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Reduced inter-hemispheric interference in ageing: Evidence from a divided field Stroop paradigm

Jean-François Delvenne
University of Leeds

Julie Castronovo
University of Hull

Abstract

One of the most important structural changes that occur in the brain during the course of life relates to the corpus callosum, the largest neural pathway that connects the two cerebral hemispheres. It has been shown that the corpus callosum, and in particular its anterior sections, endures a process of degeneration in ageing. Hence, a primary question is whether such structural changes in the brain of older adults have functional consequences on inter-hemispheric communication. In particular, whether the atrophy of the corpus callosum in ageing may lead to a higher or lower level of *inter*-hemispheric interference is currently unknown. To investigate this question, we asked young and healthy older adults to perform modified versions of the classic Stroop paradigm in which the target and distracter were spatially separated. Across two experiments, we found that the Stroop effect was significantly reduced in older adults when the two stimuli were distributed in two different hemifields as opposed to the same single hemifield. This new finding suggests that age-related callosal thinning reduces inter-hemispheric interference by facilitating the two hemispheres to process information in parallel.

Keywords

Ageing; Corpus callosum; Stroop; Inter-hemispheric communication

Corresponding Author:

Jean-Francois Delvenne, School of Psychology, University of Leeds, Leeds, LS2 9JT, United Kingdom
E-Mail: J.f.delvenne@leeds.ac.uk

Introduction

The corpus callosum (CC) is the major neural pathway in the human brain that connects homologous cortical regions of the two cerebral hemispheres according to an anterior-posterior topographical organisation. Consisting of over 200 million myelinated axonal projections, it is the largest white matter structure in the brain (Aboitiz, Scheibel, Fisher, & Zaidel, 1992) and is almost exclusively responsible for the exchange of information between the two hemispheres (Gazzaniga, 2000).

In the present study, we investigated changes in *inter*-hemispheric processing that might occur in old age in the context of a Stroop task. A decline in size and micro-structural integrity of the CC in old age has been reported by a large number of MRI studies (e.g., Burke & Yeo, 1994; Davis, Dennis, Buchler, White, Madden, & Cabeza, 2009; McLaughlin, Paul, Grieve, Williams, Laidlaw et al., 2007; Michielse, Coupland, Camicioli, Carter, Seres et al., 2010; Ota, Obata, Akine, Ito, Ikehira et al., 2006; Sullivan, Pfefferbaum, Adalsteinsson, Swan, & Carmelli, 2002; Sullivan, Rohlfing, & Pfefferbaum, 2010), and confirmed by postmortem findings (Aboitiz et al., 1992; Hou & Pakkenberg, 2012). By the 7th and 8th decades of human life, the width of the CC would even be comparable to that of a small child (Cowell, Allen, Zalatimo, & Denenberg, 1992).

Importantly, the timeline and progression of the degeneration of the CC appear to differ across its different parts. It has increasingly been shown that white matter integrity in the ageing CC follows an anterior-posterior gradient of decline. Age-related degeneration of CC fibres occurs primarily in the anterior section known as the genu (Bastin et al., 2008, 2010; Hou & Pakkenberg, 2012; Jeeves & Moes, 1996; Madden et al., 2009; Salat et al., 2005; Schulte, Sullivan, Müller-Oehring, Adalsteinsson, & Pfefferbaum, 2005), which consists of small-diameter fibres that connect the frontal lobes. In contrast, the CC fibres in the posterior section known as the splenium, which connects the occipital lobes, appears to decline only in pathological ageing such as dementia (e.g., Frederiksen et al., 2011) but not in healthy ageing (Bastin et al., 2010; Hou & Pakkenberg, 2012; Salat et al., 2005).

Nevertheless, although the atrophy of the CC in the healthy older population has been shown to be associated with general cognitive decline, such as slower processing and psychomotor speed, poorer performance at tests of working memory and executive function (e.g., Fling, Walsh, Bangert, Reuter-Lorenz, Welsh, & Seidler, 2011; Jokinen, Ryberg, & Halska, 2007; Ryberg et al., 2011; Sullivan et al., 2010; Zahr, Rohlfing, Pfefferbaum, & Sullivan, 2009), the specific effects of an ageing CC on *inter*-hemispheric communication are currently unclear. Given that the size of the CC is related to the amount of myelinated and non-myelinated transcallosal fibres needed for transmission of neuronal impulses between hemispheres (Aboitiz et al., 1992), it is plausible to suggest that *inter*-hemispheric communication would be somewhat disrupted in older age as compared to younger adulthood.

