevalence of about 1% of the population (Simner et al., 2006). Synesthesia is not related to drug use, or to psychological, psychiatric or neurological disease. Instead, synesthetes generally report that their synesthesia does not bother them, but is pleasant and useful.

It is fascinating how synesthetes can have two different, and possibly conflicting, sensations (e.g. the 'real' and the synesthetic color of a letter) in response to one and the same stimulus. These two experiences sometimes even share the same location in external space (Dixon, Smilek, & Merikle, 2004; Ward, Li, Salih, & Sagiv, 2007). Yet, synesthetes report and display

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little distraction from their synesthetic experience. In fact, the synesthesia can be used to their benefit, such as improved performance in visual detection tasks (Ramachandran & Hubbard, 2001a; Ward, Jonas, Dienes, & Seth, 2009) or memory tasks (Rothen & Meier, 2009; Smilek, Dixon, Cudahy, & Merikle, 2002). Apparently, in their daily lives synesthetes are competent at managing the 'real' and synesthetic sources of information such that the synesthetic sensation is incorporated into perception without producing noticeable interference. In this study, we aim to address this aspect of synesthesia that to date has received little attention in the literature and has remained largely exempt of experimental scrutiny, despite its prominent significance and potential consequences. To what extent does synesthesia tap into executive control processes to 'manage' the perception of extraneous features vis-à-vis the synesthetic experience that these features elicit?

A few incidental counterexamples notwithstanding (e.g. one synesthete reported her surprise upon hearing bagpipe music on the beach, until she realized the sight of the moving water evoked a synesthetic auditory experience of bagpipe music), synesthetes report that it usually takes little effort to 'know' whether a sensation is synesthetic or not. Furthermore, the additional sensations generally do not confuse or distract them. While these reports seem to indicate little conflict between synesthetic and non-synesthetic sensations, such obtained flawless performance is an end result, and does not inform us about the intermediate processes involved. As explained below, the effects of conflict between synesthetic and non-synesthetic experiences can be made visible in specifically designed behavioral experiments with synesthetes.

One of the most well-known and most extensively studied effects of conflict in synesthesia is the 'synesthetic Stroop' effect (Beeli, Esslen, & Jäncke, 2005; Berteletti, Hubbard, & Zorzi, 2010; Dixon et al., 2000, 2004; Mattingley, Rich, Yelland, & Bradshaw, 2001; Wollen, Ruggiero, & Frank, 1983). This is an adaptation of the standard Stroop paradigm, a classic paradigm to measure cognitive control skills (MacLeod, 1991; Stroop, 1935). In a standard Stroop task, a color word is presented in a congruent or incongruent typeface color. The Stroop effect is a slower report of the typeface color in the incongruent condition relative to the congruent condition. In a synesthetic Stroop task, a grapheme-color synesthete is presented with a grapheme (most often a letter or a number) that to him or her has a synesthetic color. The grapheme is presented in a typeface color that is congruent or incongruent with its synesthetic color. The synesthete is both able to report the synesthetic color and to report the typeface color, depending on the task at hand. Yet, performance tends to be slower in the incongruent trials as compared with the congruent trials, showing an effect of conflicting (versus similar) colors. Which mechanisms are involved in this interference between the two types of colors? Is there some type of 'managing' mechanism that allows the synesthetes to make few errors in the synesthetic Stroop task? In this study, we will study situations of conflict between synesthetic and 'real' (color) sensations. Furthermore, we will examine the mechanisms involved during this conflict. In particular, we will explore the role of executive functions during the additional (and possibly conflicting) synesthetic sensations.

Currently, little is known about the role of executive functions in synesthesia. There are several ways the system could deal with conflicts resulting from incongruent synesthetic and 'real' experiences. This can range from simply ignoring the irrelevant (color) experience, to engaging additional executive functions to solve the conflict. With little known about the mechanisms involved during these situations, the current study is necessarily an exploratory one. As a starting point, we assume that at least part of the functions involved in synesthesia are not yet understood. As we will explain below, this assumption is supported by neuroimaging studies.

Different accounts of the neurobiological and cognitive mechanisms underlying synesthesia coexist, the most influential model of which is the 'cross-activation' theory (Ramachandran & Hubbard, 2001b). It proposes that synesthesia arises from cross-activation of one modality-specific representation to another. The model was recently extended (Hubbard, Brang, & Ramachandran, 2011) to include the parietal lobe as a synesthesia 'hub' (Jäncke & Langer, 2011; Specht & Laeng, 2011). This model has received adequate empirical support. Still, current synesthesia models leave the role of other brain areas found to be related to synesthesia unexplained. Differences in structural (white matter) and functional (gray matter) brain properties have been obtained between the synesthete and non-synesthete brain, however, these differences are not limited to sensory and parietal cortex (Jäncke, Beeli, Eulig, & Hänggi, 2009; Laeng, 2009; Nunn et al., 2002; Rouw & Scholte, 2007; Weiss & Fink, 2009; Weiss, Zilles, & Fink, 2005). In a recent review, we found that most whole-brain fMRI studies reported activation in frontal cortex during the synesthetic experience (Rouw, Scholte, & Colizoli, 2011). In the current context, particularly the obtained relationship with lateral prefrontal cortex (PFC) is relevant, as this brain area is mostly known for its role in various executive control functions (for review see, e.g., Ridderinkhof, vandenWildenberg, Seglowitz, & Carter, 2004). Three out of nine studies found activation in response to synesthetic color, in highly similar locations in right dorsolateral PFC (Laeng, Hugdahl, & Specht, 2011; Paulesu et al., 1995; Sperling, Prvulovic, Linden, Singer, & Stirn, 2006). Lateral PFC is mostly known for its role in executive control processes that guide behavior in demanding situations (e.g., working-memory maintenance of task-goals and task-relevant information; flexible coordination of task rules; and inhibitory control over irrelevant information and inappropriate actions; Ridderinkhof et al., 2004). One possible interpretation is that the increased activation reflects increased inhibitory control, in response to the presence of the synesthetic color. This interpretation is in line with findings from Weiss and colleagues (2005), who found that conflict between the typeface color and the synesthetic color increased activation in dorsolateral prefrontal cortex. While these are only a few studies, they evoke the question whether the obtained effects in (dorsolateral) prefrontal cortex in synesthetes could reflect a relationship between executive control functions and synesthesia. Indeed, Weiss et al. concluded that their data "thus imply DLPFC as a key locus for integrating and overcoming conflicting perceptual information in synesthesia by increased cognitive control" (p. 866).

A possible analogy is that systematic changes in frontal executive functions have been obtained in bilinguals, which is assumed to be related to their management of two language systems (Bialystok et al., 2005). Bilinguals have several (linguistic) representations for one concept. Their opportunity to exercise the regulation and inhibition of (conflicting) information boosts their executive control (Bialystok, 2001). This raises the question of whether the obtained effects in prefrontal cortex in synesthetes might also be related to differences in executive control function. Is should be noted that bilingualism is used here as an analogy only, as there are clear differences between bilingualism and synesthesia. The most important difference is that children become bilingual because circumstances require it, while there are likely genetic influences on synesthesia (Asher et al., 2009; Tomson et al., 2011).

As far as we know, this is the first paper specifically addressing the relationship between executive control processes and synesthesia. This is necessarily a rather exploratory quest. We examine this relationship by addressing four sub-questions. First, can we find *general* skill differences between synesthetes versus non-synesthetes on classic executive functioning tasks (Study 1 and Study 2; Experiment 2A)? Second, is there an interaction between synesthetic functions and executive control functions, or are these functions relatively independent? Specifically, are behavioral synesthetic effects influenced by executive control manipulations (Study 2; Experiments 2B and 2C)? Third, we wish to learn about the mechanisms involved when there are different (conflicting) synesthetic and 'real' experiences. In particular, can we find evidence that inhibiting these synesthetic experiences requires effort and time (Study 3)? Fourth, can we find a relationship between 'managing' synesthetic experiences and the skills measured in executive control tasks, in an individual differences approach (Study 4)? If the two abilities depend on the same mechanisms, one would expect that they show within-group correlations. For example, those synesthetes good at inhibiting synesthetic color should be relatively good at inhibiting 'real' (typeface) color.

Our basic approach to these questions was to present synesthetes and non-synesthetes with both classic executive control paradigms and well-known synesthesia paradigms. Specifically, in Study 1, synesthetes were compared to non-synesthetes on two classic executive control paradigms (Stroop effect and task-switching). Study 2 compared synesthetes to non-synesthetes on two different classic executive control paradigms (rule switching and a stop-signal flanker task). In addition, Study 2 measured the effect of these two executive control manipulations on two synesthetic behavioral effects (the 'synesthetic crowding' effect and the 'synesthetic Stroop' effect). In Study 3, participants saw a synesthetic Stroop task (name the typeface color) as well as a reversed synesthetic Stroop task (name the synesthetic color). By including different timing conditions, this study also explored the temporal dynamics of the interference between real and synesthetic colors. Finally, individual difference analyses were performed on the behavioral variance obtained in Studies 1–3. These analyses and their results are presented in Study 4.

2. Study 1: Are there general executive control differences between synesthetes and non-synesthetes?

In this study, we compared the performance of synesthetes versus non-synesthetes on executive control tasks. We presented a Stroop task to both synesthetes and non-synesthetes. The Stroop task is a classic executive function paradigm (Stroop, 1935), which requires the deliberate inhibition of a response that is relatively automatic, and performance is affected by frontal lobe dysfunction (Perret, 1974). In three separate blocks, the participants performed (1) a Stroop task (report the color of the word), (2) a 'reverse Stroop' task (respond to the meaning of the word and ignore the color of the word) and (3) a 'task switching' block in which these two tasks are intermixed. Switching between tasks is another classic paradigm known to increase the demand on executive control function (Jersild, 1927; Rogers & Monsell, 1995). The Stroop task and task switching are thought to tap into at least partially separable executive functions (shifting and inhibition, Miyake et al., 2000). This design thus measures different effects related to executive control: the Stroop effect, the effect of task switching, and the interaction between these two effects, in the two participant groups (synesthetes versus non-synesthetes).

2.1. Participants

In all experiments in this study, synesthetes were included based on a test–retest questionnaire. This questionnaire first presented, in fixed order, the word names for all days of the week, all letters of the alphabet, and 20 different numbers (presented in digits, 1–14, 20, 50, 100, 250, 4000, and 20.000). Participants were asked to indicate which of these items to them had synesthetic colors, and to describe as exactly as possible each synesthetic color. A retest of these exact same items (but presented in a different order to make memorization of the colors more difficult) was administered after at least 3 weeks. Consistency of synesthetic experience was calculated for each participant by marking the answers that were equal or highly alike with a score of 1, and marking answers that were clearly different as 0; out of these scores an average consistency score per participant was computed. The minimum (cut-off) score used in these experiments was 80%. All participants in these experiments received either a monetary reward (€7 per hour), or student credits for their participation. All participants had normal or corrected-to-normal vision, and none were color blind.

Another procedure used in all experiments in this study, was administering the 'PA Questionnaire' (Rouw & Scholte, 2007[1]; to classify synesthetes on the 'projector/associator' subtype (Dixon et al., 2004). Projectors experience the synesthetic colors externally, in the outside world, sometimes projected onto the inducing grapheme. Associators report their synesthesia as internal, appearing 'in their mind's eye.' The PA Questionnaire includes 12 statements about synesthetic phenomenology.

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[1] The PA questionnaire can be downloaded at home.medewerker.uva.nl/r.rouw and is translated in English, German, and Polish.

Participants indicate on a five-point Likert scale to what degree these statements correspond with their synesthetic experiences (1 = strongly disagree, 5 = strongly agree). The PA score is calculated by subtracting the mean of the associator questions from the mean of the projector questions. The maximum range of these scores is from −4 to 4.

