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A process-specific approach in the study of normal aging deficits in cognitive control: What deteriorates with age?

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ABSTRACT

Bearing in mind that cognitive control is a complex function that includes several processes, it is not clear exactly which ones deteriorate with age. In fact, controversial results have been found. For example, some studies indicate that age-related deficits are observed in proactive and not in reactive control, others show that it is reactive control that is impaired and not proactive control, and some studies find no deficits at all (e.g., Kopp, Lange, Howe, & Wessel, 2014; Xiang et al., 2016). One possible reason is that the contribution of different processes to the deterioration of cognitive control was investigated separately, i.e., without testing all processes within the same paradigm. Therefore, the main goal of the present experiment was to study the impact of normal aging on several processes related to cognitive control within the same task, which included both Simon and Spatial Stroop trials. The study focused on the following processes: generation of conflict measured by automatic response capture (i.e., stronger task-irrelevant information processing compared to task-relevant information processing); conflict detection; and control implementation (which can be reactive control, both within trials and across trials, and proactive control, as a task-set strategy). The results showed larger automatic response capture for older adults when facing a stimulus-response conflict (Simon) but not a stimulus-stimulus conflict (Spatial Stroop). Similarly, older adults also showed larger detection effects for both conflicts. However, regarding control implementation, they only showed difficulties in inhibiting the early automatic response capture (within-trial reactive control) but not reactive control across trials or proactive control. In conclusion, it seems that older adults are more affected by the presence of task-irrelevant information, especially when it comes to resolving stimulus-response conflict. However, they showed no impairments in their ability to implement cognitive control both across trials and as a task-set strategy.

1. Introduction

Cognitive control is a key part that plays a crucial role in our daily life. It allows us to carry out any wished action by maintaining the action goal, enhancing the relevant information and inhibiting the irrelevant information present in the environment. As other cognitive processes, cognitive control declines with age. However, it is unclear which cognitive control processes are affected by normal aging and to what degree. Previous studies that have taken into account the different organizational structure of cognitive control have obtained different results. Some results show aged-related deficits in proactive control, that is, a greater tendency in older adults to rely on reactive rather than proactive mechanisms (e.g., Czernochowski, Nessler, & Friedman, 2010; Jimura & Braver, 2010; Kopp et al., 2014). Others show impairment of reactive control but not of proactive control in older adults (e.g., Hsieh & Lin, 2017; Xiang et al., 2016). Yet, other studies show no age-related differences in the temporal dynamics of cognitive control (e.g., Bugg, 2014; control guided by experience, e.g., Cohen-Shikora, Diede, & Bugg, 2018; verbal labelling, Kray, Schmitt, Heintz, & Blaye, 2015) and even a higher stability in the recruitment of reactive and proactive control in older adults (e.g., Staub, Doignon-Camus, Bacon, & Bonnefond, 2014).

Such controversial results could be explained by the fact that most of

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these cognitive control instances were measured with different tasks and conflict types across studies and in the absence of a single paradigm. In the present study, we propose using a single paradigm to assess the contribution of different processes involved in cognitive control: conflict generation, conflict detection, and control implementation. Moreover, we distinguish between three subprocesses within control implementation: reactive control across trials, that is, control implemented in the next trial after conflict is encountered; reactive control within trials, that is, in the same trial right after conflict is encountered; and proactive control, understood as a sustained strategy. To do so, two groups (i.e., older and younger adults) performed an interference task set up to measure cognitive control processes and subprocesses. We also tested whether conflict type would modulate the effect of aging on any of the cognitive control processes and subprocesses analysed by presenting two conflict types (Stimulus-Response, or Simon conflict, and Stimulus-Stimulus, or spatial Stroop conflict).