Here, we designed a paradigm that allowed us to explore whether and how communication between the cerebral hemispheres changes in old age as compared to young adulthood. We used a divided field Stroop paradigm in which the target and distracter are spatially separated from each other and tachistoscopically displayed either both within a single hemifield (*unilateral display*) or each in a different hemifield (*bilateral display*). When both presented within the same hemifield, the target and distracter are initially processed by the contralateral hemisphere as a result of the well-known contralateral organisation of the visual system. In that case, no *inter*-hemispheric communication is required for a Stroop effect (i.e., a slower response to the target in the presence of an incongruent distracter) to occur. In contrast, when the stimuli are displayed in different hemifields, they are initially processed by a different hemisphere and an *inter*-hemispheric exchange is therefore required for a Stroop effect to emerge. Given that the anterior part of the CC connects the left and right cingulate cortex (Locke & Yakovlev, 1965), that increased activations within the anterior cingulate cortex during a Stroop effect have been reported (Brown, Kinderman, Siegle, Granholm, Wong, & Buxton, 1998; Bush, Whalen, Rosen, Jenike, McInerney, & Rauch, 1998; Peterson, Skudlarski, Gatenby, Zhang, Anderson, & Gore, 1999; Whalen, Bush, McNally, Wilhelm, McInernery et al., 1998), and that the Stroop effect has been found to be correlated with white matter integrity of the genu (Schulte, Müller-Oehring, Javitz, Pfefferbaum, & Sullivan, 2008), the divided field Stroop paradigm is ideal to test behavioural consequences of age-related atrophy of the anterior section of the CC.

With this paradigm, three potential outcomes must be considered. Firstly, the level of *inter*-hemispheric interference in older adults may be comparable to that of younger adults. Such a result could either mean that our paradigm is not sensitive enough to reveal behavioural consequences of callosal atrophy in healthy ageing, or that the *inter*-hemispheric interference in the context of a Stroop task is not affected in older adults. Secondly, a higher level of *inter*-hemispheric interference in older adults may be observed when compared to younger adults. Here, this could suggest that the ageing CC is less efficient in maintaining independent processing between the two hemispheres. Indeed, one function of the CC (i.e., *inhibitory* function) is to act as a barrier preventing information from being unnecessarily transferred from one hemisphere to the other (Bloom & Hynd, 2005; van der Knapp & van der Ham, 2011). In the context of a divided field Stroop task, a less efficient CC (due to an age-related atrophy for instance) might struggle to prevent the incongruent stimulus to interfere with the target in a bilateral condition. Finally, a lower level of *inter*-hemispheric interference may be observed in older adults when compared to younger adults. This finding would suggest that the ageing CC is less efficient in facilitating the sharing and integration of information between hemispheres, a function of the CC known as the *excitatory* function (Bloom & Hynd, 2005; van der Knapp & van der Ham, 2011).

Therefore, the present study has two main objectives: (1) to investigate whether *inter*-hemispheric communication is affected in older age in the context of a Stroop task, and (2) to examine the nature of that potential disruption.

Experiment 1

Method

Participants

We tested 15 older adults (13 females), aged 66-76 (mean age = 70.5 ± 3.2 years) and 15 young adults (14 females), aged 18-20 (mean age = 19.2 ± 0.8 years). Older adults were recruited from the community and were screened for possible underlying neurological disturbances with the Mini Mental State Examination (MMSE) (Folstein, Folstein, & McHugh, 1975). A high cut-off score was applied (i.e., 27) and all the older adults recruited here achieved at least that score. Young adults were psychology students at the University of Leeds and participated for course credits. All participants were unaware of the purpose of the experiment. They self-reported no history of neurological problems, correct colour vision, normal or corrected-to-normal visual acuity, and a right-hand preference[1]. They also provided a written informed consent. All participants were tested at the University. The experimental protocol was approved by the School of Psychology Research Ethics Committee, from the University of Leeds.

Stimuli and Procedure

Stimuli were displayed on a 17inch screen (1280 x 1024 resolution) of a 3.20GHz PC, with responses measured on an external QWERTY keyboard connected to the PC. There were two response keys

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[1] In both experiments of the present study, handedness was assessed in the following way: participants were asked how often they use their left or right hand (i.e., always left, usually left, neutral, usually right or always right) for the following task: writing, throwing, using scissors, tooth brush, knife without a fork, spoon, and computer mouse. All of our participants responded either 'usually right' or 'always right' in all their answers.

(“2” and “3”) that were positioned approximately 9 inches to the right of the midline, so that participants could use their right hand comfortably to respond, with the index finger placed on key “2” and the middle finger placed on key “3”. Stimuli were generated using the E-Prime 2.0 computer software (Psychology Software Tools, Inc., www.pstnet.com). Participants viewed the PC screen at an approximate distance of 60 cm. All stimuli were presented on a grey screen background (200 of red, blue and green phosphors). Red (255 of red phosphor and 0 of blue and green phosphors) and Blue (255 of blue phosphor and 0 of red and green phosphors) rectangular outlines (with a thickness of approximately 0.35°) were used as target stimuli and the words “RED” and “BLUE” written in white Arial font were used as distracters. The stimuli were displayed either horizontally in half of the trials and subtended 1.33° x 2.66°, or vertically in the other half of the trials and subtended 2.66° x 1.33° (see Figure 1). The use of these two different orientations was to control for the distance between the stimuli and the centre of the visual field. Each stimulus was positioned within one of the four ‘invisible’ quadrants (i.e., upper-left, upper-right, down-left and down-right) so that the stimulus edge was always 2° from the horizontal and vertical meridian.