In the procedure of recruiting participants for Study 1, all participants were asked if anything had obstructed normal and serious participation in the experiment (one subject was excluded on these criteria as indicated she was feeling too ill to seriously participate). Furthermore, subjects were excluded if their particular age/education characteristics made it too difficult to find 'matching' non-synesthetes ($N = 2$), based on the consistency questionnaire (if the synesthetic colors were inconsistent, the synesthetic colors showed too little variation (color experiences in only one or two hues) or there were too few graphemes with colors; $N = 3$), or due to computer problems ($N = 1$).

In Study 1, 15 synesthetes (1 male) were included with a mean age of 26.5 years ($SD = 9.7$) and 15 non-synesthetes (1 male) participated with a mean age of 25.9 years ($SD = 9.6$). These participants were closely matched on age, sex, level of education, and handedness. Furthermore, additional synesthetes (a total of 29) were tested to control for the effects of individual differences (projectors versus associators) between synesthetes. The mean age of this larger group of synesthetes (1 male) was 28.5 years ($SD = 11.4$). Most synesthete (83%) and non-synesthete (100%) participants were right-handed, and all participants had either University or comparable higher-level education. Twenty-seven synesthetes completed the PA questionnaire. The score ranged from 4 to −3.7, with a mean score of −0.99 ($SD = 2.04$). Only 5 participants had a positive score on the PA questionnaire and qualified as projectors. This was defined as seeing the synesthetic color in 'external space' as opposed to 'in my mind only'. As there were too few projector synesthetes to reliably evaluate this factor, we did not look separately at the subgroup of projector synesthetes that might report the color as 'floating in space' (Ward et al., 2007).

2.2. Methods

All participants completed a Stroop task. Six color words (in Dutch) were presented on the computer screen (distance to the screen was approximately 40 cm). Each word was presented in each of the six colors corresponding to these words (red, yellow, blue, green, white and purple). Participants indicated a color by pressing one of six labeled keys on the keyboard (respectively; 'S', 'D', 'F', 'H', 'J', 'K'), with the ring, middle or index finger of the left or right hand. Thus, each word was presented in either the congruent color or in one of the five incongruent colors. Block 1 presented a classic Stroop task; participants were asked to indicate the (typeface) color of the word (name-the-color trials) and ignore the meaning of the word. In Block 2, a 'reversed Stroop task' was presented (name-the-word trials) in which participants were asked to respond to the meaning of the word and ignore the color of the represented word. In Block 3, the Stroop task was combined with task switching. Some trials were the original Stroop task (and thus the same as in Block 1) and others were the reverse Stroop task (as in Block 2). A trial always started with a cue indicating the task: a brown scribble cued the original Stroop (name the color) task, while a white Omega cued a reverse Stroop (name the word) trial. The size of the cues was 1 × 1 cm (visual angle of 1.43°). Apart from these (task-dependent) instructions, the trials were the same in the three blocks. A trial started with the cue, for 500 ms. After a black screen (300 ms), a color word was presented until key press.

To maximally trigger the inhibitory control-mechanisms we wished to study, we included more incongruent than congruent trials. Therefore, 24 congruent and 120 incongruent colored words were presented per block (each combination of color and word was repeated four times). In each block, these 144 trials were presented in semi-random order. In Block 3, trials were equally divided over the two tasks. Eighteen practice trials with feedback preceded each block. Furthermore, 36 practice trials with feedback (in which participants responded to a colored circle) preceded the experiment. This was to habituate participants to use a particular key to indicate a particular color (the correspondence between key and color remained the same throughout the experiment).

In all experiments presented in this study (Studies 1, 2, and 3), the stimuli were programmed and presented with the software package Presentation® (version 14, www.neurobs.com) on a PC with Windows version XP and CRT monitor, and responses were recorded with a USB keyboard.

2.3. Results

2.3.1. Stroop effect

Block 1 (name-the-color task) was a classic Stroop task. We contrasted the congruent with the incongruent trials in order to include both facilitation and interference effects in our measurements. We first addressed the question of whether synesthetes differ from non-synesthetes in the size of their Stroop effect. A repeated measures ANOVA was carried out with congruency as within-subject factor and synesthetes versus non-synesthetes as the between-subjects factor. Results showed longer response times to incongruent as compared to congruent trials ($F(1,42) = 4.37$, $p = .043$),[2] but no interaction with group ($F < .01$). Thus, participants showed a Stroop effect, but this Stroop effect did not differ between synesthetes and non-synesthetes (Table 1). Comparing only the 15 synesthetes to their matched 15 non-synesthetes did not show a difference in the size of their Stroop effect either (paired-samples t-test, $t(14) = -0.40$, $p = .69$). While the mean Stroop effect was slightly higher in the five projectors (27 ms) than in the 22 associators (17 ms), this effect was not significant ($F < 1$). No strong

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[2] Stroop effect itself is best measured in paired-samples t-test, $t(47) = -2.313$, $p = .025$, $d = 46$.

Table 1
Stroop effects in synesthetes and non-synesthetes in Experiment 1.

		Congruent Mean (*SD*)	Incongruent Mean (*SD*)
Synesthetes	Stroop	866 (260)	892 (258)
	Stroop and Switch	1148 (419)	1426 (540)
Controls	Stroop	896 (142)	922 (188)
	Stroop and Switch	1247 (336)	1421 (296)

Mean and *SD* response times (in ms) of congruent and incongruent trials in Block 1 (‘Stroop’) and Block 3 (‘Stroop and Switch’), ‘name the color’ trials for synesthetes and non-synesthetes.

conclusions can be drawn based on this result, as there were few projectors in the participant group, and no specific predictions were made on the relationship between PA score and the classic Stroop effect.

2.3.2. Switch effect

Block 3 (‘Stroop and Switch’) presented both Stroop and reversed Stroop trials. This allowed comparing the Stroop (name the color) trials in Block 1 with the same (name the color) trials in Block 3. A repeated measures ANOVA was conducted with congruency (congruent or incongruent), and block (1 or 3) as within-subject factors, and participant group (synesthetes or non-synesthetes) as the between-subject factor. This comparison showed an overall effect of congruency ($F(1,42) = 43.09$, $p < .001$). A significant effect of task switching was found as well (increased reaction times in Block 3 as compared with the same trials in Block 1; $F(1,42) = 115.99$, $p < .001$). Furthermore, these effects interacted (see Table 1); the congruency effect was stronger in Block 3 than in Block 1, $F(1,42) = 26.73$, $p < .001$. Thus, the context of switching increased the Stroop effect. However, no interaction effects were obtained with participant group ($F \leqslant 1.80$, $p > .18$).

No predictions were made for the reversed Stroop (name the word) trials. Still, an exploratory analysis was performed with again a $2 \times 2 \times 2$ (congruency, block [2 and 3] and participant group) repeated measures ANOVA. It showed that these trials in Block 2 and Block 3 showed the same pattern of main and interaction effects as the Stroop task trials reported above.

2.4. Discussion Study 1

The Stroop paradigm in Study 1 showed no differences between synesthetes and non-synesthetes. Perhaps a lack of power or a particular setting of this experiment obscured differences in the size of the Stroop effect in the current study. While this is possible, the overall Stroop effect was significant. Furthermore, there was sufficient power to show an increased Stroop effect when an additional executive task was presented (task switching). Again, this increase in response time in the ‘Stroop and switch’ condition is the same for synesthetes and non-synesthetes. While it is important to see if these results can be replicated with different tasks, the current results do not support general differences in executive function skills between synesthetes and non-synesthetes. The current finding is in line with Mattingley et al. (2001) and Mattingley, Payne, and Rich (2006), who reported to have found no differences between synesthetes and non-synesthetes in the normal Stroop paradigm (in both studies the Stroop task was employed to check baseline differences between the groups in a study on the synesthetic Stroop effect).

In Study 1, a between-subject group comparison was necessary. In the next study, we examine how executive functions relate to synesthetic functions, by performing within-subject group analyses. More specifically, we examined if adding an executive function manipulation influences synesthetic behavioral effects. In the following experiments, rather than looking at executive performance level, the question is: how do executive functions interact with synesthetic functions?

3. Study 2: Do synesthetic functions and executive control functions interact?

This study further examines the relation between executive control abilities and synesthesia, addressing sub-question #2: Do synesthetic functions and cognitive control functions interact? Specifically, are behavioral synesthetic effects influenced by executive control manipulations? Study 2 consists of three tasks. In two tasks, behavioral synesthetic effects (‘synesthetic Stroop’ effect and ‘synesthetic crowding’ effect) are combined with classic executive function paradigms (respectively a stop-signal task and task switching). We also presented a separate task to measure if synesthetes differ from non-synesthetes on another well-known executive function paradigm, the ‘flanker’ test. As with the synesthetic Stroop task, the flanker task was also combined with a stop-signal paradigm.

3.1. Participants

Twenty females with grapheme-color synesthesia participated in Study 2 (mean age 22.3; range = 18–28), and 20 control participants (all females, mean age = 21.06 years, range = 18–25) matched on sex, age and level of education. For this study, new synesthetes were recruited (only 4 synesthetes also participated in Study 1). Synesthetes were included based on the consistency of their reported synesthetic colors (see Study 1), but with at least 8 days in between the test and retest. For the participants in this experiment, the consistency scores ranged between 80% and 100%, but one participant had a score of 64%. This participant nonetheless was included, as she characterized her experiences as “flickering” and “shining”, “letting through shades and stripes of other colors.” This unusual but still synesthetic type of phenomenology could explain her inconsistent answers. In Study 2, no participants were excluded during the recruitment and screening procedures.

Participants filled in the PA-questionnaire (Rouw & Scholte, 2007) described in Study 1 (Section 2.1). Eight synesthetes were assessed as projectors and 12 as associators. The mean PA score in this group was −0.26 (*SD* 2.47), with PA score ranging from 4 to −3.2.

3.2. Methods

Synesthetes chose their synesthetic color for each grapheme (letters and digits) by clicking on an RGB color palette (a 64 × 64 pixel-grid covering 4096 RGB values, colors ranging in hue and brightness, together with a separate black–gray–white bar, covering 64 RGB values from black to white) on a computer screen. They gave each color-match a rating on a seven-point scale, reflecting how closely or strongly the chosen computer color matched the synesthetic sensation. Only graphemes with a rating of at least four were used as stimuli in the experiments. The RGB-codes were used to create the congruent and incongruent stimuli for Experiment 2C, and to select graphemes with contrasting versus similar synesthetic colors in Experiment 2B.

Synesthetes participated in two separate experimental sessions of approximately 1.5 h each on two separate days. The first session consisted of the grapheme-color matching procedure (see above), the stop-signal flanker task (Experiment 2A) and the combination of task switching and synesthetic crowding task (Experiment 2B). In the second session, the synesthetes performed the stop-signal synesthetic Stroop task (Experiment 2C) and the retest of the synesthesia questionnaire. Non-synesthetes (control participants) only participated in one experimental session of approximately 1 h consisting of the stop-signal flanker task (Experiment 2A) and the task switching crowding task (Experiment 2B). Thus, the session presented to non-synesthetes was identical to the first session of the synesthetes without possible training effects disrupting the comparison between the two groups. Within an experiment, trials were designed to fit each synesthete’s color associations. Each synesthete was matched with one control participant who received the exact same experiments 2A and 2B (with the exact same graphemes and colors). In the first session, the stop-signal flanker task was always performed first. Within the experiments, the different experimental blocks were counterbalanced across participants.

