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Cognitive control predicted by color vision, and vice versa

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ABSTRACT

One of the most important functions of cognitive control is to continuously adapt cognitive processes to changing and often conflicting demands of the environment. Dopamine (DA) has been suggested to play a key role in the signaling and resolution of such response conflict. Given that DA is found in high concentration in the retina, color vision discrimination has been suggested as an index of DA functioning and in particular blue–yellow color vision impairment (CVI) has been used to indicate a central hypodopaminergic state. We used color discrimination (indexed by the total color distance score; TCDS) to predict individual differences in the cognitive control of response conflict, as reflected by conflict-resolution efficiency in an auditory Simon task. As expected, participants showing better color discrimination were more efficient in resolving response conflict. Interestingly, participants showing a blue–yellow CVI were associated with less efficiency in handling response conflict. Our findings indicate that color vision discrimination might represent a promising predictor of cognitive controlability in healthy individuals.

1. Introduction

The concept of cognitive control refers to our ability to regulate our thoughts and actions in ways that allow us to reach intended goals, and to continuously adjust the processes involved to changing environmental demands. The general ability of goal-regulation is often assessed by means of conflict-inducing tasks. For instance, the Simon task (Simon & Small, 1969) calls for spatial reactions to non-spatial attributes of stimuli appearing in randomly varying locations. The standard finding shows better performance if stimuli appear in response-congruent (C) than in response-incongruent (I) locations, demonstrating that action goals are indeed challenged, and yet people can overcome these challenges by overruling misleading stimulus-induced response tendencies (Hommel, 2011; Kornblum, Hasbroucq, & Osman, 1990). Even brief drops in control strength (i.e., concentration on the goal) are immediately repaired, as shown by the observation that people are more efficient in resolving response conflict after conflict trials: the effect of congruency in the present trial (I-C) is less pronounced after an incongruent trial (iI-iC) than after a congruent trial (cI-cC; Gratton, Coles, & Donchin, 1992). This so-called "conflict-adaptation effect"(also known as Gratton effect) has been taken to reflect the increase of cognitive control triggered by the experience of conflict (Botvinick, Braver, Barch, Carter, & Cohen, 2001[1]).

Dopamine (DA) has been suggested to play a key role in representing and maintaining task goals in the face of challenges (Botvinick, 2007). Indeed, the detection of response conflict seems to rely on the anterior cingulate cortex (ACC) (Peterson, Kane, & Alexander, 2002; Kerns et al., 2005) and DA is thought to play a key role in both signaling and resolving such conflict (Botvinick, 2007; Holroyd & Coles, 2002). The main idea is that both response conflict and (registered) response errors induce a phasic reduction in DA levels, which again initiates processes that either prevent the error altogether or at least adapt the control system to prevent such errors in the future.

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[1] It is worth mentioning that episodic memory retrieval of stimulus and response associations (Hommel, Proctor, & Vu, 2004; Mayr, Awh, & Laurey, 2003) may account for sequential modulation effects observed in some of previous studies. However, although there are reasons to doubt that the Gratton effect is a pure measure of conflict adaptation, there is evidence suggesting that it does reflect control adaptations to some degree, as control-related aspects of the effect remain even when controlling for episodic binding effects (Verguts & Notebaert, 2008; Egner, 2007).

The direct assessment of DA function in humans is only possible by positron emission tomography (PET) so far, which is very expensive and highly invasive due to radioactive contamination and arterial blood sampling (Volkow, Fowler, Wang, Baler, & Telang, 2009). Interestingly for our purposes, however, DA can be found in high concentration in the amacrine and interplexiform cells of the retina (Bodis-Wollner & Tzelepi, 1998; Witkovsky, 2004). Abnormal color discrimination has been described for several neuropsychiatric conditions underlying altered dopaminergic functions, such as Parkinson's and Huntington's disease, Tourette syndrome, ADHD, and cocaine use (Melun, Morin, Muise, & DesRosiers, 2001; Paulus, Schwarz, Werner, & Lange, 1993; Pieri, Diederich, Raman, & Goetz, 2000; Tannock, Banaschewski, & Gold, 2006; Hulka, Wagner, Preller, Jenni & Quednow, 2013). Moreover, Lagerlöf (1982) found evidence that the intake of DAD2 receptor-antagonists, such as haloperidol, induces moderate blue–yellow deficits. Along the same line, Roy, Roy, Berman, and Gonzalez (2003) suggested that blue–yellow color vision impairment (CVI) indicates a central hypodopaminergic state.