All participants were tested individually in a quiet room. Each trial commenced by the presentation of a central black fixation cross (0.3° x 0.3°) at the centre of the screen for 500ms. Participants were encouraged to keep their eyes fixated on the centre of the screen. After a blank interval of variable duration (400 to 700 ms), one coloured rectangular outline and one word were presented simultaneously in two separate quadrants for 180ms, a time generally considered as brief enough to prevent saccadic eye movements (Bourne, 2006; Carpenter, 1988). In half of the trials, the coloured rectangular outline and the word were displayed horizontally whereas in the other half of the trials, they were presented vertically. In half of the trials, the coloured rectangular outline and the word were displayed in horizontally opposite visual quadrants (*bilateral display*) (upper-left/upper-right or lower-left/lower-right), thus in two different hemifields. In the other half of the trials, the coloured rectangular outline and the word were displayed in vertically opposite visual quadrants (*unilateral display*) (upper-left/lower-left or upper-right/lower-right), thus within the same single hemifield. The two types of stimuli could be either *congruent* (i.e., the colour of the rectangular outline matched the name of the colour denoted by the word) or *incongruent* (i.e., the colour of the rectangular outline and that denoted by the word were different) (Figure 1). Participants were instructed to ignore the word and to focus merely on the rectangular outline. They had to decide as quickly as possible whether the colour of the rectangular outline was red or blue. Responses had to be made within 2000 ms of the onset of the stimuli by pressing the appropriate numerical key on the computer keyboard (“2” = blue; “3” = red). The next trial began 1000ms after a response had been made or after 2000 ms if no response has been recorded.

The experiment consisted of a training block of 12 trials and eight experimental blocks of 24 trials each. This resulted in a total 24 randomly distributed observations per participant in each of the 2 (display: bilateral vs. unilateral) x 2 (congruity: congruent vs. incongruent) x 2 (orientation: vertical vs. horizontal) repeated measures conditions.

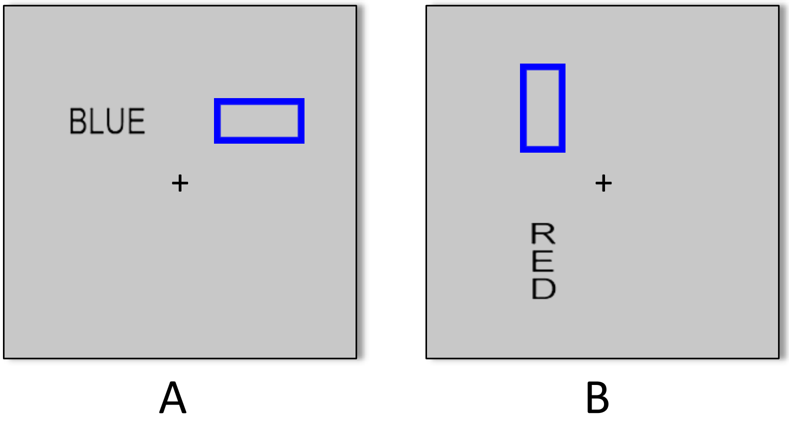

Fig. 1. Illustrations of the different conditions. (A) Example of a congruent trial in a bilateral display with the stimuli horizontally presented. (B) Example of an incongruent trial in a unilateral display with the stimuli vertically presented. The stimuli are not drawn to scale for illustration purposes.

Results and discussion

Because no effects of orientation of the stimuli were found in both the accuracy scores and the reaction times (RTs), this variable was removed from the subsequent analyses.

Accuracy

Even though reaction time (RT) was the primary dependent measure as the responses were speeded, we first conducted a mixed-design analysis of variance (ANOVA) on the percentage of correct responses, with congruity (congruent vs. incongruent) and display (unilateral vs. bilateral) as two within-participant variables, and group (young vs. older people) as one between-participant variable. As it can be seen in Table 1, performance was very high and the analysis revealed a significant effect of group [$F(1, 28) = 7.85$, $p < .01$, partial $\eta^2 = .22$] with higher accuracy for the older adults when compared to the young adults. No other effects were found.

	Young Adults		Older Adults	
	M	SE	M	SE
Bilateral				
Congruent	95	1.2	97.3	1.2
Incongruent	92.1	1.6	98.7	1.6
Unilateral				
Congruent	95	1.3	97.5	1.3
Incongruent	97.5	1.0	98.3	1.0

Table 1. Mean Accuracy (M) in percentage of correct responses and Standard Error (SE) in Experiment 1.

Reaction time

The same mixed-design ANOVA on RTs (Table 2) revealed a significant effect of group [*F*(1, 28) = 12.54, $p < .001$, partial η^2 = .31], with older adults being slower than young adults. There was a significant effect of congruity [*F*(1, 28) = 24.95, $p < .001$, partial η^2 = .47], with longer RTs for incongruent trials than for congruent trials. The effect of display was not significant ($p > .250$), suggesting similar overall performance between unilateral and bilateral displays. There was no significant display x congruity interaction ($p = .138$), suggesting a similar overall effect of congruity for unilateral and bilateral displays. The group did not interact with the display ($p > .250$) or with the congruity ($p > .250$). That is the groups did not differ in their susceptibility to the Stroop effect in general, at least when the data from unilateral and bilateral displays are combined. This supports the results of the meta-analysis by Verhaeghen and Meersman (1998) that found no significant difference in the Stroop interference effect between young and older adults. Interestingly however, the interaction between display, congruity, and group was significant [*F*(1, 28) = 4.84, $p < .05$, partial η^2 = .15].