3.3. Experiment 2A: Stop-signal flanker task

In this experiment we used another classic executive control task, the Eriksen flanker task (Eriksen & Schultz, 1979; Botvinick, Nystrom, Fissell, Carter, & Cohen, 1999). Thus, we compared synesthetes with non-synesthetes on a cognitive control task, as we did in Experiment 1, but with different participants and a new set of tasks. We presented an arrow flanker task, in which none of the stimuli elicited synesthetic colors. In an arrow flanker task (Ridderinkhof, Molen, & Bashore, 1995), participants see a row of simple arrows either pointing in the same direction (e.g. <<<<<; congruent) or with the outer four arrows pointing in a different direction than the middle arrow (e.g. >><>>; incongruent). The participant should indicate the direction of the middle arrow. Responses are typically slower during incongruent trials compared to congruent trials. In Experiment 2A, the flanker task was combined with a stop-signal paradigm, often used to investigate inhibitory control (Logan, 1994). In a stop-signal task, in some portion of trials the target stimulus is followed by a stop-signal (e.g. a tone). During these stop-trials, the participant should refrain from responding. Conflict tasks such as the flanker task have been combined with a stop-signal paradigm in earlier studies (Ridderinkhof, Band, & Logan, 1999; Verbruggen, Liefooghe, Notebaert, & Vandierendonck, 2005), showing that inhibitory control is compromised when the target and distractor imposed additional response conflict. While the main question is the size of the arrow flanker effect in the two groups, this design allows to examine in addition this effect of inhibitory control.

3.3.1. Methods

A trial consisted of a jittered fixation cross of 500–1500 ms (at fixation, in the middle of the screen), followed by a left-pointing or right-pointing target arrow with congruent or incongruent flanker arrows. The arrows had a response window of 1500 ms (the trial ended after responding) after which a blank screen appeared, which was jittered between 500 and 1500 ms. On 25% of the trials, an auditory stop signal was presented. Participants were instructed to indicate the direction of the middle arrow of the row (left or right by pressing the ‘Z’ or ‘/’ keyboard button, respectively), but refrain from responding during the stop-trials. The stop-signal consisted of a 100 ms auditory sine wave of 900 Hz. Successful stop trials ended after 1500 ms. Four consecutive blocks of 56 trials were presented (with an equal number of left and right correct answers). All blocks contained congruent (50% of the trials) and incongruent arrow flanker trials. Participants were instructed to respond as fast and as accurately as possible.

The time between the presentation of the arrows and the stop-signal (the stop-signal delay, or SSD; Logan & Cowan, 1984) was initially set at 200 ms and adaptively changed according to a staircase procedure, such that participants would eventually converge to a probability of successful stopping of 50%. During a stop-signal block, the SSD was increased or decreased (with a step size of 25 ms) depending on whether performance was below or above this threshold, respectively. This is a well know procedure in studies using the stop-signal task (for a review, see Verbruggen & Logan, 2009) that makes it possible to compute the time it takes for a participant to inhibit an intended response: the stop-signal reaction time (SSRT).

The SSRT is the time between start and finish of the stop process. The start is the stop signal, and the finish time can be derived from the reaction time (RT) distribution on go trials (Band, Van der Molen, & Logan, 2003). In this experiment, the quantile RT was used in the so-called 'integration method' (Verbruggen and Logan, 2009). For each participant, the quantile RT is determined by finding the RT in this distribution, corresponding to the proportion of failed stop trials for that person. If a participant withheld a response in 50% of the stop-trials, this measure of efficiency of the inhibition process is the time between the stop-signal and the median (i.e. the first 50%) RT of the successful go trials (go-RT) distribution (Logan and Cowan, 1984). However, not all participants always converge to 50% stopping but instead to a probability '*P*(stop)'. The SSRT was calculated by subtracting the average stop-signal delay from this quantile RT.

3.3.2. Results

Over all different blocks, an average of 10.3% of trials for synesthetes and 10.6% for control participants were removed because of errors (incorrect response on go-trials) and reaction time outliers (>2.5 *SD* of the average RT per participant). An overall repeated measures ANOVA on RTs with the within-subjects factors congruency (congruent versus incongruent flankers) and between-subjects factor participant group (synesthetes versus controls) revealed a significant arrow-flanker effect: participants slowed down on incongruent arrows compared to congruent arrows ($F(1,38) = 91.93$, $p < .001$). However, this effect did not differ between synesthetes and non-synesthetes ($F < 0.1$; see Fig. 1). In Experiment 4, the relationship between the arrow flanker effect and synesthetic behavioral effects is further examined in an individual differences analysis.

The arrow flanker manipulation influenced SSRT: in general, participants had a lower SSRT on incongruently flanked arrows compared to congruent arrows ($F_{(1,38)} = 11.41$, $p = .002$, $\eta^2 = 0.231$). An interaction with group did not reach significance ($F_{(1,38)} = 3.378$, $p = .074$, $\eta^2 = 0.082$). No differences were found on RT or SSRT between projectors and associators within or between the congruent and incongruent arrow conditions.

3.3.3. Discussion

A significant arrow flanker-effect was obtained. This effect did, however, not differ between synesthetes and non-synesthetes. Thus, this experiment obtained, with a different participant group and employing a different paradigm, results that are similar to those obtained in Study 1. The effect of executive control is obtained, but it does not interact with participant group (synesthete versus non-synesthete). While the congruency effects were obtained as expected, the interaction of these effects with the stop signal manipulation were in an opposite direction than expected, and are hard to interpret.

3.4. Experiment 2B: Task-switching and crowding task

In this experiment, the effect of executive control manipulation on synesthetic behavior was tested with a 'crowding' paradigm. The visual crowding effect reflects the observation that a target stimulus in the peripheral visual field becomes harder to identify when it is flanked (i.e. surrounded on all sides) by similar distractors (e.g. He, Cavanagh, & Intriligator, 1996; Pelli, Palomares, & Majaj, 2004). The visual crowding effect takes place at early (visual) stages of processing (Whitney & Levi, 2011). The crowding-effect is reduced when stimuli are colored (Kooi, Toet, Tripathy, & Levi, 1994). Synesthetes can experience a similar advantage of their synesthetic colors when identifying crowded black graphemes. Specifically, Hubbard, Arman, Ramachandran, and Boynton (2005) found that in a crowding task, three out of six synesthetes performed better than controls, where every synesthete was tested separately against a different group of 12 non-synesthetic participants.

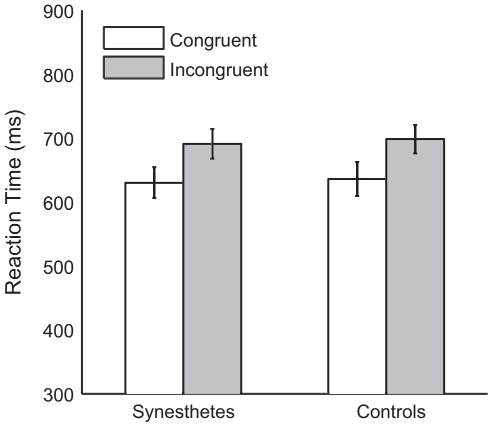

Fig. 1. Mean response times for synesthetes and non-synesthetes on congruent (CG) and incongruent (IC) arrow flanker trials. Error bars represent one standard error of the mean.

Furthermore, a task-switching paradigm was employed in conjunction with the crowding task in order to manipulate cognitive control load during the synesthetic crowding task. A task-switching paradigm presents two alternating task-sets (for a review, see Monsell, 2003). Typically, participants slow down or make more errors on switch-trials than on non-switch trials. We used task-cueing on a trial-by-trial basis (similar to Monsell, Sumner, & Waters, 2003).

3.4.1. Method

Five graphemes were presented in a '+' shaped array, either left or right from a fixation cross. The middle grapheme had a different identity from the four identical surrounding graphemes. Participants identified either the middle grapheme ('middle grapheme rule') or the surrounding graphemes ('surrounding grapheme rule'). Relatively impaired performance in the former rule is predicted, due to crowding. As a task-switching cue, the fixation cross was either presented inside a horizontal square ('identify the middle grapheme') or inside a diamond ('identify the surrounding graphemes').

Per synesthete, an experimental 'contrast' condition was created by choosing a set of four graphemes that elicited contrasting synesthetic colors for that synesthete (e.g. red, green, blue, and yellow; judged from the RGB-output of the grapheme-color matching procedure, see Study 1). Additionally, a baseline condition was created by choosing, for each synesthete, four graphemes that elicited either no synesthetic colors or highly similar synesthetic colors (as indicated by the chosen RGB values). Each of the four graphemes in a set was used as a target, with each of the three other graphemes as distractor, creating 12 possible configurations per condition. These were each presented four times to the left and four times to the right of fixation. The baseline condition was created to provide additional evidence for the hypothesis that the potential benefit in crowding by synesthetic colors (Hubbard et al., 2005) is a result of the graphemes eliciting contrasting colors. Baseline trials could not have such benefit, since they elicit either no synesthetic colors or highly similar synesthetic colors. Each non-synesthetic control participant was paired with one synesthete: participant-pairs performed the exact same task (including the same configurations of graphemes and the same order of blocks). Synesthetes (but not controls) are expected to show an increase in accuracy for the contrast condition as compared with the baseline condition.

All participants completed six blocks with 96 trials each. The blocks consisted of two contrast blocks, two baseline blocks, and two task switching blocks. For both the contrast and baseline conditions, within each block only one rule applied (either 'identify the middle grapheme' or 'identify the surrounding graphemes'). In the task switching blocks repetitive trials (4–7 trials) of one rule switched to repetitive trials of the other rule, with a total of 48 trials per rule. During these task switching blocks, the same stimuli and settings were used as in the experimental contrast block (i.e. graphemes had contrasting synesthetic colors). The order of the blocks was counterbalanced across participants. Trials within a block were presented in semi-random order (with no more than four times the same target–distractor configuration in succession on one side).

A trial consisted of a fixation cross jittered between 500 and 1500 ms, then a horizontal or tilted square overlaying the fixation cross for 100 ms, followed by the crowded graphemes (left or right of fixation) for 100 ms (Fig. 2). The fixation cross and surrounding square remained on the screen during the presentation of the crowded graphemes, and this was followed by a blank screen for 250 ms to avoid a backward-masking effect. The short presentation time of the graphemes was in order to prevent eye-movements to the target stimulus. After each trial, a four-alternative forced choice (4AFC) frame appeared with the four graphemes (of that participant for that block). Participants identified the target grapheme by pressing one of four keyboard-buttons with their left ('D' or 'F') or right ('J' or 'K') hand. The four buttons corresponded from left to right to the positions of the four alternatives on the screen (see Fig. 2).

The distance from eyes to the screen was 56 cm, held constant with a chin-rest. The graphemes (capital letters and digits) were presented in Arial font on a computer screen (16″; 1024 × 768, 100 Hz). Graphemes were black on a white background to maximize a beneficial contrast effect on synesthetic experience (see Hubbard et al., 2005). Graphemes subtended a visual angle of 1.02°. In the crowding task, the middle grapheme was presented 9.13° left or right from fixation, and the average center-to-center spacing between the graphemes was 1.53°. We based these angle parameters on a pilot study to approach the threshold of crowding. Perceptual effects of synesthetic colors (e.g. in visual search paradigms) have been shown to arise only if the graphemes are close to or within the 'spotlight' of visual attention (e.g. Laeng, Svartdal, & Oelmann, 2004; see also Ward, Jonas, Dienes, & Seth, 2010).

3.4.2. Results

Overall accuracy during the surrounding-grapheme-rule condition was 88%, versus 53% during the middle-grapheme-rule (see Table 2). For both groups, performance dropped significantly during the middle-grapheme-rule condition compared to the surrounding-grapheme-rule condition: an overall repeated measures ANOVA with the within-subject factors of grapheme rule (middle versus surrounding grapheme) and condition (contrast, baseline, and task switching), and one between-subject factor of group (synesthetes versus controls) revealed a main effect of grapheme rule on accuracy ($F(1,37) = 273.5$, $p < .0005$). This decreased accuracy in identifying the middle grapheme indicates successful crowding by the surrounding graphemes (see also Table 2). There was also a main effect of condition ($F(2,36) = 6.58$, $p < .005$), but this did not interact with the grapheme rule ($F(2,36) < 1$), nor with group ($F(2,36) = 1.86$, $p = .16$).