1.1. Measuring cognitive control

In the laboratory, cognitive control processes have been studied using interference tasks. In such tasks, the information presented for information processing is of two kinds: task-relevant and task-irrelevant. Task-relevant processing is voluntary, since it is necessary for a successful performance. However, task-irrelevant processing is involuntary, since it can interfere with performance. Therefore, attention is selectively biased toward task-relevant information for its processing while attention is involuntary captured by task-irrelevant information. Due to these voluntary and involuntary attentional processes, more than one response is active, resulting in several incompatible response options, causing a conflict. The typical example is the classical Stroop colour-word task (e.g., Stroop, 1935), in which participants have to name the colour in which a word is written while ignoring its meaning (e.g., the word "red" written in green). When the colour in which the word is written and its meaning match (i.e., congruent trials) responses are fast. By contrary, when they do not match as in the example (i.e., incongruent trials), responses slow down. This happens because task-irrelevant and task-relevant information generate incompatible responses, so the system needs time to select the appropriate response among the incompatible ones. The difference between congruent and incongruent trials is called congruence effect, with larger congruence effects reflecting stronger conflict. Therefore, any reduction in congruence effects is interpreted as a result of greater control, as the influence of the conflict is reduced.

Other interference tasks used to study cognitive control processes are the Simon or Spatial Stroop tasks (e.g., Simon, 1968). In the Simon task, participants have to respond to a certain dimension of a given stimulus with their left or right hand. Crucially, the stimulus can be displayed to the left or right to a centered fixation cross, causing interference when both location and response hand do not match, in spite of stimulus location being completely irrelevant for the task. In the Spatial Stroop task, an arrow (or a word denoting a location) can appear above or below fixation, pointing up or down. In this task, interference arises when the direction (or meaning) and the location of the arrow mismatch (e.g., an arrow pointing down appears above fixation). Importantly, the different interference tasks do not share the same dimensional overlap from which interference arises. Thus, for example, the Simon task involves the overlapping of an irrelevant stimulus feature and response location, whereas the Spatial Stroop task involves the overlapping between relevant and irrelevant stimulus features, as highlighted by Kornblum in his taxonomy (Kornblum, Hasbroucq, & Osman, 1990). Moreover, Stroop and Simon tasks present differences in time course, as explored by Pratte, Rouder, Morey, and Feng (2010). The authors compared both effects with delta plots and found different patterns, showing the largest Simon effect for fast responses and a reduction of the effect for slow responses and the opposite pattern for the Stroop effect (i.e., the effect increased for slow responses and decreased for fast responses). In the single paradigm used in the present experiment, the Simon and Spatial Stroop tasks were used to analyse different types of conflict at both the dimensional and temporal levels.

As mentioned above, conflict is reflected in larger congruence effects. Therefore, any reduction of congruence effects is interpreted as the result of the allocation of control, since the impact of conflict is reduced. There are two laboratory manipulations that lead to effects consisting of such reduction of congruence effects and are related to different cognitive control processes: sequential congruent (SC) effects (Gratton, Coles, & Donchin, 1992) and proportion congruent (PC) effects (Lowe & Mitterer, 1982). In the former, the congruence effect is reduced in the current trial after facing an incongruent trial as compared to the situation where the previous trial is congruent. That is explained by a conflict adaptation mechanism that enhances task-relevant information after encountering conflict in the previous trial. By contrast, PC effects are observed in contexts where the proportion of congruent and incongruent trials is manipulated. Specifically, high proportion congruent contexts, in which congruent trials are highly frequent, lead to reliance on automatic processes that do not differentiate between relevant and irrelevant information and result in fast responses for congruent trials but very slow responses for incongruent trials. As a result, large congruence effects are observed. However, in low proportion congruent contexts, where incongruent trials are highly frequent, attention is constantly biased toward task-relevant information, resulting in little benefit in congruent trials and reduced conflict experienced in incongruent trials, which leads to overall reduced congruence effects. PC and SC effects have been proposed to reflect two different cognitive control mechanisms depending on situational demands or individual differences (e.g., Braver, Gray, & Burgess, 2007): a reactive control mechanism, which acts at the same time of the response, after stimulus onset; and a proactive control mechanism, which allows the subject to prepare for conflict resolution before the response, that is, before stimulus onset (e.g., Braver et al., 2007; Braver & Barch, 2002; Torres-Quesada, Funes, & Lupiáñez, 2013). Based on that concept, SC effects can be defined as carry-over effects of reactive control processes while PC effects reflect proactive control processes. Similarly, the activation-suppression model also describes processes related to cognitive control based on congruence effects. Yet, in this case it uses distributional analysis of congruence effects to expose their dynamics, which would otherwise be masked by overall measures of mean interference effects. According to the model, there is an early automatic response capture toward irrelevant information that tests whether processing of task-irrelevant information is initially stronger than processing of task-relevant information (reflected in larger early congruence effects); there is also a later controlled suppression mechanism that allows for the suppression of the automatic response and, in turn, favours the activation of the relevant response. This results in a reduction of congruence effects as a function of response speed since the suppression mechanism needs time to build up.

