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Research report

Structural hemispheric asymmetries underlie verbal Stroop performance

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ABSTRACT

Performance on tasks involving cognitive control such as the Stroop task is often associated with left lateralized brain activations. Based on this neuro-functional evidence, we tested whether leftward structural grey matter asymmetries would also predict inter-individual differences in combatting Stroop interference. To check for the specificity of the results, both a verbal Stroop task and a spatial one were administered to a total of 111 healthy young individuals, for whom T1-weighted magnetic resonance imaging (MRI) images were also acquired. Surface thickness and area estimations were calculated using FreeSurfer. Participants' hemispheres were registered to a symmetric template and Laterality Indices (LI) for the surface thickness and for the area at each vertex in each participant were computed. The correlation of these surface LI measures with the verbal and spatial Stroop effects (incongruent–congruent difference in trial performance) was assessed at each vertex by means of general linear models at the whole-brain level. We found a significant correlation between performance and surface area LI in an inferior posterior temporal cluster (overlapping with the so-called visual word form area, VWFA), with a more left-lateralized area in this region associated with a smaller Stroop effect only in the verbal task. These results point to an involvement of the VWFA for higher-level processes based on word reading, including the suppression of this process when required by the task, and could be interpreted in the context of cross-hemispheric rivalry.

1. Introduction

Cognitive control includes the capacity to enhance the activation of task-relevant processes while suppressing distracting ones. In the Stroop paradigm [1], a typical cognitive control task, one has to name the font color of words and ignore their meaning. Color naming time and errors increase when the word color and meaning are incongruent (e.g., BLUE written in red) relative to when they are congruent (e.g., BLUE written in blue) or neutral (e.g., BLUE written in black). Classical explanations suggest that, to combat interference during incongruent conditions, cognitive control processes suppress a habitual reading mode and activate controlled color naming [2,3].

Cognitive control requires the complementary activation of the anterior cingulate and lateral prefrontal cortex, as demonstrated in functional neuroimaging studies [4,5]. Specifically, verbal Stroop-related activations have been observed in the dorso- and ventro-lateral prefrontal cortex, predominantly in the left hemisphere (e.g., [6,7]; also see Ref. [8], for a recent example of converging neuropsychological evidence of a left prefrontal involvement in verbal Stroop). Thus, based on functional neuroimaging (and neuropsychological) data, one could hypothesize that a leftward hemispheric asymmetry in the lateral prefrontal cortex helps to combat Stroop interference. However, left and right hemispheric activations are not usually compared through direct statistical tests. Moreover, a different scenario seems to emerge with structural neuroimaging evidence. In a recent voxel-based morphometry study, it was found that regional grey matter volume in the anterior cingulate cortex, cerebellum and, importantly, right ventrolateral prefrontal cortex was negatively related to the amount of verbal Stroop interference [9]. Thus, if structural MRI data are taken into consideration, one could posit diverging expectations regarding which direction of frontal asymmetry supports better Stroop performance.

Another region that may be involved in verbal Stroop performance

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is the so-called Visual Word Form Area (VWFA), a word-sensitive region located in the left inferior posterior temporal cortex [10,11]. Evidence from functional magnetic resonance imaging (fMRI) studies shows that activity in the VWFA and Broca's area is modulated by Stroop interference (e.g., [12]). Another fMRI study also found differential activity in a region proximal to the VWFA in the incongruent vs. congruent contrast for a verbal Stroop version but not for a spatial one [13]. Collectively, these works corroborate the hypothesis that the VWFA integrates feed-forward visual processing with top-down influences from more anterior areas controlling phonological and semantic processing during written word recognition [14]. The fact that this region is specifically involved in the Stroop effect in some studies [12,13], however, suggests that it could also be more specifically involved in cognitive conflict resolution, at least for verbal material. According to a recent magnetoencephalography study [15], the VWFA is recruited not only early on for lower-level word processing [16], but also at later stages for gating lexico-semantic processing (see also Refs. [17–19]), arguably the stage where interference occurs in word-color Stroop incongruency.

The present study aimed to understand whether grey matter structural characteristics in healthy young participants could explain individual differences in Stroop performance in regions previously found to be functionally involved in Stroop interference, including the left lateral prefrontal cortex (e.g., Broca's area) and the VWFA. This goal was achieved by assessing complementary surface-based measures of grey matter structure, in particular, cortical thickness and surface area. Since relationships between cortical structure and function are still unclear (e.g., [20]) and in order to minimize the risk of diluting subtle regional differences, we opted for a whole-brain approach instead of selectively analyzing a priori defined brain regions. Moreover, given the strong left lateralization obtained in fMRI studies of verbal Stroop tasks, we particularly focused on (left vs. right) brain asymmetries as a possible fine-grained way to explain inter-individual differences (cf., [21]) in the performance on this cognitive control task.