To further examine the effect of synesthesia on the crowding effect, we did an additional $2 * 2$ condition (contrast versus baseline condition) by group (synesthetes versus controls) repeated measures ANOVA. It revealed a main effect of condition that approached significance ($F(1,38) = 3.70$, $p = .062$), with no interaction with group ($F(1,38) < 1$). Exploratory one-tailed paired samples t-tests revealed higher accuracy during the contrast condition than during the baseline condition for synesthetes ($t(19) = 1.839$, $p = .041$), but not for non-synesthetes ($p = .21$). While current results do not allow to draw conclusions

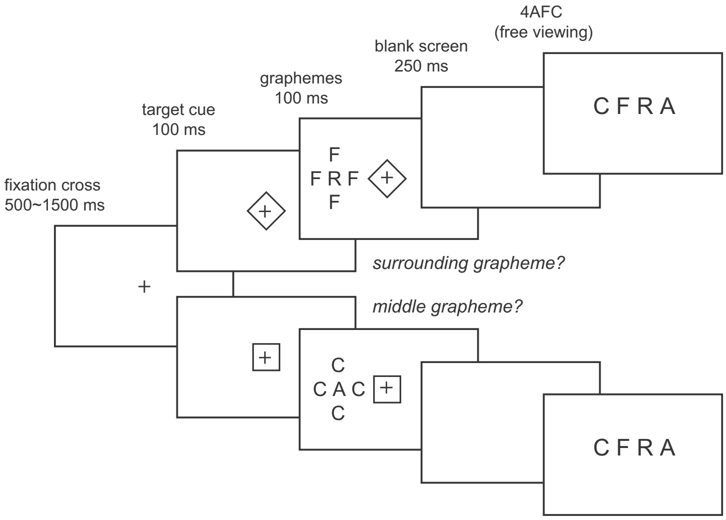

Fig. 2. Trial sequence in the task-switching crowding task. The diamond indicates the 'surrounding grapheme' rule while the square indicates the 'middle grapheme' rule.

Table 2
Crowding effects in Experiment 2B.

Task rule	Condition	Synesthetes Mean (*SD*)	Controls Mean (*SD*)
Middle grapheme	Contrast	59.01 (15.93)	54.84 (15.77)
	Baseline	52.34 (15.46)	52.14 (14.49)
	Switch	56.88 (15.91)	45.68 (17.17)
Surrounding grapheme	Contrast	89.84 (16.81)	89.64 (11.45)
	Baseline	90.03 (8.29)	88.75 (8.54)
	Switch	85.16 (12.09)	83.28 (8.92)

Mean accuracy and *SD* of synesthetes and controls on the rule-switching crowding task for the two rules: (1) name the middle grapheme and (2) name the surrounding grapheme and the three conditions: (1) experimental condition with contrasting colors, (2) baseline condition with similar colors, and (3) task-switching condition with contrasting colors.

about differences between the groups, this exploratory test indicates that for synesthetes photisms of similar colors induced stronger crowding than photisms of different colors. Note that the increased accuracy is not likely explained by merely the (shapes of) stimuli used, as the non-synesthetes saw the exact same grapheme configurations. Thus, similar to the findings by Hubbard et al. (2005), we did not find a main effect of synesthesia in crowding. However, including a baseline condition did provide some evidence for a role of synesthetic experience in a perceptual task.

The main question of this experiment was how performance on the synesthetic crowding effect is influenced by the manipulation of executive control (i.e. task switching). To evaluate this, we looked at those trials where graphemes had contrasting synesthetic colors (to the synesthetes), and the middle-grapheme rule applied. We compared accuracy on the contrast condition of the crowding task (with the middle-grapheme rule) with performance on these same trials in the switch condition. Note that these trials were only different in the absence or presence of a context of task switching, as not only the same middle-grapheme rule applied, but also the same graphemes were used in these two sets of trials. A 2 (contrast versus switch condition) × 2 (synesthetes versus controls) ANOVA revealed a main effect of condition ($F(1,38) = 11.89$, $p = .001$), showing improved performance when participants did not have to switch between rules. In addition, there was a significant interaction between switching (i.e. with or without switching) and group (synesthete versus non-synesthete) ($F(1,38) = 4.60$, $p = .038$). Within-group post-hoc analyses showed that performance of the non-synesthetes dropped in the task switching condition, as compared to the same (contrast condition) block without switching ($t(19) = 4.53$, $p < .0005$). Synesthetes showed no difference in accuracy between the contrast and the switch condition ($p = .42$). Apparently, the additional load of task-switching did not affect the crowding experiment the same way for synesthetes as it did for non-synesthetes. Indeed, synesthetes showed better performance than non-synesthetes on the switch condition ($t(38) = 2.139$, $p = .019$). An exploratory analysis showed that careful interpretation of these results is necessary, as synesthetes were faster in the no-switch than in the switch condition (709 ms versus 821 ms), while controls did not show this effect (869 ms versus 851 ms). This condition by group interaction was significant ($F(1,38) = 5.4$, $p = .026$). Therefore, a more careful conclusion in this experiment is that synesthetes and non-synesthetes differ in how they change their response bias (increased accuracy with longer response times) as cognitive control load changes during the crowding task (Fig. 3). Further research is needed to explore these different biases in synesthetes and non-synesthetes.

To examine the reduction in switching-cost over trials (i.e. the reconfiguration process; Monsell, 2003), we performed a trend analyses with the four trials after a switch as subsequent time-points. This repeated measures ANOVA showed a significant linear increase in accuracy over the four trials ($F(3,114) = 8.59$, $p < .001$) for both groups. Importantly, this increase remained equal across groups (i.e. no significant interaction between groups and trend, $F(3,114) = < 1$). Thus, both groups showed similar task-set reconfiguration after switching (between the middle-grapheme-rule trials and the surrounding-grapheme-rule trials).

In addition, we looked for possible differences between projectors and associators in crowding effect and task-switching. To this end, we ran the same ANOVAs as described above, but now with projector versus associator as a between-participant factor (thus without the non-synesthetic control group). These analyses did not reveal any effect of synesthesia subtype (all p-values > .05).

3.4.3. Discussion

Both crowding and switching-cost effects were obtained in the experiment. Including a baseline condition provided some evidence for a role of synesthetic experience in a perceptual task. Non-synesthetes performed worse due to the switching, while synesthetes did not show this decline in performance. Alternatively, one could say that non-synesthetes show facilitation during repetition trials whereas synesthetes do not. While this indicates a relatively better performance for synesthetes in the switch condition, the slower response times in this condition indicate that it should instead be viewed as part of a different response bias for synesthetes (as compared with non-synesthetes). One possible explanation is that synesthetes are more motivated and more careful during the experiment (as they are highly interested in synesthesia-related studies), which specifically in this relatively difficult task leads to increased accuracy (and increased response times) in synesthetes as compared with non-synesthetes. In the other experiments, no such trade-off effects were observed.

Another possibility is that the synesthetic experience was aiding performance during this task, but that the additional color experience not only increased accuracy during cognitive load, but also somehow slowed down the overall process. One aspect of this experiment (differentiating it from Experiment 2C), is that in this task synesthesia can actually aid task performance rather than interfere with it. Perhaps resources that are normally employed in the crowding task are now employed to counter the switching cost (employing these resources could take extra time while increasing accuracy).

3.5. Experiment 2C: Stop-signal and synesthetic Stroop task

Participants performed a synesthetic Stroop task, in which they were presented with colored letters. Participants named either the letter's real color ('color naming'), or its synesthetic color ('photism naming'). Each synesthete had his or her own set of stimuli, such that real colors of the letters were either congruent or incongruent with the synesthetic color of that letter. This synesthetic Stroop task was combined with a stop-signal manipulation (see Section 3.3 for general information on the stop-signal task).

3.5.1. Method

Six different graphemes were chosen as stimuli, such that each individual synesthete had maximally contrasting synesthetic colors. Per synesthete, each grapheme was colored in its own synesthetic color ('congruent'), and in the five

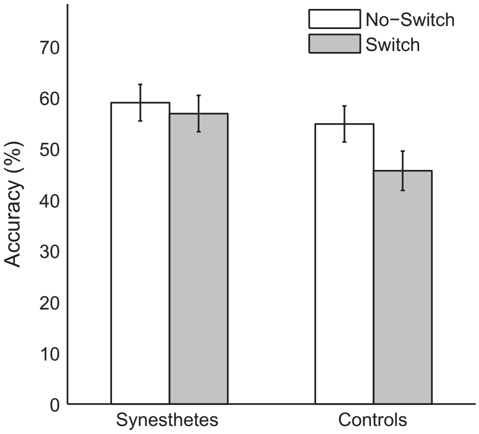

Fig. 3. Synesthetes and non-synesthetes show a different response to increased cognitive load during the crowding task. Synesthetes' versus non-synesthetes' mean accuracy scores, comparing a condition where trials are mixed with rule-switch trials ('Switch') with a condition without switching trials ('No Switch'). Error bars represent one standard error of the mean.

synesthetic colors of the other graphemes (‘incongruent’). The six different color responses corresponded to six labeled keys on the keyboard. The participant indicated the (synesthetic or real) color of the grapheme, by pressing one of these six keys (‘S’, ‘D’, ‘F’ and ‘J, ‘K’, ‘L’) with the ring, middle and index finger of the left and the right hand. Participants were instructed to refrain from responding after each stop-signal, which consisted of a 100 ms auditory sine wave of 900 Hz. A short training session to get familiar with these responses preceded the actual experiment (42 trials).

Four consecutive blocks were presented: regular color naming, regular photism naming, stop-signal color naming and stop-signal photism naming. The order of the blocks was counterbalanced across participants. The stop-signal blocks contained 240 trials (90 congruent go-trials, 90 incongruent go-trials, 30 congruent stop-trials, 30 incongruent stop-trials), and the two regular-trial blocks contained 120 trials (always go-trials; 60 congruent, 60 incongruent). Trials were presented in random order within each block. Each trial consisted of a fixation cross with a duration jittered between 500 and 1500 ms, followed by a colored grapheme at fixation with a response window of 1500 ms (trial ended after responding), which was followed by a blank screen again jittered between 500 and 1500 ms. In the two stop-signal blocks, an auditory stop-signal was randomly presented in 25% of the trials. Participants were instructed to inhibit their response after each stop-signal. Successful stop trials ended after 1500 ms. The manipulation of the SSD was adaptively changed with the same staircase-tracking procedure as described in Experiment 2A. The SSRT was also calculated in the same way as in Experiment 2A (i.e. based on the average SSD over trials and the Go-RT distribution; see Verbruggen et al., 2005). All blocks were preceded by 12 practice trials where feedback on accuracy and speed of the response was given. At a distance of 56 cm, the graphemes subtended a visual angle of 2.56° in the synesthetic Stroop task.

3.5.2. Results

Over all different blocks, an average of 7.7% of the trials were removed because of errors (incorrect responses on go-trials). Of all correct go-trials, an additional 5.3% were classified as reaction time outliers (±2.5 times the standard deviation) and omitted from further analyses.