If so, color vision may predict conflict management because both are driven by dopamine. In the present study, we thus investigated whether individual color discrimination performance, and in particular blue–yellow color vision, predicts individual differences in cognitive control in an auditory Simon task. In particular, we tested whether color vision predicts the efficiency of handling response conflict, as reflected by the size of the Simon congruency effect (with smaller effects indicating tighter control). Furthermore, we explored whether color vision may also predict dynamic behavioral adjustments (i.e., trial-to-trial variability) in the Simon task, as indexed by the size of the Gratton effect.

2. Method

2.1. Participants

Seventy-eight young healthy adults (63 female and 15 male; aged 18–29 years; mean age 19.64) participated in the experiment for partial fulfillment of course credit. All participants were naïve about the purpose of the experiment.Participants who self-reported inherited dichromacy (protanopia and deuteranopia, i.e., red–green blindness predominantly present in males) were not tested.

Written informed consent was obtained from all participants after the nature of the study was explained to them. The protocol was approved by the local ethical committee (Leiden University, Institute for Psychological Research).

2.2. Apparatus, stimuli and procedure

All participants were tested individually and they were required to complete two tasks: the Lanthony Desaturated Panel D-15 Test (LD-15; Lanthony, 1978), and the Simon task (Simon & Small, 1969). Half of the participants completed the LD-15 Test before performing the Simon task, while the other half performed the Simon task followed by the LD-15.

2.3. Lanthony Desaturated Panel D-15 Test (color vision discrimination)

The D-15 test has been previously used to investigate CVI in recreational and dependent stimulant users, were blue–yellow CVI was correlated with cognitive (or more exactly memory) performance (Hulka et al., 2013).

The test is composed of a fixed reference cap and 15 changeable color caps that have to be ordered in sequence. Colors are of low saturation (decreased chroma) and increased lightness. The test was carried out under a daylight fluorescent lamp supplying an illumination of 1400 lx. No time limit was imposed to complete the test.

Quantitative color scoring was derived from the color scoring method proposed by Geller (2001), who provided a table to compute the total color distance score (TCDS). An ideal score of 56.41 is achieved when all the caps are arranged in the right order, while higher scores reflect color vision deficits.

Following Hulka et al. (2013), qualitative color scoring was performed by plotting the participant's cup order on a template that describes a hue circle based on the placement of the caps in the *International Commission on Illumination Color Space* (Wyszecki & Stiles, 1982). Single cap inversions (e.g. 1-3-2-4- …) are classified as minor errors or normal confusion, whereas cap reversals spanning two or more positions are considered major errors. The presence of two or more major errors is indicative of a specific disorder. Four reference axes (protan, deutan, tritan and tetartan) reproduced on the template allow for the specific disorder-type classification: protan (red), deutan (green) and tritan/tetartan (blue–yellow) color vision deficits. Types of acquired dyschromatopsia relied on Verriest's classification: type I reflects CVI along the red–green axis; type II is a combined impairment of the red–green and blue–yellow axis; type III reflects blue–yellow axis impairment; type IV is diagnosed when no clear pattern can be determined.

2.4. Simon task

In the Simon task participants were requested to press a left and a right key (the "z" and "m" character on a QWERTY computer keyboard, respectively) in response to two acoustic signals (A and B). The acoustic signals were designed by van Steenbergen (2007) and consisted of two spoken Dutch color words ("groen" [green] and "paars" [purple]) that were compressed and played in reversed order, leading to easily distinguishable sounds (sounding like "oerg" and "chap") without any obvious semantic meaning. The acoustic signals were equiprobably presented to the right or to the left ear by means of earphones until the response was given or 2000 ms had passed. Participants were to ignore the location of the ear in which the tone was presented and to base their response exclusively on the identity of the acoustic signal. Half of the participants were instructed to press the left key in response to the sound "oerg" and the right key in response to the sound "chap". The opposite mapping was assigned to the other participants. Responses were to be given as fast as possible while keeping error rates below 15% on average; feedback was provided at the end of a trial block. The task consisted of one practice block of 20 trials and eight experimental blocks of 60 trials. In half of the trials stimulus and response positions corresponded (S-R congruent trials), whereas, in the other half, stimulus and response positions did not correspond (S-R incongruent trials).