	Young Adults		Older Adults	
	M	SE	M	SE
Bilateral				
Congruent	423	31	591	31
Incongruent	466	38	617	38
Unilateral				
Congruent	420	32	565	31
Incongruent	454	32	639	34

Table 2. Mean Reaction Times (M) in milliseconds and Standard Errors (SE) in Experiment 1.

Before exploring this three-way interaction further, we rescaled the data into z-scores (Table 3) to control for the clear baseline RT differences across the groups (Faust, Balota, Spieler & Ferraro, 1999), as the older adults were in average 162 ms slower than the young adults. The mixed-design ANOVA on z-scores confirmed the significant effect of congruity [$F(1, 28) = 30.96$, $p < .001$, partial $\eta^2 = .52$] and the absence of significant effect of display ($p > .250$). It also revealed a display x congruity interaction $F(1, 28) = 5.66$, $p < .05$, partial $\eta^2 = .17$], showing a larger overall effect of congruity for unilateral displays than for bilateral displays. The group did not interact with display ($p > .250$) or with congruity ($p > .250$). Finally, these analyses confirmed the significant interaction between display, congruity, and group [$F(1, 28) = 4.88$, $p < .05$, partial $\eta^2 = .15$].

	Young Adults		Older Adults	
	Z	SE	Z	SE
Bilateral				
Congruent	-.207	.064	-.053	.063
Incongruent	.075	.068	.041	.063
Unilateral				
Congruent	-.230	.075	-.328	.072
Incongruent	.065	.052	.158	.050

Table 3. Z-score transformation of Reaction Times and Standard Errors (SE) in Experiment 1.

Therefore, to explore this three-way interaction, we conducted separate repeated measures ANOVAs on RTs for each group with display and congruity as the two within-participant variables. Those analyses confirmed the significant effect of congruity in each group, with longer RTs for incongruent trials than for congruent trials: young adults [$F(1, 14) = 23.66$, $p < .001$, partial $\eta^2 = .63$] and older adults [$F(1, 14) = 9.89$, $p < .01$, partial $\eta^2 = .41$]. The effect of display was not significant in any of the groups ($p > .250$). The interaction between display and congruity was not significant in young adults ($p > .250$), suggesting that young adults were equally susceptible to the Stroop effect when interference involves *inter*-hemispheric and intra-hemispheric communication. In contrast, the interaction between display and congruity was significant in older adults [$F(1,14) = 7.06$, $p < .02$, partial $\eta^2 = .33$], showing an effect of congruity only for unilateral displays ($p < .001$) but not for bilateral displays ($p = .223$). These results clearly show that older adults differ in their reaction to congruent and incongruent presentations only when interference involved intra-hemispheric communication. In order to obtain another and, perhaps, clearer representation of those results, the values of the 'Combined Stroop Effect (CSE)', which is simply the difference between RTs for incongruent and congruent trials for each display in each group, are shown in Figure 2. As it can be seen, the CSE was much larger for unilateral displays as compared to bilateral displays in older people.

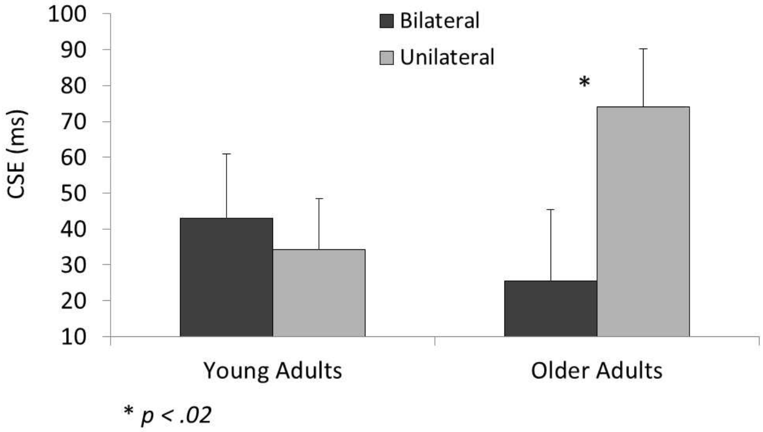

Fig. 2. Combined Stroop Effect (CSE) in milliseconds in Experiment 1. Error bars represent standard errors of the means.