To our knowledge, there is only one recent study [22] that investigated the relationship between structural brain asymmetries and performance on a Stroop task. By using voxel-based morphometry, it was found that a leftward asymmetry in the thalamus was associated with better performance on a paper-and-pencil version of the Stroop test, at least in male participants. However, that study examined a heterogeneous sample of older adults (mean age: 65.2 ± 8.0 years). Thus, its results cannot be easily generalized to a healthier and younger population.

We additionally employed a spatial version of the Stroop paradigm (e.g., [23]) as a “control” task. The spatial Stroop task could however be interesting in and of itself. On the one hand, an association between left lateralization and the spatial Stroop effect may be predicted as a beneficial role of leftward intrinsic functional lateralization in the middle frontal gyrus, assessed with resting state electroencephalography (EEG), has been shown for both the verbal and spatial Stroop effects [24]. On the other hand, one could envisage mirrored patterns for the verbal and spatial tasks based on recent neuropsychological literature showing that the lateralization of prefrontal regions critical for the performance of conflict tasks is domain-dependent [25]. Specifically, an increased verbal Stroop effect resulted after left ventro-lateral prefrontal lesions, while the performance on a spatial conflict task (i.e., the flanker task) was impaired following right ventro-lateral prefrontal lesions (also see Ref. [6], for recent meta-analytic evidence).

2. Materials and methods

2.1. Participants

A total of 111 university students voluntarily took part in the experiment (79 females, 32 males; mean age = 22.4 years, SD = 1.4 years, range: 19–26 years). Right-handedness was used as an inclusion criterion. This was confirmed for all participants with the Edinburgh Handedness Inventory (Ref. [27]; mean score = 85.9, SD = 15.3, range: 30–100). Further, all participants had normal or corrected-to-normal visual acuity and reported having normal color vision and no history of any neurological or psychiatric disease. Participants were compensated for their time and gave written informed consent prior to participation. This study was approved by the Bioethical Committee of the Azienda Ospedaliera of Padova, Italy, and the ethical committee of the Scuola Internazionale Superiore di Studi Avanzati (SISSA) in Trieste, Italy.

2.2. Behavioral tasks and procedures

Participants were tested individually on two computerized versions of the Stroop task, as well as additional tasks not reported here. The two Stroop tasks were presented in a counterbalanced order across participants.

2.3. Verbal Stroop

Stimuli consisted of four Italian color words (BLU-blue, ROSSO-red, VERDE-green, GIALLO-yellow) presented individually in one of four colors (blue, red, green, yellow). Participants were asked to ignore the word and identify the ink color through a button press as quickly and accurately as possible. Participants used their index and middle fingers of both hands to provide the responses; the exact color-to-finger mappings were counterbalanced across the participants (mapping 1: left middle-blue, left index-red, right index-green, right middle-yellow; mapping 2: left middle-yellow, left index-green, right index-red, right middle-blue). Each stimulus was categorized as congruent (e.g., BLU presented in blue) or incongruent (e.g., BLU in red).

The task consisted of two blocks of 64 trials each with a short break between the blocks. Congruent and incongruent trials were randomly and equally distributed. To minimize both positive and negative priming confounds, only complete alternation sequences were employed, meaning that neither the color nor the word presented on trial n were used in either way (color or word) on trial $n + 1$ (see Ref. [26], for details). Trials consisted of stimulus presentation in the center of the screen for 500 ms, a 2000 ms blank response screen, and an additional blank screen beyond the response time limit, which was jittered randomly and continuously between 250 and 700 ms. Prior to the experimental blocks, participants completed a training block to ensure that they understood the task. This training block was composed of 16 items representing all possible word-color combinations. Items were presented on screen until a response was given. Feedback about accuracy and speed followed the response and lasted on screen for 1200 ms, followed by a 500 ms inter-trial interval. Participants moved on to the experimental blocks after performing at least 10 correct trials out of 16 (one participant repeated the training block twice to reach this criterion).

2.4. Spatial Stroop

This paradigm was similar to that used in previous studies [23]. Stimuli consisted of arrows pointing to the upper-left, upper-right, lower-left, and lower-right corners presented in one of the four quadrants of the screen. Participants were asked to ignore the position and indicate the direction of the arrow through a spatially compatible key press (R, O, V, M) as quickly and accurately as possible by using the index and middle fingers of both hands. As in the verbal Stroop task, stimuli were categorized as congruent (e.g., upper-right pointing arrow in the upper-right quadrant) or incongruent (e.g., upper-right pointing arrow in the lower-right quadrant). The details of the task and training procedures were identical to the ones used in the verbal Stroop task. Three participants repeated the training block twice, and another participant repeated it three times to reach the criterion to begin the