Four scores were calculated: (1) the size of the stimulus-response congruency effect (i.e., the Simon effect), calculated as the difference in RT between (correct) incongruent (I) and congruent (C) trials, and taken to reflect the efficiency of handling response conflict; (2) the size of the Simon effect for the percentage of errors (PE; incongruent minus congruent); (3) the size of the conflict-adaptation effect (i.e., Gratton effect), calculated as the difference between the Simon effect following congruent trials (cI-cC; incongruent trial following congruent trial – congruent trial following congruent trial) and the Simon effect following incongruent trials (iI-iC; incongruent trial following incongruent trial – congruent trial following incongruent trial)[2]; (4) the size of the Gratton effect in PE ((cI-cC)-(iI-iC)).The conflict-adaptation effect served as a measure of control fluctuation and resulting adaptation.

2.5. Statistical analysis

As a manipulation check (to assess reliable Simon and conflict-adaptation effects), mean correct RTs and PEs from the Simon task were submitted to a repeated-measures analysis of variance (ANOVA), with congruency in present trial (S-R congruence vs. S-R incongruence) and congruency in previous trial (S-R congruence vs. S-R incongruence) as within-subjects factors.

To assess whether individual differences in color vision discrimination can predict differences in cognitive control, Pearson correlation coefficients were computed between the size of the Simon in RT and PE and the conflict-adaptation effects and the TDCSs (where high scores reflect poor performance).

Finally, to provide additional clues in favor of the hypothesis that difficulties in resolving response conflict may reflect low levels of DA, performance of participants showing a specific blue–yellow color vision disorder, which is assumed to reflect a central hypodopaminergic state (Hulka et al., 2013; Desai, Roy, Roy, Brown, & Smelson, 1997; Roy, Smelson, & Roy, 1996), was compared with performance of participants who did not show such an impairment. In order to test our directional hypothesis, a nonparametric one-tailed Mann–Whitney's U test was used to compensate for unbalanced samples size (Hayes, 1988).

3. Results

3.1. Simon task

ANOVAs revealed that, as expected, responses were faster and more accurate on S-R congruent (504 ms, SD=86.5; 0.7%, SD=0.8) than on S-R incongruent trials (554 ms, SD=86.9; 3.5%, SD=2.7), $F(1,77)=530.06$, $p<0.0001$, $p\eta^2=0.87$ (RT), $F(1,77)=105.52$, $p<0.0001$, $p\eta^2=0.58$ (PE). A reliable conflict-adaptation effect was also found, as indicated by a significant interaction between

[2] For the conflict adaptation analysis, the following trials were removed: trials with errors, trials following an error, and the first trial of each block.

congruency in present trials and congruency in previous trials, $F(1,77)=182.51$, $p<0.0001$, $p\eta^2=0.70$ (RT), $F(1,77)=49.91$, $p<0.0001$, $p\eta^2=0.39$ (PE). As usually found, the Simon effect in both RT and PE was larger after congruent (79 ms, SD=29; 4.3%, SD=3.9) than after incongruent trials (21 ms, SD=25; 1.4%, SD=1.8). The main effect of congruency in the previous trial was not significant for the RT analysis, $F(1,77)=2.37$, $p=0.13$, $p\eta^2=0.03$, but it was significant for the PE analysis, $F(1,77)=27.53$, $p<0.0001$, $p\eta^2=0.26$: As usually observed, participants made less errors after incongruent (1.6%, SD=1.3) than after congruent trials (2.6%, SD=2.2).

3.2. LD-15 Test

The TCDS scores varied between 56.41 and 99.15 with a mean value of 67.33 (SD=8.09). Six participants (7.7%) showed no error, 33 (42.3%) presented only minor errors, 32 (41.0%) showed one major error along the blue–yellow axis, and only 7 participants (9.0%) showed a disorder along the blue-yellow axis (type III). Among participants showing a disorder along the blue–yellow axis, one participant showed also one major error along the red-green axis (type II). None of the participants exhibited any disorder along the remaining axes (i.e., Types I and IV).

3.3. Correlation and comparison analyses

For the RT data, TCDSs were significantly positively correlated with the individual sizes of both the stimulus-response congruency effect, $r(78)=0.23$, $p=0.039$, and the conflict-adaptation effect, $r(78)=0.33$, $p=0.003$, see Fig. 1. In other words, better color discrimination was associated with smaller congruency effects and less pronounced trial-to-trial fluctuation/adaptation. No correlation was observed between Simon and Gratton effects, $r(78)=0.08$, $p=0.51$. For the PE data, TCDSs did not correlated neither with the size of the Simon effect nor with the Gratton effect ($p_s \geq 0.62$). A positive correlation was found between Simon and Gratton effects, $r(78)=0.68$, $p<0.001$.