1.2. Processes and subprocesses involved in cognitive control

The cognitive control processes and subprocesses under study are based on theoretical models of cognitive control that explain the congruence effects and their modulation described above. Specifically, to explore the *generation of conflict*, we used the automatic response capture from the activation-suppression model (Ridderinkhof, 2002a, 2002b). As mentioned before, when attention to task-irrelevant information is greater than attention to task-relevant information, conflict arises. Top-down control models were used to study *conflict detection, reactive control across trials* and *proactive control implementation*. Top-down control models (e.g., Botvinick, Braver, Barch, Carter, & Cohen, 2001; Botvinick, Nystrom, Fissell, Carter, & Cohen, 1999; Braver, 2012; Braver et al., 2007) differentiate between two processes: a conflict detection and monitoring process that evaluates ongoing information, detects conflict and sends the information for recruiting control; and a control process in charge of implementing control (e.g., Botvinick et al., 1999; Botvinick et al., 2001; Braver, 2012; Braver et al., 2007). Moreover, such models distinguish between reactive and proactive control based on their temporal dynamics: reactive control is applied after stimulus onset whereas proactive control acts before stimulus onset. Finally, to study *reactive control within trials*, we used the selective suppression mechanism from the Ridderinkhof (2002a, 2002b) model. As described, the suppression mechanism inhibits the initial automatic response capture, which means that conflict is reduced.

2. Method

2.1. Participants

Thirty-two older adults recruited through Birmingham University (12; 5 females; 1 left-handed) and the University of Granada (20; 11 females; all right-handed) participated in the study. Possible neuropsychological deficits and general cognitive decline were controlled. Specifically, the older adults recruited through Birmingham University completed the Birmingham Cognitive Screen (Humphreys, Bickerton, Samson, & Riddoch, 2012) and the older adults recruited through the University of Granada performed the K-Bit test (Kaufman, 1990). Moreover, participants declared no history of neurological impairments, no subjective experience of cognitive deficits and being functionally independent. Their ages ranged from 57 to 75 (with a mean age of 67.7 years). In addition, 34 younger adults recruited through the University of Granada (25 females; 2 left-handed) participated in the experiment, with a mean age of 24.3 years. As a priori power analyses were not performed, a sensitivity analysis using G*power was conducted (Faul, Erdfelder, Lang, & Buchner, 2007). Results showed that, with this sample size ($N = 66$), the minimum effect size that could have been detected for $\alpha = 0.5$ and $1 - \beta = 0.80$ was $f = 0.1452$ (minimum detectable effect; $\eta_p^2 = 0.021$) for 2 groups and 2 within-variable conditions and $f = 0.1284$ (minimum detectable effect; $\eta_p^2 = 0.016$) for 2 groups and 3 within-variable conditions, which are smaller effect sizes than those observed in most of the critical analyses.

All participants had normal or corrected-to-normal vision, were naive to the specific hypothesis of the experiment, and gave written informed consent following the ethics for human subject research of the Department of Experimental Psychology of the University of Granada and the School of Psychology of Birmingham University. Both committees guaranteed the fulfillment of the Helsinki Declaration for human experimentation.

2.2. Apparatus, task and procedure

Participants were tested on a Pentium computer running *E*-prime software (Schneider, Eschman, & Zuccolotto, 2002a, 2002b) and responded to stimuli presented on a 15-inch color Samsung monitor at a viewing distance of about 57 cm. The background was black whereas the fixation cross and the target were white. All the stimuli consisted of arrows pointing either up or down and subtending 0.54° of visual angle in width and 1.08° in length. The target could appear in one of four possible locations; left, right, above, or below fixation (a plus sign at the centre of the screen). The four target locations were equidistant to fixation (4.32°). Responses were given by pressing on the keyboard either the "v" key (left response) with the index finger of the left hand or the "m" key (right response) with the index finger of the right hand.