Finally, we conducted separate repeated measures ANOVAs on RTs with congruity (congruent vs. incongruent) and target location (left vs. right) to analyse hemifield asymmetries in unilateral and bilateral displays in each group. In young adults, there was a significant effect of congruity in both unilateral [$F(1, 14) = 8.43$, $p < .02$, partial $\eta^2 = .38$] and bilateral displays [$F(1, 14) = 11.65$, $p < .005$, partial $\eta^2 = .45$]. The interaction between congruity and target location in unilateral displays was also significant [$F(1, 14) = 6.58$, $p < .03$, partial $\eta^2 = .32$], showing a larger congruency effect in the right hemifield. No other significant effects were found ($p > .250$). In older people, there was a significant effect of congruity in unilateral displays [$F(1, 14) = 20.58$, $p < .001$, partial $\eta^2 = .59$]. No other significant effects were found ($p > .200$).

Overall, these results suggest that older adults are less susceptible to the Stroop effect when interference involves *inter*-hemispheric transfer as compared to *intra*-hemispheric transfer, whereas young adults are equally susceptible to both types of hemispheric transfer. A larger Stroop effect was also found in young adults when both words and coloured rectangle outlines were presented to the left hemisphere (i.e., in the right hemifield). This asymmetry can be explained by the preferential processing of verbal information by the left hemisphere and is consistent with previous reports (e.g., Schulte, Müller-Oehring, Salo, Pfefferbaum, & Sullivan, 2006; Weekes & Zaidel, 1996). Interestingly, such an asymmetry was lacking in older adults.

Prior to discussing those findings, a second experiment was conducted with stimuli known as being less lateralised than words. Specifically, digits (i.e., Arabic numerals) and dots were used instead of words and colours, respectively, as those former stimuli have been shown to be less lateralised in the brain (Ratinckx, Brysbaert, & Reynvoet, 2001). This second experiment was also necessary to ensure that the main finding of the current study (i.e., a reduced *inter*-hemispheric interference in older adults) can be replicated with different stimuli and on a new sample of participants.

Experiment 2

Method

Participants

We tested 12 new older adults (8 females), aged 62-82 (mean age = 71.4 ± 6.2 years) and 20 new young adults (15 females), aged 18-23 (mean age = 20.8 ± 1.5 years). Participants were recruited and screened in the same way as for experiment 1. All older adults passed the MMSE and all participants self-reported no history of neurological problems, correct colour vision, normal or corrected-to-normal visual acuity, and a right-hand preference. All young adults and half of the older adults were tested at the University, whereas the rest of the older adults were tested at their home. The experimental protocol was approved by the School of Psychology Research Ethics Committee, from the University of Leeds.

Stimuli and Procedure

As in Experiment 1, participants completed a divided-field Stroop task however the following changes were made. For the participants tested at the University (n=26) stimuli were displayed on a 17inch screen (1280 x 1024 resolution) of a 3.20GHz PC, with responses measured on an external QWERTY keyboard connected to the PC. For the participants tested outside the University premises, (n=6) stimuli were displayed on a 15.4-inch screen (1366 x 768 resolution) of a 2.2GHz laptop PC, with responses measured on the laptops QWERTY keyboard. Participants viewed the PC screen at an approximate distance of 60 cm and the laptop screen at an estimated distance of 50 cm. All stimuli were presented on a grey screen background (200 of red, blue and green phosphors), which was divided into the four 'invisible' visual field quadrants. On both the PC and laptop screens, each quadrant subtended approximately 3.33° x 3.33° and was positioned so that the centre of each quadrant was 3.66° from the horizontal and vertical meridian. Two or three black dots were used as target stimuli and were randomly displayed within one quadrant. The dots subtended 0.67° x 0.67° each and they were separated from each other with a minimum distance (centre to centre) of 1°. One digit (i.e., Arabic numeral) "2" or "3" was used as the distracter stimulus. It subtended 1.33° x 1.33° and was positioned at the centre of a quadrant, so that the centre of the digit was 3.66° from the horizontal and vertical meridian.

As in Experiment 1, each trial started by the presentation of the central black fixation cross for 500ms. After a blank interval of variable duration (400 to 700 ms), two or three dots and one digit ("2" or "3") were presented simultaneously in two separate quadrants for 150ms. In half of the trials, the dots and the digit were displayed in horizontally opposite visual quadrants (*bilateral display*), while in the other half of the trials, the dots and the digit were displayed in vertically opposite visual quadrants (*unilateral display*). The two types of stimuli could be either *congruent* (i.e., both the number of dots and the digit represented the same quantity) or *incongruent* (i.e., the number of dots and the digit represented different quantities) (Figure 3). Participants had to decide as quickly as possible whether there were two or three dots by pressing the appropriate numerical key on the computer keyboard ("2" = two dots "3" = three dots).

The experiment consisted of a training block of 12 trials and four experimental blocks of 24 trials each. This resulted in a total 24 randomly distributed observations per participant in each of the 2 (display: bilateral vs. unilateral) x 2 (congruity: congruent vs. incongruent) repeated measures conditions.