An overall repeated measures ANOVA was performed on all of the go-trial RTs with congruency (congruent versus incongruent), control level (regular versus stop-signal), and task (color naming versus photism naming) as within-participant factors, and synesthesia subtype (projectors versus associators) as between-participant factor. The synesthetic Stroop effect was obtained: a strong effect of congruency ($F(1,19) = 149.97$, $p < .001$) indicated that participants responded significantly faster to congruently than to incongruently colored graphemes. This effect interacted with task: the congruency effect was stronger for color naming than for photism naming ($F(1,19) = 11.48$, $p = .003$). Additionally, a main effect was found for control level: the go-trials were responded to more slowly in the stop-signal condition than in the regular condition ($F(1,19) = 37.89$, $p < .001$). Importantly, there was no interaction between congruency and control level ($F(1,19) < 1$), and no three-way interaction of these factors with task ($F(1.19) < 1$). In other words, the interference effects between synesthetic and typeface colors were not affected by the executive control manipulation (Fig. 4). Furthermore, synesthesia Subtype (projector versus associator) did not interact with any of these factors or interactions.

Even though no interaction effects were found with the level of control, this is not evidence that no control is necessary during synesthetic experiences. In blocks with only Go-trials, the accuracies in congruent and incongruent trials were 96% and 85% in the ‘color naming’ task and 97% and 90% in the photism-naming task, respectively. In blocks with mixed go- and

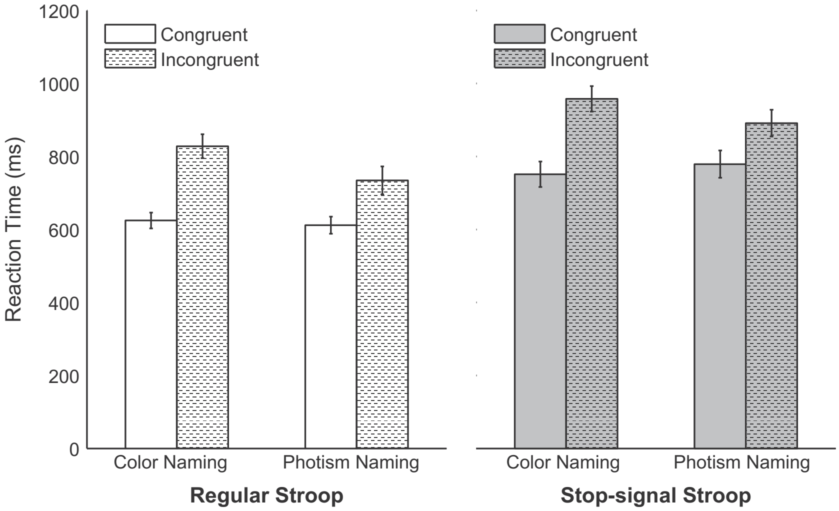

Fig. 4. No interaction between synesthetic Stroop and executive control manipulation. Mean RT increases in incongruent (dotted bars) as compared with congruent (solid bars) condition in color or photism naming, during Block 1 (regular trials) and Block 3 (stop-signal task). Error bars represent one standard error of the mean.

stop-trials, accuracies in congruent and incongruent trials were 97% and 87% in the ‘color naming’ task and 98% and 90% in the photism-naming task, respectively. These high accuracies show that synesthetes were generally well able to switch to the relevant task (real versus synesthetic color naming) and inhibit the inappropriate color (during the incongruent condition).

A repeated measures ANOVA was performed on the SSRT with congruency (congruent versus incongruent) and task (color naming versus photism naming) as within-subject factors and synesthesia subtype (projectors versus associators) as the between-subject factor. This did not reveal main effects of congruency ($F(1,18) = 1.78$, $p = .20$) and task ($F < 1$). However, there was a significant interaction between synesthesia subtype and task ($F(1,18) = 5.0$, $p = .038$). Post-hoc analyses showed that projectors were less efficient in inhibiting a color naming response (i.e. had higher SSRTs) than associators ($t(18) = 2.53$, $p = .021$). The groups did not differ in the speed of inhibition during photism naming ($t < 1$). In the study from Dixon et al. (2004), projector synesthetes were slower in responding to color naming, while associators were slower in photism naming. Thus, the longer SSRT in color naming in projectors might be in line with such overall slower processes in this condition.

3.5.3. Discussion

The expected synesthetic Stroop-effect was obtained in the correct direction. Also, increased demand on executive control functions impaired performance; go-trial responses were slower when mixed with stop-trials. However, the synesthetic Stroop effect was not affected by the executive control manipulation: the synesthetic behavioral effects were unaffected by increased demand on executive control functions.

3.6. Discussion Study 2

From the results of Study 2, two sub conclusions can be drawn. First, as in Study 1, the results indicated that synesthesia is not related to a general skill difference in executive functioning. No differences were obtained between synesthetes and non-synesthetes in the arrow flanker task (Experiment 2A).

Second, executive control manipulations did not interact with behavioral synesthetic effects. We presented a perceptual synesthetic paradigm (synesthetic crowding). In this paradigm, the synesthetes showed increased accuracy during an executive control manipulation (task switching), however, this was part of a speed-accuracy trade-off. We also presented the synesthetic Stroop effect, which may (as the classic Stroop effect, MacLeod, 1991), arise from inhibition or conflict at different levels of processing. In this task, synesthetic color (as measured in a synesthetic Stroop paradigm) was unaffected by a cognitive control manipulation (stop-signal task).

Thus, we found no evidence for effects of classic cognitive control manipulations in the situations where there is conflict between synesthetic and real colors. We will return to this issue in Study 4, where individual difference analyses are employed to further examine the relationship between synesthetic behavior and executive control functions. First, the synesthetic interference effect is further examined. In Study 3, we address the third sub-question of this study: What can we learn about the (timing) properties of the processes involved during conflict between synesthetic and real color experiences?

4. Study 3: Does inhibiting synesthetic experiences require effort and time?

In Study 2, synesthetes showed high accuracy performance even when synesthetic and real color information were incongruent. Which mechanisms underlie the synesthete’s ability to deal with the simultaneous presence of two types of color representations? Do these mechanisms take effort and time? The current experiment tested whether the interference effect of synesthetic colors on (real) color perception changes over time. Specifically, does ‘dealing’ with the incongruent colors imply a decreased interference effect of the (synesthetic) color? We employ the synesthetic Stroop paradigm as this is a well-known paradigm to measure the strength of synesthetic color interference (Beeli et al., 2005; Berteletti et al., 2010; Dixon et al., 2000, 2004; Mattingley et al., 2001; Wollen et al., 1983). An important parameter in the current paradigm is presentation time. A small increase in presentation time was used as the experimental manipulation, as this allows changes in interference effects to be measured while the colored graphemes are present.

The literature provides a quite clear prediction of when early effects of interference between synesthetic and real colors are present. Mattingley et al. (2001) showed that at a masked presentation time as short as 56 or 28 ms, conscious identification of the graphemes was no longer possible for the synesthetes. Furthermore, at these presentation times the effect of congruency on color-naming times was completely absent. Therefore, our presentation times were set to exceed this threshold. Similarly, in a MEG study Brang, Hubbard, Coulson, Huang, and Ramachandran (2010) found that presenting color-eliciting graphemes evoked activity of the grapheme ROI between 105 and 109 ms and activity of V4 (color) ROI between 110 and 114 ms. This study shows that synesthetic color activation is fully present around 112 ms. EEG studies confirm this early effect of synesthetic color (Goller, Otten, & Ward, 2009) and furthermore show that the effect of conflict between the two response sets is also present during the early N170 component (Sagiv, Knight, & Robertson, 2003; Cohen Kadosh, Cohen Kadosh, & Henik, 2007). Beeli, Esslen, and Jäncke (2008) reported that auditory presentation of letters showed a difference between synesthetes and controls in OFC and ventromedial cortex, as early as 122–220 post-stimulus, but also more laterally beyond that time window.

Taken together, the MEG and EEG studies suggest an early effect of synesthetic color between 110 and 114 ms. Effects related to the conflict are already measurable in this early time window between 100 and 150 ms and extend beyond it (Beeli et al., 2007; Cohen Kadosh et al., 2007). In our synesthetic Stroop paradigm, we included a 100 ms presentation time condition. Pilot studies confirmed that at this short presentation time participants reported being able to see the letter and its color. Therefore, these durations should be long enough to measure interference effects. A second timing condition was set at 150 ms. Based on literature, this change from 100 ms to 150 ms seemed the best time window to measure early changes in the interference effect.

We measured not only the interference of the synesthetic color on the real color, but also the interference of the real (typeface) color on the synesthetic color. Thus, both a 'name the typeface color' and a 'name the synesthetic color' task were included. For both tasks, the interference effects (differences between congruent and incongruent trials) are measured in two timing conditions: 100 ms versus 150 ms.

4.1. Participants

Twenty-one synesthetes (all female, mean age 26 years, *SD* = 7.4, range = 18–50), participated in the synesthetic Stroop experiment. All participants had academic or comparable higher-level education, two were left-handed, one was ambidexter, and the rest was right-handed. All but one participant also participated in Study 1 (in a separate testing session). This allows for a comparison between a synesthetes' Stroop and synesthetic Stroop effect (see Study 4). Synesthetes were included in the experiment based on consistent test–retest report of their letter-color associations (see Study 1). The PA questionnaire showed that only 5 of the 21 participants were projector synesthetes (PA questionnaire score > 0, see Study 1). The PA scores of these synesthetes ranged from -3.67 to 4.00, the mean score was -0.92 (*SD* = 2.25).

4.2. Method

The experiment was presented on the computer screen (computer tasks were run by Presentation (Neurobs version 11.1, www.neurobs.com). In a separate session, participants were presented with all letters of the alphabet as well as 20 numbers, and asked to indicate the associated synesthetic color (with the computer program Paint) of a minimum of 10 graphemes that elicit a strong synesthetic color experience. From these graphemes, we chose six graphemes that differentiated clearly between each other. In order to increase the sensitivity to the interference effect by making the task more difficult, we lowered chance-levels (to 16.7%) and chose six (rather than four, Dixon et al., 2004) response colors. Accordingly, six keys ('S', 'D', 'F', 'H, 'J' and 'K') were color-labeled. The testing session began with the same color-to-key practice task as described in Study 1. In the experiment, each grapheme was presented in each of its six typeface colors.

Participants saw four blocks of trials; the grapheme was presented for 150 ms in Block 1 and 2, and for 100 ms in Block 3 and 4. Participants were asked to report the typeface color of the grapheme in Block 1 and 3 (color naming), and to report the synesthetic color of the grapheme in Block 2 and 4 (photism naming). Each block had 144 trials in semi-random order, in which 24 graphemes were congruently colored and 120 graphemes were incongruently colored (congruency refers to the comparison of the typeface and the synesthetic color). The block was preceded by 36 practice trials (without feedback) in which all the possible color-grapheme combinations were presented. After the four blocks, all participants filled in an exit questionnaire and were paid for their participation.

A trial started with a 1000 ms white fixation cross on a black screen, followed by a colored grapheme. The grapheme was masked by a colored pattern containing all the individual's synesthetic colors for 150 ms, followed by a grayscale mask presented until a total trial duration of 1000 ms. The mask was used to ascertain that these were the presentation times used (not influenced by color or shape after-effects). Pilot studies showed that the best way to mask the colored graphemes was by using this particular pattern with different colors. The grapheme was presented for either 100 ms or 150 ms. The grapheme was in Arial in capital letters (visual angle of 6.44°). The distance between the screen and the participant was approximately 40 cm.

4.3. Results

Response times longer than 2.5 times the standard deviation from individual average reaction times were treated as outliers and excluded from analyses. Outliers were found and excluded in all 4 blocks, with an average of 2.40% excluded trials with a maximum of 3.18%.