Participants were instructed to make left/right key presses in response to the up/down direction of an arrow. Half the participants responded to the "up" direction by pressing the letter "v" (left response) with the index finger of their left hand and to the "down" direction by pressing the letter "m" (right response) with the index finger of their right hand. The opposite mapping was used for the other participants. For targets appearing on the vertical axis, that is, above or below fixation, a pure Spatial Stroop effect (i.e., stimulus-stimulus interference) was measured. By contrast, for targets appearing on the horizontal axis, that is, left or right of fixation, a pure Simon effect (i.e., stimulus-response interference) was measured. Within each block, half of the trials were Simon conflict trials and the other half were Spatial Stroop conflict trials. Trials were congruent whenever the arrow location matched the arrow direction (in Spatial Stroop trials) or with the response location (in Simon trials). Incongruent trials were defined as those where the arrow location did not match the arrow direction or the response location (for Spatial Stroop and Simon tasks, respectively). Instructions stressed the need to respond as fast as possible while trying to avoid errors. Participants were asked to maintain fixation at the centre of the screen before the target was presented.

The sequence of events in each trial was as follows: The fixation point was displayed for 750 ms, after which the target was displayed for 200 ms. Following the offset of the target, the fixation point remained alone on the screen until participants' response or for 2000 ms if no response was given. Auditory feedback (a 500 Hz, 50 ms computer-generated tone) was given in error trials or in trials in which no response was provided within 2000 ms. Intertrial interval (ITI) was 1500 ms. Trials were grouped in blocks and presented randomly within each block. The experiment stopped between blocks with self-administered rests. Participants were instructed to rest for a few seconds between blocks, and then resume the experiment by pressing the spacebar (Fig. 1).

2.3. Design

The experiment consisted of 32 practice trials (not included in the statistical analysis), followed by 512 experimental trials (16 blocks of 32 trials each).

There were three within-participant factors: proportion of congruence (high proportion of congruence, low proportion of congruence), conflict type (Simon, Spatial Stroop), and congruence (congruent, incongruent); and two between-participant factors: manipulated conflict (Simon or Spatial Stroop) and age group (older vs. younger adults). Simon and Spatial Stroop trials were intermixed within each block of trials, with equal proportions of the two conflict types in each block (i.e., 16 trials of each conflict type). Proportion congruence was manipulated within each block (changing between high and low proportion congruence in alternating blocks) but only for one conflict type (the other one was always 50% congruent). The proportion of congruent trials alternated between high and low across blocks (there were a total of 8 blocks with high proportion congruence and 8 blocks with low proportion congruence), counterbalancing the starting condition (high or low) across subjects. Moreover, the conflict type for which proportion congruence alternated between high and low was manipulated between participants (i.e., manipulation of conflict type factor). For some participants (26 participants in total; 12 older adults, of whom 5 were females, and 14 younger adults, of whom 13 were females), the Simon task was manipulated and the Spatial Stroop task was always 50% congruent; for other participants (40 participants in total; 20 older adults, of whom 11 were females, and 20 younger adults, of whom 12 were females), the Spatial Stroop task was manipulated and the Simon task was always 50% congruent.[2] Therefore, in the high proportion congruent condition, 75% of the manipulated conflict trials were congruent (i.e., 12 out of 32 trials per block) and 25% were incongruent (i.e., 4 out of 32 trials per block). By contrast, in the low proportion congruent condition, 25% of the manipulated conflict trials were congruent and 75% were incongruent. However, non-manipulated conflict trials were 50% congruent (and 50% incongruent) in all conditions (i.e., 8 congruent and 8 incongruent out of 32 trials per block).

[2] Originally, the two conditions, in which the proportion of congruent trials was manipulated for Simon tasks and not for Spatial Stroop tasks or vice versa, were run as separate experiments. However, for the sake of simplicity and since no large differences were observed between experiments, this factor was included as a between-participant variable in the same general analysis.