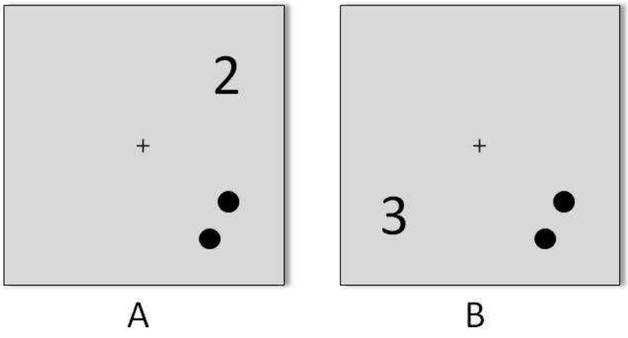

Fig. 3. Illustrations of the different conditions. (A) Example of a congruent trial in a unilateral display. (B) Example of an incongruent trial in a bilateral display. The stimuli are not drawn to scale for illustration purposes.

Results and discussion

Accuracy

The mixed-design ANOVA on the percentage of correct responses (Table 4), with congruity and display as two within-participant variables, and group as one between-participant variable, revealed a significant effect of congruity [*F*(1, 30) = 15.87, p < .001, partial η^2 = .35], with more errors in the incongruent condition (8.6%) than in the congruent condition (2.7%). No other effects were observed on accuracy.

	Young Adults		Older Adults	
	M	SE	M	SE
Bilateral				
Congruent	98.1	0.8	97.4	1.1
Incongruent	91.2	2.8	89	3.7
Unilateral				
Congruent	98.1	1	95.3	1.3
Incongruent	94.1	2.4	91.1	3.1

Table 4. Mean Accuracy (M) in percentage of correct responses and Standard Error (SE) in Experiment 2.

Reaction time

The mixed-design ANOVA on RTs (Table 5) revealed a significant effect of group [*F*(1, 30) = 18.04, *p* < .001, partial η^2 = .38], with older adults being slower than young adults. There was a significant effect of congruity [*F*(1, 30) = 77.17, *p* < .001, partial η^2 = .72], with longer RTs for incongruent trials than for congruent trials. The effect of display was not significant (*p* > .250), suggesting similar overall performance between unilateral and bilateral displays. There was no significant display x congruity interaction (*p* = .120), suggesting a similar overall effect of congruity for unilateral and bilateral displays. The group did not interact with the display (*p* > .250) or with the congruity (*p* > .250). That is the groups did not differ in their susceptibility to the Stroop effect in general. However, like in Experiment 1, the interaction between display, congruity, and group was significant [*F*(1, 30) = 5.38, *p* < .03, partial η^2 = .15].

	Young Adults		Older Adults	
	M	SE	M	SE
Bilateral				
Congruent	488	30	673	39
Incongruent	547	33	702	43
Unilateral				
Congruent	487	29	658	38
Incongruent	539	34	727	44

Table 5. Mean Reaction Times (M) in milliseconds and Standard Errors (SE) in Experiment 2.

The mixed-design ANOVA on z-scores (Table 6) confirmed the significant effect of congruity [*F*(1, 30) = 49.28, *p* < .001, partial η^2 = .62]. It also revealed a marginal display x congruity interaction *F*(1, 30) = 3.68, *p* = .065, partial η^2 = .11], suggesting a somewhat larger overall effect of congruity for unilateral displays than for bilateral displays. The group did not interact with display (*p* > .250) but did marginally interact with congruity *F*(1, 30) = 3.65, *p* = .066, partial η^2 = .11], suggesting that the older adults were somewhat less susceptible to the Stroop effect in general. Finally, the interaction between display, congruity, and group remained, however just marginally, significant [*F*(1, 30) = 3.17, *p* = .085, partial η^2 = .10].

	Young Adults		Older Adults	
	Z	SE	Z	SE
Bilateral				
Congruent	-.372	.073	-.143	.094
Incongruent	.274	.068	.037	.088
Unilateral				
Congruent	-.419	.079	-.286	.102
Incongruent	.241	.052	.281	.068

Table 6. Z-score transformation of Reaction Times and Standard Errors (SE) in Experiment 2.

Separate repeated measures ANOVAs for each group with display and congruity as the two within-participant variables were then conducted on RTs to explore the three-way interaction. A significant effect of congruity was found in each group: young adults [$F(1, 19) = 64.01$, $p < .001$, partial $\eta^2 = .77$] and older adults [$F(1, 11) = 23.42$, $p < .001$, partial $\eta^2 = .68$]. The effect of display was not significant in any of the groups ($p > .250$). The interaction between display and congruity was not significant in young adults ($p > .250$), suggesting that young adults were equally susceptible to the Stroop effect when interference involves *inter*-hemispheric and *intra*-hemispheric communication. In contrast, the interaction between display and congruity was significant in older adults [$F(1,11) = 5.35$, $p < .05$, partial $\eta^2 = .33$], showing larger effect of congruity for unilateral displays ($p < .001$) than for bilateral displays ($p = .064$). Once again, these results clearly show that older adults differ significantly more in their reaction to congruent and incongruent presentations when interference involved *intra*-hemispheric communication as compared to *inter*-hemispheric communication.

Figure 4 shows the CSE values. Again, it can be seen that the CSE was larger for unilateral displays as compared to bilateral displays in older people.