An overall $2 \times 2 \times 2$ repeated measures ANOVA was performed on RTs with the within-subject factors of task (color naming or photism naming), time (100 ms or 150 ms), and congruency (congruent or incongruent). Participants were faster to photism naming (respond to synesthetic color) than to real color naming (respond to the typeface color) $F(1,20) = 18.46$, $p < .001$. They were faster to graphemes presented for 100 ms than to graphemes presented for 150 ms $F(1,20) = 7.25$, $p < .05$, and faster to congruent than to incongruent trials $F(1,20) = 28.18$, $p < .001$. These factors also interacted: task by time $F(1,20) = 9.22$, $p < .01$, time × congruency $F(1,20) = 26.10$, $p < .001$, and task × time × congruency $F(1,20) = 10.98$, $p < .005$. We will discuss the direction of these interactions below. The same overall $2 \times 2 \times 2$ ANOVA was performed with PA group as the between-subjects factor, which showed that none of the factors interacted with PA group ($F \leqslant 2$).

The first interaction showed that real color naming is slower than photism naming at 100 ms but not at 150 ms presentation. Furthermore, the congruency effects were smaller with the longer (150 ms) than with the shorter (100 ms) presentation time. This effect differed for the two tasks. Synesthetic (photism) interference showed a strong decrease during the longer as compared with the shorter presentation times (from 170 ms to 58 ms). Real color interference showed a much smaller decrease during longer presentation time (from 87 ms to 66 ms, see Table 3).

A separate ANOVA was run to affirm that synesthetic interference decreases with longer presentation time. The 2 × 2 (time and congruency) ANOVA on only the real-color-naming trials (synesthetic interference) showed faster responses during congruent compared to incongruent trials, $F(1,20) = 22.33$, $p < .001$. Importantly, this congruency effect showed a significant interaction with presentation time $F(1,20) = 27.47$, $p < .01$. This analysis confirms a significant decrease of the synesthetic interference effect in the longer presentation duration condition.

Finally, separate analyses were performed to see if the three way interaction obtained in the overall ANOVA indicated a different pattern for the two timing conditions (100 ms and 150 ms presentation time). In 100 ms presentation, there was a main effect of task $F(1,20) = 40.73$, $p < .001$, and of congruency $F(1,20) = 32.30$, $p < .001$. Furthermore, a significant interaction $F(1,20) = 10.40$, $p < .005$ reflects the strong interfering effect of photisms on real color naming with no interfering effect of real color on photism naming (see Table 3 and Fig. 5). During the 150 ms presentation duration condition, there was a significant overall effect of congruency $F(1,20) = 17.74$, $p < .001$ and a trend effect of task $F(1,20) = 3.57$, $p = .07$. However, in this 150 ms condition the interaction of congruency with task was not significant ($F < 1$; Fig. 5). These analyses showed that the strong interfering effect of synesthetic photism (as compared with real color interference) is present with shorter, but not with longer grapheme presentation durations.

Mean percentage correct was over 80% in all conditions. To check for trade-off effects, the same ANOVAs were performed on accuracy. Corresponding to the response times, results showed better performance on congruent compared to incongruent trials ($F(1,20) = 36.30$, $p < .001$). There was also a slightly better performance in photism rather than real color naming task ($F(1,20) = 3.00$, $p = .099$). No other effects were obtained. A separate ANOVA showed no interactions with PA group on these accuracy data.

4.4. Discussion Study 3

This experiment measured interference effects between synesthetic and real (typeface) colors. Properties of the synesthetic interference effect were revealed in two findings. First, at the shortest (100 ms) presentation time, the

Table 3
Congruency effects in Experiment 3.

Condition	Congruent	Incongruent	Congruency effect
100 ms, Real	705 (142)	875 (172)	170 (140)
100 ms, Syn	615 (97)	702 (166)	87 (94)
150 ms, Real	755 (137)	814 (132)	58 (98)
150 ms, Syn	697 (173)	763 (189)	66 (64)

Mean Congruency Effect (difference between Congruent RT and Incongruent RT) in four conditions. Mean and *SD* (in ms) in 100 ms or 150 ms presentation, in either 'name the real color' (Real) or 'name the synesthetic color' (Syn) task.

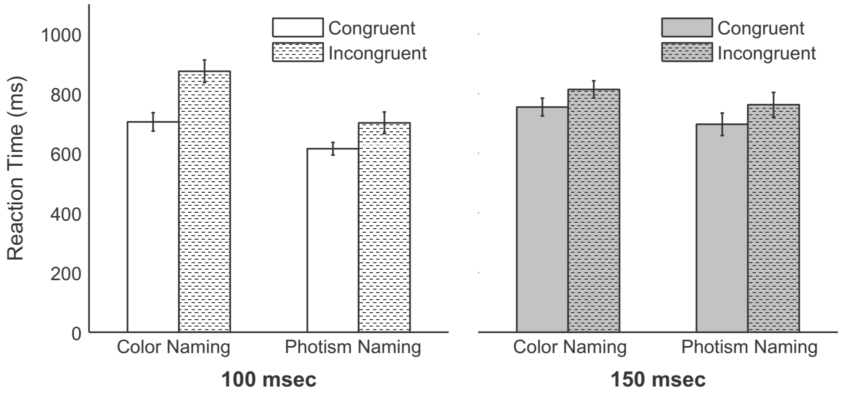

Fig. 5. Strong interference of synesthetic color on real color naming at 100 ms presentation time (first panel) and no interaction between task and interference effect at 150 ms presentation time (second panel). Mean RT (in ms) in Congruent and Incongruent trials, in either 'name the real color' ('Real') or 'name the synesthetic color' ('Syn') task Error bars represent one standard error of the mean.

synesthetic color interference (on real color naming) is stronger than the real color interference (on synesthetic color naming). Second, the synesthetic interfering effect was strongest during the shortest (100 ms) presentation time and declines with increased (150 ms) presentation time. At 150 ms, the synesthetic color interference was equal to the real color interference.

While increasing presentation time decreased the interference effect in both tasks, this effect was much stronger in synesthetic color interference. What could explain this relatively strong decline in synesthetic color interference effect with prolonged presentation time? Evidently, the size of an interference effect is determined by two factors: First, the (synesthetic versus real) color percept, and secondly, the possible inhibition of the task-inappropriate color. An explanation based on color strength *per se* would entail the paradoxical assumption of increased typeface color perception as compared with synesthetic color between the 100 ms and 150 ms presentation duration conditions. While this explanation cannot conclusively be ruled out, there is no clear logical or empirical reason to assume that prolonged presentation of the grapheme leads to a change in the typeface color percept. Another explanation is that in this experiment, at this time window, the prolonged presentation time led to increased opportunity to inhibit the irrelevant synesthetic color information. If this is the case, the finding of decreased synesthetic color interference with prolonged presentation time is in line with the proposition that inhibition of synesthesia takes time and effort.

A somewhat unexpected finding is that at the shortest presentation time condition, synesthetic color interference was stronger than real (typeface) color interference. In the classic Stroop test, two explanations are prevalent for explaining asymmetrical effects, between the Stroop (name the color) and the reverse Stroop (name the word) conditions (for a review, see MacLeod, 1991). In the relative speed-of-processing explanation, the two dimensions are processed in parallel, and priority is determined by speed. The faster dimension is taken to interfere more with the slower processed dimension. While there is evidence for extremely fast processing of synesthetic color (Brang et al., 2010, Beeli et al., 2008), this is necessarily dependent on, and following, the processing of the perceived letter (Laeng et al., 2004; Mattingley et al., 2001). This makes an explanation based on faster processing of synesthetic color dimension than the real color dimension less likely. The second explanation for finding asymmetrical effects in a Stroop paradigm is the automaticity account. In the classic Stroop paradigm, reading the word is seen as more obligatory, better learned or more automatic, and draws less on attentional resources than naming the typeface color. Perhaps the current findings reflect the automatic and obligatory cross-association of a particular synesthetic color when viewing a certain grapheme. The hue of a synesthetic color is generally highly consistent and over-learned with that particular grapheme throughout life.

This size of synesthetic interference (as compared with real color interference) however likely depends on experimental settings. In previous studies, stronger real color interference (as compared with synesthetic color interference) was obtained Dixon et al. (2004) and Ward et al. (2007). One reason why in our experiment a reversed pattern of stronger interference of synesthetic than real color was obtained is that there are important differences in the experimental setup. In particular, it seems relevant that our experiment had short and masked presentations of stimuli while both Dixon et al. (2004) and Ward et al. (2007) presented graphemes until a response was given. Note that in our experiment, increased presentation time resulted in decreased interference effect of the synesthetic color. Perhaps even longer presentation times would have shown an even stronger decrease of synesthetic interference effect such that, similar to the previous studies, the real color interference is now stronger. Currently these explanations are speculations however, as more studies are required to better understand these effects of different experimental settings on the synesthetic Stroop effect.

In our experiment, the projector/associator distinction does not interact with the interference effects. There is currently a debate on the exact nature of the projector/associator dichotomy (e.g. Rouw & Scholte, 2010; Ward et al., 2007). Clear differences between projectors and associators have been demonstrated in functional brain properties (Hubbard et al., 2005; Rouw & Scholte, 2010) as well as structural properties of both white and gray matter (Rouw & Scholte, 2007; Rouw & Scholte, 2010). Perhaps the synesthetic Stroop is not the most appropriate paradigm to reveal differences between projectors with associators; non-synesthetes that acquire 'synesthesia-like' color associations (Meier & Rothen, 2009; Colizoli, Murre, & Rouw, 2012) also show the synesthetic Stroop effect. Furthermore, in the synesthetic Stroop paradigm (as in the classic Stroop effect) interference may take place at different levels of processing (see Introduction). Therefore, differences in processing mechanisms between projectors and associators do not necessarily show up in this paradigm, as both may suffer from the incongruent presentation at some level of processing. Most important, however, is that both in our and in the previous studies, the number of participants is quite small for an individual differences analyses. A study with larger samples of both projectors and associators is needed to shed light on this issue.

The main conclusion of the current experiment is that different presentation times effect the size of the synesthetic Stroop effect. This is possibly caused by inhibition of synesthetic (color) experiences within the 100–150 ms time window. Future research can use this paradigm to further explore how timing alters interference due to synesthetic experiences and to further decipher the relationship between executive control functions and synesthetic functions.

5. Study 4: An individual differences approach

The current study aims to examine the relationship between cognitive control processes and synesthesia. In Studies 1–3, similar paradigms were presented that are either related to synesthesia (e.g. synesthetic Stroop effect) or are not related to synesthesia (e.g. the classic Stroop effect). One question is whether 'general' executive control abilities (such as inhibition of irrelevant information, and shifting between tasks) are involved in controlling or ‘managing’ synesthetic experiences. If this is the case, one would expect that participants with the strongest executive control effects in their synesthetic sensations would also be relatively good at highly similar tasks that tap into general executive control ability. In the current experiment, an individual difference approach of these results is employed in order to probe the relationship between synesthetic and classic executive control functions.

5.1. Participants

All but one of the participants in Study 3 also participated in Study 1 and were included in the first (correlation) analyses. These 20 females all had academic or comparable higher-level education. Mean age was 26 years (*SD* = 7.59, range = 18–50). Seventeen participants were right-handed, two were left-handed and one was ambidextrous. Only four participants were projector synesthetes, the rest was associator synesthete (see Study 1 for a description of the PA questionnaire). The mean PA score was −1.05 (*SD* = 2.23, range = −3.67 to 4.00). Only four participants from Study 2 participated also in Study 1 (and Study 3). Therefore, the second analyses were performed by comparing scores on the different subtests in Study 2.

5.2. Methods

Study 4 employs individual differences analyses on the results obtained in Studies 1–3. First, the correlation was calculated between performance on the classic Stroop task and performance on the synesthetic Stroop task in Study 1 and Study 3. Second, in a different group of participants, performance on synesthetic Stroop task was correlated with their performance on the arrow flanker task.