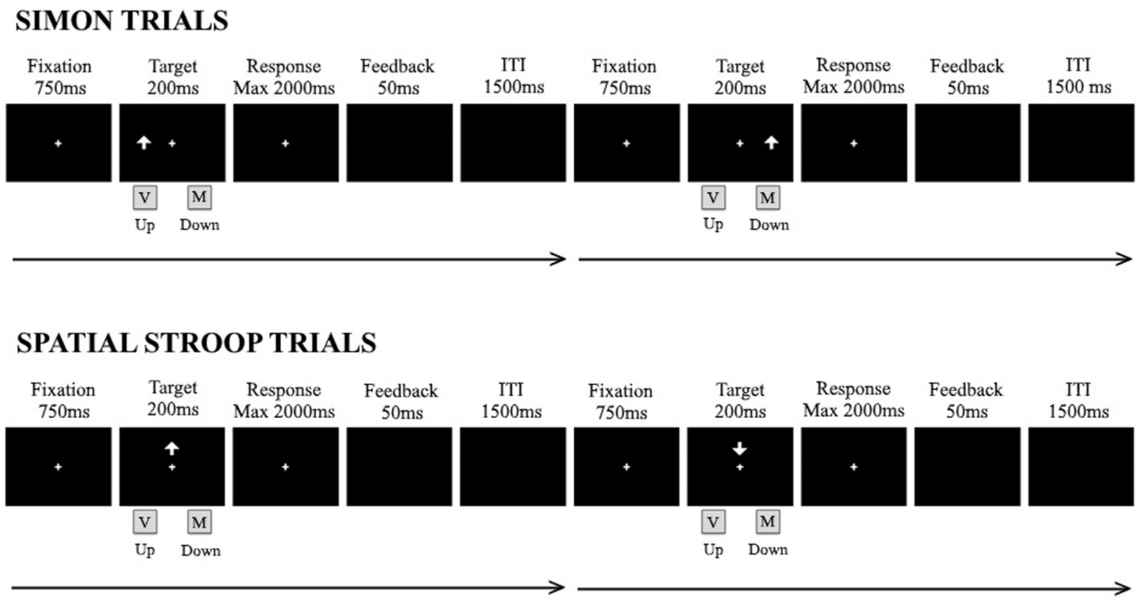

Fig. 1. Sequence of events for Simon (top panel) and Spatial Stroop (bottom panel) trials. Both types of trials were randomly mixed within each block of trials. In Simon trials, arrow targets are presented to the left/right of the fixation cross and are congruent when the location of the arrow matches that of the response (e.g., top panel, first target) or incongruent when it does not (e.g., top panel, second target). In Spatial Stroop trials, arrow targets are presented above/below the fixation cross and are congruent when the arrow location matches the arrow direction (e.g., bottom panel, first target) or incongruent when it does not (e.g., bottom panel, second target). The answer keys were switched for half of the participants.

In addition to these variables, sequential effects were recoded offline by creating two additional within-subject variables (i.e., previous congruence and conflict type shift). The previous congruence variable was created to code the level of congruence encountered in the previous trial with two possible levels: previous congruent and previous incongruent. The conflict type shift coded whether the type of conflict encountered in the current trial was a repetition or an alternation of the kind of conflict encountered in the previous trial. Conflict type repetition trials consisted of a Spatial Stroop trial followed by another Spatial Stroop trial (i.e., both appearing along the vertical axis), or a Simon trial followed by another Simon trial (i.e., both appearing along the horizontal axis). Conflict type alternation trials consisted of any Spatial Stroop trial in the vertical axis preceded by a Simon trial in the horizontal axis or vice versa.

In order to examine the processes and subprocesses of cognitive control under study separately, the different factors to be included in each of the analyses were selected. To explore the *generation of conflict* process, the early automatic response capture was examined. That is, congruence effects were analysed as a function of response speed. To do so, we conducted a distributional analysis of reaction times (RTs) in error rates depending on response speed. To study *conflict detection*, sequential congruence effects (both on reaction times and error rates) were used but only congruence effects preceded by congruent trials. Encountering a congruent trial relaxes the system, allowing it to rely on task-irrelevant information. Therefore, in incongruent trials the conflict experience will be higher when the previous trial is congruent compared to when the previous trials are incongruent. In control implementation, three subprocesses were distinguished: reactive control across trials, reactive control within trials, and proactive control. To study *reactive control across trials,* sequential congruence effects were again used but this time focusing on congruence effects preceded by incongruent trials, that is, focusing on the sequence of trials where the SC effect can be observed. To study *reactive control within trials*, congruence effects as a function of response speed were again used, but this time, an RT distributional analysis of reaction times was carried out to study selective suppression (i.e., how conflict is reactively resolved within the trial as a function of response speed since the suppression mechanism needs time to build up). To study *proactive control*, proportion congruent effects (both on reaction times and error rates) were measured. To compute PC effects, we only used trials in which conflict type alternated. Although, in principle, PC effects can theoretically be considered as different from SC effects, they could likely arise from the accumulation of SC effects. In fact, cognitive control models have interpreted PC effects as the results of SC effects (Botvinick et al., 2001, 1999). This has been based on the fact that in contexts where incongruent trials are frequent (i.e., high conflict contexts), incongruent-incongruent transitions are most common. Therefore, the overall reduction in congruence effects might simply be the sum of all the SC effects that have taken place within the high conflict context. However, recent studies have dissociated PC and SC effects by showing that, while SC effects are typically specific to conflict type, PC effects can generalize across conflict type (Funes, Lupiáñez, & Humphreys, 2010; Torres-Quesada et al., 2013; see Aschenbrenner & Balota, 2019). More importantly, a previous study in our laboratory showed PC effects in the absence of SC effects (Torres-Quesada, Lupiáñez, Milliken, & Funes, 2014).