Table 1 provides an overview of the size of the Simon and conflict-adaptation effects in both RT and PE as a function of participants' performance in the LD-15 Test. For the PE data, one-tailed Mann–Whitney's U tests revealed that the three groups of participants (i.e., participants with a disorder along the blue–yellow axis, participants showing a perfect score and/or only minor errors, and participants exhibiting one major error only) were comparable in terms of Simon and Gratton effects ($p_s \geq 0.25$). Notably, for the RT data, one-tailed Mann–Whitney's U tests revealed that participants showing a disorder along the blue–yellow axis (Type III) exhibited a larger Simon effect as compared to participants showing a perfect score and/or only minor errors ($p=0.037$; $d=0.61$), and to participants showing one major error only ($p=0.036$; $d=0.68$). The size of the Simon effect did not differ between participants showing a perfect score and/or only minor errors and those who made only one major error ($p=0.47$). No difference between groups was observed when comparing the size of the conflict-adaptation effect ($p_s \geq 0.36$). Importantly, additional one-tailed Mann–Whitney's U tests showed that the three groups were comparable in terms of mean RTs and PEs ($p_s \geq 0.24$). This rules out the possibility that the larger Simon effect showed by participants with a disorder along the blue-yellow axis may reflect possible differences in speed and/or accuracy between groups.

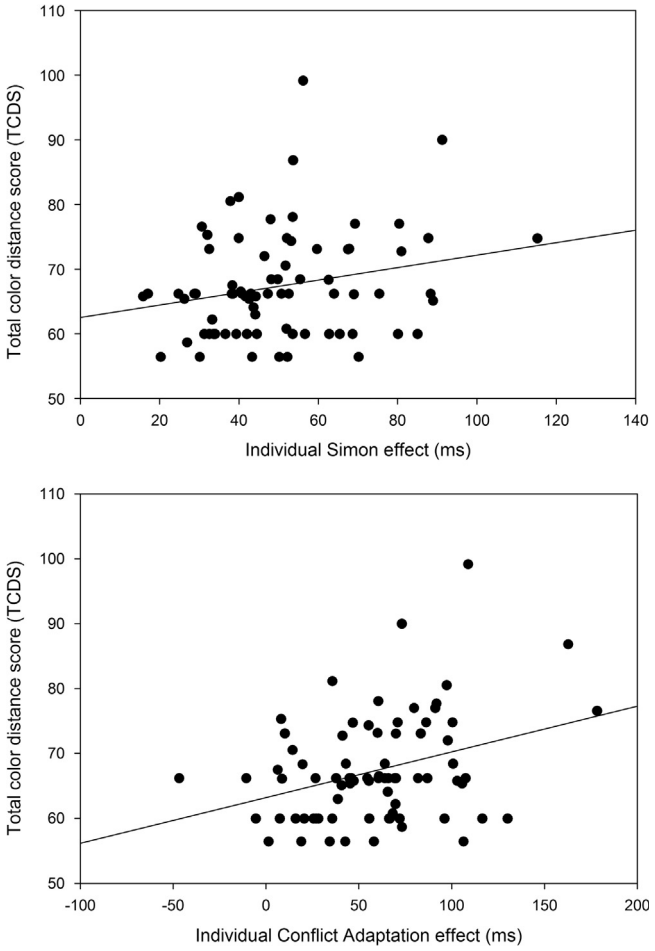

Fig. 1. Scatter diagrams of individual total color distance score (TCDS)—with higher scores representing poorer performance—against the individual size of the stimulus-response congruency effect (higher panel) and the conflict-adaptation effect (lower panel).

4. Conclusion

Our findings reveal that individual differences in color vision discrimination, a marker of DA functioning, can statistically predict differences in the strength and stability of cognitive control, as reflected by the Simon effect and the conflict-adaptation effect, respectively. As expected, the size of the stimulus-response congruency effect and the conflict-adaptation effect was proportional to TCDSs, showing that better color discrimination was associated with smaller congruency effects and less pronounced trial-to-trial fluctuation/adaptation. Furthermore, participants showing a disorder along the blue-yellow axis showed a larger Simon effect than people with perfect score and/or only minor errors, thus reflecting a deficit in selecting the correct response in the face of a competing stimulus-induced alternative response.