5.3. Results

Correlations were calculated on the congruency effects (the mean difference between RTs during incongruent and congruent trials) in synesthetic or non-synesthetic tasks. Nonparametric correlation tests were employed as not all variables were normally distributed; Shapiro-Wilk statistic was significant ($p < .05$).

Twenty synesthetes participated in both Study 1 and Study 3. This allows addressing the question of whether the size of the classic Stroop effect (Block 1 in Study 1) predicts the size of the synesthetic Stroop effect (in Study 3). In both these experiments, the task is to name the ‘real’ (typeface) color. Correlations between the Stroop effect in Study 1 and the congruency effects in Study 3 (at both 100 ms and 150 ms presentation time) were not significant (Spearman’ rho is resp. $rs(18) = -0.10$, $p = .68$; and $rs(18) = -0.08$, $p = .74$).

An exploratory analysis showed that the classic Stroop effect also did not correlate with the ‘reversed synesthetic Stroop effect’ in Study 3 (where the task is to name the synesthetic color), $rs(18) = -0.24$, $p = .30$; and $rs(18) = -0.06$, $p = .81$. Furthermore, the congruency effects measured in the other conditions presented in Study 1 (‘reversed Stroop’ in Block 2 and the ‘Stroop and rule-switching’ condition in Block 3) were not correlated with the four (two tasks and two timing) conditions of Study 3. Spearman’ rho was between −0.38 and 0.34, $p > .1$). Thus, even without Bonferroni corrections, these ten correlations were not significant. This is not due to a general lack of strength of the effects (such as lack of variability in the measures), as shown by significant correlations in other comparisons (the synesthetic interference on real color naming at 150 ms presentation correlates with synesthetic interference at 100 ms presentation (Spearman $rs(18) = 0.58$, $p = .006$). Furthermore, there were considerable individual differences in the congruency effects of both Study 1 and in Study 3[3] (*SD* of the effects are reported in Tables 1–3).

Unfortunately, only a few participants performed Study 2 as well as either Study 1 or Study 3. We could, however, compare performances on a synesthetic behavioral task and a cognitive control task within Study 2. We correlated the size of synesthetic Stroop-effect (as measured in the blocks with only Go-trials in Experiment 2C) with the size of the arrow-flanker effect (flanker arrows are congruent versus incongruent to the target). Neither the synesthetic Stroop effect, nor the reversed synesthetic Stroop effect correlated with the arrow flanker effect ($rs(18) = -0.04$, $p = .86$ and $rs(18) = -0.18$, respectively). Thus, a synesthete showing a strong synesthetic Stroop effect (in Study 2) did not necessarily show a strong congruency effect on the arrow flanker task. Again, performance level in a synesthetic behavioral task did not show a relationship with performance level in a executive control task.

5.4. Discussion Study 4

These analyses showed no relationship between synesthetic interference effects and non-synesthetic cognitive control ability. Intuitively, the synesthetic Stroop effect seems to contain the same core ability of inhibiting the inappropriate response as a classic Stroop task. However, the classic Stroop effect did not predict the size of the synesthetic Stroop effect. In correspondence with our earlier findings, in these analyses no relationship was found between synesthetic behavior

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[3] In Experiment 1, the mean Stroop effect is 26 ms, but it ranges from 127 ms to −97 ms. The mean Stroop effect in the context of switching is 277 ms, but it ranges from 1113 ms to −41 ms. In Experiment 3, the mean synesthetic color interference at 100 ms presentation time is 170 ms, but ranges from 642 ms to −87 ms. At 150 ms presentation time, the mean synesthetic color interference 58 ms, but ranges from 303 ms to −164 ms.

and cognitive control. A null finding always leaves alternative interpretations open. Perhaps not the right tests or experimental settings were used to obtain correlations between the test scores. Furthermore, if the obtained scores were not reliable enough to reflect stable individual characteristics, this would also obscure existing relationships. While more research is needed to learn about these possibilities, the current studies do not support a relationship between scores on these synesthetic and non-synesthetic paradigms. If there is indeed no such relationship, this would raise the question if there is relatively independent functioning of certain synesthesia-related processes, e.g. when dealing with conflicting synesthetic colors and real colors.

6. General discussion

Synesthesia provides us with an extraordinary opportunity to study some of the most hotly debated issues in cognitive neuroscience (e.g. the 'binding problem', multi-sensory integration, and perceptual awareness). In this study, we address an aspect of synesthesia that has received little attention so far. What underlies the synesthete's strong ability to 'manage' or control the simultaneous presence of two sets of representations? For a grapheme-color synesthete, a letter can have both a 'real' and a synesthetic color, and these colors can even share the same (external) space (Dixon et al., 2004; Rouw & Scholte, 2010; Ward et al., 2007). This 'conflict' has a measurable effect in behavioral experiments, such as increased response time in a synesthetic Stroop paradigm. However, synesthetes typically do not make mistakes or feel confused in these types of 'conflict' situations. Which mechanisms are involved during these situations where synesthetic and 'real' sensations are incongruent? As a starting point, we examined the relationship between synesthesia and executive control functions. The findings provide us with tentative initial conclusions.

First, we found no general skill differences between synesthetes and non-synesthetes in executive control functions. This was found consistently across different participant groups and using different tasks. Synesthetes did not differ from non-synesthetes in a classic Stroop effect (Study 1), in the switch-cost during a classic Stroop task (Study 1), or in an arrow flanker effect (Experiment 2A). The second question addressed in this study is whether behavioral synesthetic effects are influenced by an additional cognitive control manipulation. Across different experiments and participant groups, employing both within- and between-participants analyses, we did not obtain evidence for such an effect. For example, an interference effect of synesthetic color, as measured in the synesthetic Stroop task, was not influenced by a simultaneous stop-signal task manipulation. Thirdly, we examined timing effects in a situation where synesthetic experiences interfere with 'real' experiences. We found that in the synesthetic Stroop task, a very short presentation time of the stimulus leads to a relatively large interference of the incorrect synesthetic color on real color naming. The interference effect of the synesthetic color decreases when the presentation time is longer. This finding is in line with the hypothesis that inhibition of the irrelevant synesthetic color takes effort and time. The fourth sub-question was addressed using an individual differences approach. There was no trace of a correlation between the size of the Stroop effect and the size of the synesthetic Stroop effect. This finding is counter to what one would expect if these two effects share the same functions or resources.

As far as we know, this is the first study to explicitly address the relationship between the ability to control synesthetic experiences and the skills measured in classic cognitive control paradigms. The results failed to show any *generally* increased executive functioning in synesthetes as compared with non-synesthetes. Moreover, little evidence was found for a relationship between performance on 'synesthetic control' situations and performance on cognitive control paradigms. The results might suggest that the two abilities depend on at least partially different mechanisms. This raises the question of what happens exactly in situations where synesthetic experiences conflict with 'real' sensations.

One possible account is that synesthetes do control their additional responses with the general executive function mechanisms used in other (non-synesthesia related) tasks, such as those involved in resolving perceptual interference, response inhibition, and task switching. This account would predict that synesthetes do use their executive functions during synesthetic experiences. The lack of interaction effects between cognitive control manipulations and synesthetic interference is inconsistent with this prediction. Previous studies have shown that if two different executive function tasks tap into similar control mechanisms, they will affect each other (Ridderinkhof et al., 1999; Verbruggen et al., 2005). The currently obtained lack of interaction patterns suggests that synesthetic management does not tap into the type of control mechanisms involved in Stroop, flanker, stop, or switch tasks.

Another account is that little control or 'managing' is needed when synesthetic and 'real' sensations are incongruent. Synesthetes can simply choose to neglect or ignore the irrelevant (color) information, and either report the 'real' or the 'synesthetic' sensation as required. In this explanation, an alternative interpretation is needed for the obtained decreased synesthetic interference effect with longer presentation times (Study 3). It also raises the interesting question of which mechanisms *are* involved in these types of conflict situations. What allows synesthetes to effortlessly 'see' or 'know' what is synesthetic and what is not? In this context, it would be interesting to learn more about the similarities and differences between synesthetic and non-synesthetic sensations (or qualia).

In sum, then, it appears that synesthetic management does not entail executive control over the sources and salience of real and synesthetic sensations, especially when synesthetic experiences are incongruent with 'real' experiences. Synesthetic management processes appear to be relatively independent from the processes involved in resolving other types of perceptual interference (such as in Stroop or flanker tasks), in inhibiting inappropriate responses (such as in stop tasks), or in cognitive flexibility (such as in task switching). The results of Study 3 suggest that the specific control processes involved in synesthetic management might entail the selective suppression of synesthetic sensations, an energy-demanding process that takes time (at least 150 ms) to become fully operational. In this scenario, the condition of synesthesia would thus entail mechanisms involved in *having* synesthetic experiences as well as mechanisms involved in *handling* these experiences such that behavior benefits from, or at least does not suffer from these additional experiences. This conjecture thus raises the question of which cognitive and neurological mechanisms are altered during the development of synesthesia. Both a genetic predisposition (Asher et al., 2009; Tomson et al., 2011) and the experiences of the young synesthete (Witthoft & Winawer, 2006) might affect the synesthete's developmental pattern.

Understanding executive control functions in synesthesia is not only important in order to gain insight in the synesthetic condition. In pathological additional sensations, such as hallucinations during psychosis, a defining characteristic is that patients are not able to discern their internally generated sensations (such as 'voices') from 'real' sensations. Synesthesia shows that the presence of an additional sensation is not disturbing *per se*. A better understanding of synesthesia aids our understanding of the difference between healthy additional sensations, and pathological additional sensations. If we know more about mechanisms involved in synesthesia, this will also further our knowledge on these severe clinical conditions.

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References

Asher, J. E., Lamb, J. A., Brocklebank, D., Cazier, J. B., Maestrini, E., Addis, L., et al (2009). A whole-genome scan and fine-mapping linkage study of auditory–visual synesthesia reveals evidence of linkage to chromosomes 2q24, 5q33, 6p12, and 12p12. *The American Journal of Human Genetics, 84*(2), 279–285.

Band, G. P. H., Van der Molen, M. W., & Logan, G. D. (2003). Horse-race model simulations of the stop-signal procedure. *Acta Psychologica, 112*, 105–142.

Barnett, K. J., Finucane, C., Asher, J. E., Bargary, G., Corvin, A. P., Newell, F. N., et al (2008). Familial patterns and the origins of individual differences in synaesthesia. *Cognition, 106*(2), 871–893.

Baron-Cohen, S., Wyke, M. A., & Binnie, C. (1987). Hearing words and seeing colours, an experimental investigation. *Perception, 16*(6), 761–767.

Beeli, G., Esslen, M., & Jäncke, L. (2005). Synaesthesia – When coloured sounds taste sweet. *Nature, 434*(7029), 38.

Beeli, G., Esslen, M., & Jäncke, L. (2008). Time course of neural activity correlated with colored-hearing synesthesia. *Cerebral Cortex, 18*(2), 379–385.

Berteletti, I., Hubbard, E. M., & Zorzi, M. (2010). Implicit versus explicit interference effects in a number-color synesthete. *Cortex, 46*(2), 170–177.

Bialystok, E. (2001). *Bilingualism in development: Language, literacy, and cognition*. New York: Cambridge Univ. Press.

Bialystok, E., Craik, F. I. M., Grady, C., Chau, W., Ishii, R., Gunji, A., et al (2005). Effect of bilingualism on cognitive control in the Simon task: Evidence from MEG. *NeuroImage, 24*, 40–49.

Botvinick, M., Nystrom, L. E., Fissell, K., Carter, C. S., & Cohen, J. (1999). Conflict monitoring versus selection-for-action in anterior cingulate cortex. *Nature, 402*, 179–181.