2.4. Data analysis

The statistical analysis was conducted with Statistica software (StatSoft, 2007). Different filters were applied depending on the type of analysis to be performed. For the analysis of reaction times (RTs) using standard ANOVAS, post-error trials and the first trial of each block were excluded (16.26%). From the remaining trials, RTs above or below 2.5 standard deviations from the overall mean for each participant were also ruled out (2.46%) (after applying the filters, a minimum number of 6 observations per cell were obtained). However, for standard ANOVAs of error rates, only post-error trials and the first trial of each block were excluded (10.73%). Subjects with a mean error rate above 2.5 standard deviations from the mean of the group were also removed, excluding only one older adult subject (the remaining subjects had a minimum of 7 observations per cell). For the distributional RT analysis, only error trials, post-error trials and the first trial of each block were eliminated; for the distributional error rate analysis, similarly to the standard analysis, only post-error trials and the first trial of each block were ruled out. Those filters were applied after computing bins. For the distributional analysis, two subjects were excluded because they had empty cells in some conditions (the remaining subjects had a minimum of 11 observations per cell).

To perform the distributional analysis, five bins per subject per condition were computed. Specifically, reaction times were ordered from fastest to slowest for each subject and for each factorial combination of conflict type and congruence and divided them into 5 different bins. These five bins were applied to the analysis of error rates (to study the automatic response capture) and reaction times (to study the suppression mechanism).

Interactions were analysed using partial ANOVAs that followed a priori hypotheses.

3. Results

Prior to studying the different processes involved in cognitive control, we explored whether there were general differences in congruence effects between older and younger adults, looking for signs of altered cognitive control process in the latter. To do so, a mixed ANOVA including Conflict type, Congruence, Age group and Manipulated conflict was performed, with the last two variables as between-participant factors.

As expected, a Congruence by Age group interaction for both RTs ($F(1,61) = 17.22$, $p < .001$, $\eta_p^2 = 0.22$) and for error rates ($F(1,61) = 7.10$, $p = .010$, $\eta_p^2 = 0.10$) was observed, indicating larger congruence effects (i.e., a larger difference between incongruent and congruent trials) for older adults (59 ms and 0.06 errors) than for younger ones (30 ms and 0.03 errors).[3] Once this was observed, the following planned analyses were performed to study the nature of these differences.

3.1. Generation of conflict

To test the generation of conflict based on task-irrelevant response capture (i.e., automatic response capture), an RT distributional analysis of error rates was performed. To do so, an ANOVA of error rates including Congruence, Conflict type, Bin, Age group and Manipulated conflict was carried out, with the last two variables as between-participant factors. Results indicated an interaction between Conflict type, Congruence and Bin, $F(4,236) = 7.59$, $p < .001$, $\eta_p^2 = 0.11$, showing larger congruence effects for Simon than for Spatial Stroop conflict in early bins (0.18 and 0.10 for the Simon task, 0.06 and 0.009 for the Spatial Stroop task respectively for bin one and bin two; no significant congruence effects for the rest of the bins or for either conflict type). That interaction was modulated by the Manipulated conflict (Conflict type x Congruence x Bin x Manipulated Conflict, $F(4,236) = 3.35$, $p = .011$, $\eta_p^2 = 0.05$), indicating larger congruence effects in early bins for Simon than for Spatial Stroop conflict when Spatial Stroop was the conflict being manipulated.