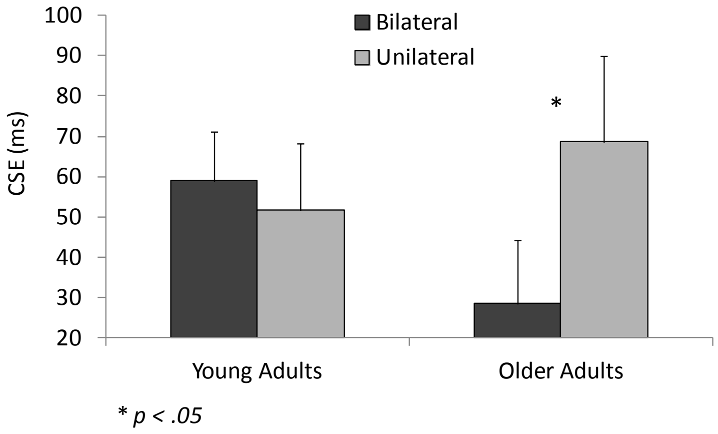

Fig. 4. Combined Stroop Effect (CSE) in milliseconds in Experiment 2. Error bars represent standard errors of the means.

Finally, separate repeated measures ANOVAs with congruity (congruent vs. incongruent) and target location (left vs. right) were conducted in each group to analyse hemifield asymmetries in unilateral and bilateral displays. In young adults, there was a significant effect of congruity in both unilateral [$F(1, 19) = 41.43$, $p < .001$, partial $\eta^2 = .69$] and bilateral displays [$F(1, 19) =3.50$, $p < .001$, partial $\eta^2 = .64$]. In older people, there was a significant effect of congruity in unilateral displays only [$F(1, 11)$

= 28.20, $p < .001$, partial $\eta^2 = .72$]. No other effects were found. Therefore, the use of digits and dots successfully removed the laterality effect found in experiment 1 in young people when words and colours were used.

In conclusion, this second experiment replicated the main finding from Experiment 1: the Stroop effect was significantly reduced in older adults when the two stimuli were distributed in two different hemifields as opposed to the same single hemifield.

Discussion

By using a divided field Stroop paradigm, the present study investigated *intra*- and *inter*-hemispheric attentional interference in young and older adults. Overall, the results showed that older adults were less affected by the Stroop effect when interference involves *inter*-hemispheric transfer than when it involves *intra*-hemispheric communication. In contrast, young adults were equally affected by the Stroop effect in those two types of hemispheric transfer.

Stroop interference is a robust effect that can also be elicited using other stimuli than the typical word-colour pair used in the original study by Stroop (1935) and in the majority of previous Stroop studies that have followed. In particular, Experiment 2 showed that a Stroop effect can be observed when small numbers of dots have to be enumerated in the presence of unmatched Arabic digits, which suggests that processing dots quantity may impede the more automatic process of the numerical symbolic system. Furthermore, along with previous studies (Dyer, 1973; Phillips, Woodruff, & David, 1996; Ratinckx & Brysbaert, 2002; Weekes & Zaidel, 1996), this study also showed that the target and distracter do not necessarily have to be spatially integrated and displayed into a single location (like a coloured word, for instance) in order to interfere with each other. Instead, the two stimuli can be presented in two different locations within the visual field and still produce a significant Stroop effect.

In the present study, we directly compared the extent of the Stroop effect between a condition where the target and distracter were both displayed within the same single hemifield and a condition where they were distributed in opposite hemifields. The results revealed that control participants (i.e., young adults) showed the same degree of Stroop interference regardless of whether the target and distracter were distributed unilaterally or bilaterally. This suggests that a fully developed and healthy CC automatically facilitates exchange of information between the hemispheres, even though this transmission may be detrimental to task performance. Indeed, our findings in young adults showed that the distracter received by one hemisphere influenced the target received by the other hemisphere albeit the task explicitly required ignoring the irrelevant information. In contrast, older participants showed a significant reduction of *inter*-hemispheric interference when compared to *intra*-hemispheric interference, suggesting a somewhat disruption of the automaticity nature of *inter*-hemispheric transfer. This finding was not simply a result of speed-accuracy trade-offs. If such trade-offs were present, then the reduced Stroop effect for bilaterally presented stimuli on speed should have been associated with a larger Stroop effect on accuracy. However, the analyses on accuracy have shown that this was not the case.