Brang, D., Hubbard, E. M., Coulson, S., Huang, M., & Ramachandran, V. S. (2010). Magnetoencephalography reveals early activation of V4 in grapheme color synesthesia. *NeuroImage, 53*, 268–274.

Cohen Kadosh, R., Cohen Kadosh, K., & Henik, A. (2007). The neuronal correlate of bidirectional synesthesia: A combined event-related potential and functional magnetic resonance imaging study. *Journal of Cognitive Neuroscience, 19*(12), 2050–2059.

Colizoli, O., Murre, J. M. J., & Rouw, R. (2012). Pseudo-synesthesia through reading books with Colored letters. *PLoS One, 7*(6), e39799.

Dixon, M. J., Smilek, D., Cudahy, C., & Merikle, P. M. (2000). Five plus two equals yellow. *Nature, 406*, 365.

Dixon, M. J., Smilek, D., & Merikle, P. M. (2004). Not all synaesthetes are created equal: Projector versus associator synaesthetes. *Cognitive and Affective Behavioral Neuroscience, 4*(3), 335–343.

Goller, A. I., Otten, L. J., & Ward, J. (2009). Seeing sounds and hearing colors: An event-related potential study of auditory–visual synesthesia. *Journal of Cognitive Neuroscience, 21*(10), 1869–1881.

He, S., Cavanagh, P., & Intriligator, J. (1996). Attentional resolution and the locus of visual awareness. *Nature, 383*(6598), 334–337.

Hubbard, E. M., Arman, A. C., Ramachandran, V. S., & Boynton, G. M. (2005). Individual differences among grapheme-color synesthetes: Brain-behavior correlations. *Neuron, 45*, 975–985.

Hubbard, E. M., Brang, D., & Ramachandran, V. S. (2011). The cross-activation theory at 10. *Journal of Neuropsychology, 5*, 152–177.

Jäncke, L., Beeli, G., Eulig, C., & Hänggi, J. (2009). The neuroanatomy of grapheme-color synesthesia. *European Journal of Neuroscience, 29*(6), 1287–1293.

Jäncke, L., & Langer, N. (2011). A strong parietal hub in the small-world network of coloured-hearing synaesthetes during resting state EEG. *Journal of Neuropsychology, 5*, 178–202.

Jersild, A. T. (1927). Mental set and shift. *Archives of Psychology, 89*, 5–82.

Kooi, F. L., Toet, A., Tripathy, S. P., & Levi, D. M. (1994). The effect of similarity and duration on spatial interaction in peripheral vision. *Spatial Vision, 8*, 255–279.

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

Laeng, B., Hugdahl, K., & Specht, K. (2011). The neural correlate of colour distances revealed with competing synaesthetic and real colours. *Cortex, 47*(3), 320–331.

Laeng, B., Svartdal, F., & Oelmann, H. (2004). Does color synesthesia pose a paradox for early-selection theories of attention? *Psychological Science, 15*, 277–281.

Logan, G. D. (1994). On the ability to inhibit thought and action: A user's guide to the stop signal paradigm. In D. Dagenbach & T. H. Carr (Eds.), *Inhibitory processes in attention, memory and language* (pp. 189–239). San Diego: Academic Press.

Logan, G. D., & Cowan, W. B. (1984). On the ability to inhibit thought and action–a theory of an act of control. *Psychological & Review, 91*, 295–327.

MacLeod, C. M. (1991). Half a century of research on the Stroop effect: An integrative review. *Psychological Bulletin, 109*, 163–203.

Mattingley, J. B., Payne, J. M., & Rich, A. N. (2006). Attentional load attenuates synaesthetic priming effects in grapheme-colour synaesthesia. *Cortex, 42*, 213–221.

Mattingley, J. B., Rich, A. N., Yelland, G., & Bradshaw, J. L. (2001). Unconscious priming eliminates automatic binding of colour and alphanumeric form in synaesthesia. *Nature, 410*(6828), 580–582.

Meier, B., & Rothen, N. (2009). Training grapheme-colour associations produces a synaesthetic Stroop effect, but not a conditioned synaesthetic response. *Neuropsychologia, 47*, 1208–1211.

Miyake, A., Naomi, P., Friedman, M. J., Emerson, A. H., Witzki, H. A., & Wager, T. D. (2000). The unity and diversity of executive functions and their contributions to complex “Frontal Lobe” tasks: A latent variable analysis. *Cognitive Psychology, 41*, 49–100.

Monsell, S. (2003). Task switching. *Trends in Cognitive Sciences, 7*, 134–140.

Monsell, S., Sumner, P., & Waters, H. (2003). Task-set reconfiguration with predictable and unpredictable task switches. *Memory and Cognition, 31*, 327–342.

Nunn, J. A., Gregory, L. J., Brammer, M., Williams, S. C. R., Parslow, D. M., Morgan, M. J., et al (2002). Functional magnetic resonance imaging of synesthesia: Activation of V4/V8 by spoken words. *Nature Neuroscience, 5*(4), 371–375.

Palmeri, T. J., Blake, R. B., Marois, R., Flanery, M. A., & Whetsell, W. O. (2002). The perceptual reality of synesthetic color. *Proceedings of the National Academy of Sciences of the United States of America, 99*, 4127–4131.

Paulesu, E., Harrison, J., Baron-Cohen, S., Watson, J. D. G., Goldstein, L., Heather, J., et al (1995). The physiology of coloured hearing A PET activation study of colour-word synaesthesia. *Brain, 118*(3), 661–676.

Pelli, D. G., Palomares, M., & Majaj, N. J. (2004). Crowding is unlike ordinary masking: Distinguishing feature integration from detection. *Journal of Vision, 4*, 1136–1169.

Perret, E. (1974). The left frontal lobe of man and the suppression of habitual responses in verbal categorical behaviour. *Neuropsychologia, 12*, 323–330.

Ramachandran, V. S., & Hubbard, E. M. (2001a). Synaesthesia: A window into perception, thought and language. *Journal of Consciousness Studies, 8*, 3–34.

Ramachandran, V. S., & Hubbard, E. M. (2001b). Psychophysical investigations into the neural basis of synaesthesia. *Proceedings of the Royal Society B: Biological Sciences, 268*, 979–983.

Ridderinkhof, K. R., Band, G. P. H., & Logan, G. D. (1999). A study of adaptive behavior: Effects of age and irrelevant information on the ability to inhibit one’s actions. *Acta Psychologica, 101*, 315–337.

Ridderinkhof, K. R., Molen, M. W., & Bashore, T. R. (1995). Limits on the application of additive factor logic: Violations of stage robustness suggest a dual-process architecture to explain flanker effects on target processing. *Acta Psychologica, 90*, 29–48.

Ridderinkhof, K. R., vandenWildenberg, W. P. M., Seglowitz, S. J., & Carter, C. S. (2004). Neurocognitive mechanisms of cognitive control: The role of prefrontal cortex in action selection, response inhibition, performance monitoring, and reward-based learning. *Brain and Cognition, 56*, 129–140.

Rogers, R. D., & Monsell, S. (1995). The cost of a predictable switch between simple cognitive tasks. *Journal of Experimental Psychology: General, 124*, 207–231.

Rothen, N., & Meier, B. (2009). Do synesthetes have a general advantage in visual search and episodic memory? A case for group studies. *PLoS One, 4*(4), e5037.

Rouw, R., & Scholte, H. S. (2007). Increased structural connectivity in grapheme-color synesthesia. *Nature Neuroscience, 10*, 792–797.

Rouw, R., & Scholte, H. S. (2010). Neural basis of individual differences in synesthetic experiences. *The Journal of Neuroscience, 30*, 6205–6213.

Rouw, R., Scholte, H. S., & Colizoli, O. (2011). Brain areas involved in synaesthesia: A review. *Journal of Neuropsychology, 5*(2), 214–242.

Saenz, M., & Koch, C. (2008). The sound of change: Visually-induced auditory synesthesia. *Current Biology, 18*, 650–651.

Sagiv, N., Knight, R. T., & Robertson, L. C. (2003). Electrophysiological markers of synesthesia. *Journal of Cognitive Neuroscience* (Suppl. 15), 153.

Simner, J., Mulvenna, C., Sagiv, N., Tsakanikos, E., Witherby, S. A., Fraser, C., et al (2006). Synaesthesia: The prevalence of atypical cross-modal experiences. *Perception, 35*, 1024–1033.

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

Smilek, D., Dixon, M. J., Cudahy, C., & Merikle, P. M. (2001). Synaesthetic photisms influence visual perception. *Journal of Cognitive Neuroscience, 13*, 930–936.

Smilek, D., Dixon, M. J., Cudahy, C., & Merikle, P. M. (2002). Synesthetic color experiences influence memory. *Psychological Science, 13*, 548–555.

Specht, K., & Laeng, B. (2011). An independent component analysis of fMRI data of grapheme-colour synaesthesia. *Journal of Neuropsychology, 5*, 203–213.

Sperling, J. M., Prvulovic, D., Linden, D. E. J., Singer, W., & Stirn, A. (2006). Neuronal correlates of colour-graphemic synaesthesia: A fMRI study. *Cortex, 42*(2), 295–303.

Stroop, J. R. (1935). Studies of interference in serial verbal reactions. *Journal of Experimental Psychology, 18*(6), 643–662.

Tomson, S., Avidan, N., Lee, K., Sarma, A. K., Tushe, R., Milewicz, D., et al (2011). The genetics of colored sequence synesthesia: Suggestive evidence of linkage to 16q and genetic heterogeneity for the condition. *Behavioural Brain Research, 223*, 48–52.

Verbruggen, F., Liefooghe, B., Notebaert, W., & Vandierendonck, A. (2005). Effects of stimulus–stimulus compatibility and stimulus–response compatibility on response inhibition. *Acta Psychologica, 120*, 307–326.

Verbruggen, F., & Logan, G. D. (2009). Models of response inhibition in the stop-signal and stop-change paradigms. *Neuroscience & Biobehavioral Reviews, 33*, 647–661.

Ward, J., Jonas, C., Dienes, Z., & Seth, A. (2009). Grapheme-color synaesthesia improves detection of embedded shapes, but without pre-attentive ’pop-out’ of synaesthetic colour. *Proceedings of the Royal Society B: Biological Sciences, 277*, 1021–1026.

Ward, J., Jonas, C., Dienes, Z., & Seth, A. (2010). Grapheme-colour synaesthesia improves detection of embedded shapes, but without pre-attentive ’pop-out’ of synaesthetic colour. *Proceedings of the Royal Society B: Biological Sciences, 277*, 1021–1026.

Ward, J., Li, R., Salih, S., & Sagiv, N. (2007). Varieties of grapheme-colour synaesthesia: A new theory of phenomenological and behavioural differences. *Consciousness & Cognition, 16*(4), 913–931.

Ward, J., & Simner, J. (2003). Lexical-gustatory synaesthesia: Linguistic and conceptual factors. *Cognition, 89*(3), 237–261.

Weiss, P. H., & Fink, G. R. (2009). Grapheme-colour synaesthetes show increased grey matter volumes of parietal and fusiform cortex. *Brain, 132*(1), 65–70.

Weiss, P. H., Zilles, K., & Fink, G. R. (2005). When visual perception causes feeling: Enhanced cross-modal processing in grapheme-color synesthesia. *NeuroImage, 28*(4), 859–868.

Whitney, D., & Levi, D. M. (2011). Visual crowding: A fundamental limit on conscious perception and object recognition. *Trends Cognitive Science, 15*(4), 160–168.

Witthoft, N., & Winawer, J. (2006). Synesthetic colors determined by having colored refrigerator magnets in childhood. *Cortex, 42*(2), 175–183.

Wollen, K. A., Ruggiero, F. T., & Frank, T. (1983). Coloured-letter synaesthesia. *Journal of Mental Imagery, 7*(2), 83–86.