Even though the correlative nature of our findings does not directly speak to the underlying causal relations, the observed pattern fits with previous demonstrations that populations suffering from dopaminergic imbalance have more trouble in processing conflicting information and additionally display blue-yellow CVI, such as in Parkinson's disease (Wylie, Ridderinkhof, Bashore, & van den Wildenberg, 2010; Pieri et al., 2000), Huntington's disease and Tourette syndrome (Georgiou, Bradshaw, Phillips, Bradshaw, & Chiu, 1995; Paulus et al., 1993; Melun et al., 2001), ADHD (Spinelli et al., 2011; Tannock et al., 2006) and cocaine use (Sellaro, Hommel & Colzato, 2014; Hulka et al., 2013). Thus, given the relation between DA and response conflict (Botvinick, 2007), our data provide additional clues in favor of the hypothesis that blue-yellow CVI is likely to indicate a central hypodopaminergic state (Roy et al., 2003; Lagerlöf (1982). Future studies might look into whether blue-yellow CVI can be compensated by the

Table 1
Mean reaction times (RT; in ms) and percentage of errors (PE, in %) in the Simon task as a function of participants' performance in the LD-15 Test. Standard errors of the mean are shown within parentheses.

Variables	Perfect score/minor errors only		Only 1 major error		Blue–Yellow disorder	
Simon task	**RT**	**PE**	**RT**	**PE**	**RT**	**PE**
Congruent trial following a congruent trial	486 (14)	0.5 (0.1)	483 (16)	0.4 (0.1)	518 (34)	0.4 (0.3)
Incongruent trial following a congruent trial	565 (14)	4.9 (0.7)	562 (16)	5.0 (0.7)	608 (34)	3.7 (1.6)
Congruent trial following an incongruent trial	419 (14)	0.9 (0.2)	515 (15)	0.9 (0.2)	540 (33)	0.7 (0.4)
Incongruent trial following an incongruent trial	540 (14)	2.3 (0.3)	535 (15)	2.2 (0.4)	569 (33)	2.3 (0.8)
Gratton effect	58 (6)	2.9 (0.6)	59 (7)	3.3 (0.7)	61 (15)	1.7 (1.4)
Simon effect	49 (3)	2.9 (0.4)	49 (3)	2.9 (0.4)	61 (7)	2.7 (0.9)

supplementation of tyrosine, or tyrosine-containing diets, which increase the plasma tyrosine and enhance brain DA synthesis (Acworth, During & Wurtman, 1988; During, Acworth & Wurtman, 1988). Finally, it would be of high interest whether genetic variation in dopamine synthesis and neurotransmission contributes to inter-individual differences in blue-yellow color vision performance and response conflict.

One limitation of our study is that we did not perform any objective or subjective assessment of drug use (e.g., urine and/or hair toxicology analyses, self-reports), so that we cannot exclude undeclared use of illicit drugs. A previous study (Hulka et al., 2013) has shown that color vision discrimination is not affected by MDMA (commonly known as 'ecstasy') use, and has suggested that positive cannabis screening tests as well is unlikely to impact color vision performance. However, given that no study has ever directly investigated the effect of cannabis use on color vision, whether or not cannabis is associated with color vision impairments remains an open question and future research should address this issue. Taken together, our observations suggest that color vision discrimination may represent a simple and promising predictor of cognitive control efficiency, not only in populations with suboptimal dopaminergic functions but in healthy individuals as well. This is not to say that color vision alone is sufficient to infer cognitive control ability. Complex cognitive functions are unlikely to be captured by a single task (Phillips, 1997). This becomes obvious if one looks at the size of the correlations we observed, which clearly shows that color vision performance accounts for only a small amount of variance in the Simon task. This is not surprising as different cognitive functions may underlie performance on a given task and correlations between tasks do not directly reflect the magnitude of association between the respective (assumed) underlying functions. Future studies should thus extend our findings by either exploring more genuine tasks reflecting cognitive control efficiency or combining multiple tasks that are assumed to tap cognitive control operations, as required by more sophisticated (confirmatory) statistical analyses (e.g., confirmatory factor analysis and/or structural equation modeling analyses; see Miyake, Friedman, Emerson, Witzki, & Howerter, 2000 for an example of application of these methods). That being said, our results may well represent an important step in stimulating research aimed at developing reliable and easy applicable tools to predict cognitive control ability.

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