Since the CC in older adults is going through a degenerative process (Aboitiz et al., 1992; Burke & Yeo, 1994; Davis et al., 2009; Hou & Pakkenberg, 2012; McLaughlin et al., 2007; Michielse et al., 2010; Ota et al., 2006; Sullivan et al., 2002, 2010), it can be assumed that the reduced *inter*-hemispheric interference might be a direct consequence of callosal atrophy in ageing. We propose that the capacity to inhibit *inter*-hemispheric transfers in the context of a Stroop task is inversely correlated to the integrity of the CC, for which the main function is to facilitate *inter*-hemispheric communication. This suggestion is consistent with a recent Diffusion Tensor Imaging (DTI) study (Qin, Ray, Ramakrishnan, Nashiro, O'Connell, & Basak, 2016) that showed a positive correlation between the integrity of the posterior CC and the degree of opposite hemifield illusory conjunctions (i.e., the mistaken combination of various features of an object) in a visual short-term memory task. More specifically, the study showed that it is the individuals with the greatest posterior CC integrity who made the largest number of bilateral illusory conjunctions. Our claim is also supported by another Transcranial Magnetic Stimulation (TMS) study (Ridding, Brouwer, & Nordstrom, 2000) that showed that transcallosal *inter*-hemispheric inhibitory circuits activated by TMS are less effective in individuals with a large anterior CC (i.e., musicians – see Schlaug, Jancke, Huang, Staiger, & Steinmetz, 1995) when compared to controls (i.e., non-musicians). More related to the present study, Christman (2001) found that left-handers, whose corpus callosum have been shown to have greater degree of connectivity (Witelson, 1985), were more sensitive to the Stroop effect than right-handers when the two dimensions of information (i.e., local vs. global information) are preferentially processed in opposite hemispheres. Again, this supports our view according to which the more the CC develops, the less effective it becomes to inhibit certain types of *inter*-hemispheric transfers. Naturally, a more direct link between white matter integrity of the CC and the level of divided field Stroop interference would need to be confirmed, using for instance DTI (Beaulieu, 2002).

Another interesting finding from the present study is the absence of hemifield asymmetry in experiment 1 for older adults. While young adults showed a greater Stroop effect in the right hemifield, most likely due to the nature of the irrelevant stimuli (i.e., words) that are known to be preferentially processed by the left hemisphere, older adults did not show that asymmetry. Hemispheric asymmetries are known to undergo dynamic changes during the life span and two main models of age-related changes in hemispheric asymmetry have been proposed, namely the *right hemi-ageing* (RHA; Albert & Moss, 1988; Brown & Jaffe, 1975; Ellis & Oscar-Berman, 1989) model and the *hemispheric asymmetry reduction in old adults* (HAROLD; Cabeza, 2002) model. The RHA model proposes that the right hemisphere ages and declines more rapidly than the left hemisphere. The HAROLD model proposes that (mainly frontal) activity during cognitive performance tends to be less lateralised in older than in younger adults. If an age-related decline is especially pronounced in the right hemisphere, as proposed by the RHA model, there should be no reasons why older adults would not show a greater Stoop effect in the right hemifield like the young adults. The results of the present study do better support the HAROLD model, which would predict a reduction of lateralised frontal activity in older adults, and therefore a reduction or absence of an asymmetry in the Stroop effect.

The present study is not free of limitations. Firstly, most of the participants were female and all of them were right-handed participants. Previous studies have demonstrated differences in the brain organisation between right- and left-handed individuals (e.g., Isaacs, Barr, Nelson, & Devinsky, 2006), as well as between male and female (Ruigrok et al., 2014). Future research would need to include gender and handedness as additional variables to further investigate the effect of age on *inter*-hemispheric interference. Secondly, this study would benefit from being replicated using larger samples of participants before definitive conclusions can be drawn. Limited statistical power may have played a role in limiting the significance of some of the statistical comparisons conducted due to the sample size in the present study (n= 30 in experiment 1; n = 32 in experiment 2). A post hoc power analysis with the program G*Power (Faul, Erdfelder, Lang, & Buchner, 2007) was conducted to find out whether our design and sample size in the two experiments had enough power to detect the main effect, which is the 3-way interaction observed on reaction times. In Experiment 1, the effect size of this interaction was 0.42 (i.e., a large effect, according to Cohen's, 1977). The power to detect an effect of this size was determined to be 0.89. In Experiment 2, the effect size of this interaction was 0.33 (i.e., a medium effect, according to Cohen's, 1977). The power to detect an effect of this size was determined to be 0.72. Although the power in Experiment 1 seemed appropriate as it was over the recommended 80% (Cowen, 1977), that in Experiment 2 was a little bit on the low side. However, both experiments have led to similar results, strongly supporting the conclusion of reduced *inter*-hemispheric interference with age.

In conclusion, the present study provides evidence of reduced *inter*-hemispheric interference in older adults aged of +60 when compared to *intra*-hemispheric interference. We suggest that this effect is a direct consequence of progressive atrophy in the anterior part of the CC in older people. These findings lend support to the hypothesis that decreased callosal myelination during ageing have functional significance. In particular, the automaticity nature of *inter*-hemispheric transmission observed in adulthood is disrupted in old age. The divided field Stroop paradigm used in the present study could potentially be adapted and theoretically be useful in the study of some clinical conditions where abnormalities of the CC have been reported, such as Alzheimer’s disease and Mild Cognitive Impairment (see Di Paola et al., 2010, for a review).

Author Contributions

J.-F. Delvenne developed the study concept and design. Testing and data collection were performed by J.-F. Delvenne and J. Castronovo. J.-F. Delvenne performed the data analysis and provided interpretation. J.-F. Delvenne drafted the manuscript and J. Castronovo provided critical revisions. Both authors approved the final version of the manuscript for submission.

Declaration of Conflicting Interests

The authors declared that they had no conflicts of interest with respect to their authorship or the publication of this article.

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