Importantly, the Conflict type x Congruence x Bin interaction was also modulated by Age group, $F(4,236) = 4.20$, $p = .003$, $\eta_p^2 = 0.07$. Focusing on the first bin, where the strongest response capture took place, no differences between conflict types for the younger group were observed ($F < 1$, with 0.13 and 0.12 error rates for Simon and Spatial Stroop conflict types respectively; Fig. 2). However, there were significant differences between conflict types in the older group, $F(1,27) = 13.84$, $p < .001$, $\eta_p^2 = 0.34$, with 0.24 and 0.09 error rates for Simon and Spatial Stroop conflict respectively.

3.2. Conflict detection

Sequential congruent effects were used to study group differences in conflict detection, focusing on the congruence effects preceded by congruent trials only. To do so, an ANOVA including Previous congruence, Congruence, Conflict type, Age group and Manipulated conflict was performed, with the last two variables as between-participant factors, but only in consecutive conflict-type repetition trials preceded by congruent trials (note that, as described in the introduction, SC effects only occur when the same conflict type is repeated in consecutive trials).

For RTs, results showed the typical pattern of SC effects (Previous congruence x Congruence), $F(1,61) = 256.21$, $p < .001$, $\eta_p^2 = 0.81$, with larger and significant congruence effects when the previous trial was congruent ($F(1,61) = 236.07$, $p < .001$, $\eta_p^2 = 0.79$; 83 ms) and no congruence effects when the previous trial was incongruent ($F < 1$; 0 ms). Interestingly, SC effects were modulated by Age group (Previous congruence x Congruence x Age group), $F(1,61) = 29.93$, $p < .001$, $\eta_p^2 = 0.33$. It is important to highlight, as shown on the left side of Fig. 3, that both groups differed in their congruence effects after congruent trials (Congruence x Age after congruent trials, $F(1,61) = 25.15$, $p < .001$, $\eta_p^2 = 0.29$). This indicated larger SC for the older group (110 ms) than for the younger group (56 ms). Moreover, neither Conflict type (Previous congruence x Congruence x Age x Conflict type, $F(1,63) = 2.15$, $p = .148$) nor Manipulated conflict (Previous congruence x Congruence x Age x Manipulated conflict, $F < 1$) modulated this interaction.

Mirroring RT results, error rates also showed SC effects (Previous congruence x Congruence, $F(1,63) = 42.69$, $p < .001$, $\eta_p^2 = 0.41$) modulated by Age group (Previous congruence x Congruence x Age, $F(1,61) = 5.53$, $p = .022$, $\eta_p^2 = 0.08$). Once again, the modulation of SC effects by Age group was mainly due to larger congruence effects after congruent trials in the older (0.11) than in the younger group (0.05), $F(1,61) = 8.66$, $p = .005$, $\eta_p^2 = 0.12$. As for RTs, neither Conflict type (Previous congruence x Congruence x Age x Conflict type, $F < 1$) nor Manipulated conflict (Previous congruence x Congruence x Age x Manipulated conflict, $F(1,63) = 1.82$, $p = .182$) modulated this interaction.

3.3. Control implementation

3.3.1. Reactive control across trials

Sequential congruent effects were used to explore reactive control implementation across trials, focusing on the congruence effects preceded by incongruent trials only. That is, the analyses were based on the same ANOVA used for conflict detection (Previous congruence, Congruence, Conflict type, Age group and Manipulated conflict in consecutive conflict-type repetition trials), but focused on congruence effects preceded by incongruent trials. Importantly, in this case there were no differences in congruence effects between age groups when the previous trial was incongruent either for RTs ($F(1,61) = 0.06$, $p = .81$) or error rates ($F(1,61) = 0.06$, $p = .80$). As can be observed when comparing the left with the right side of Fig. 3, both groups gave faster responses in incongruent trials preceded by incongruent trials, so as to completely overcome the congruence effect.

3.3.2. Reactive control within trials

For reactive control implementation within trials, following the Ridderinkhof activation-suppression model (Ridderinkhof, 2002a, 2002b), congruence effects as a function of response speed were plotted and the analysis focused on late bins (where the suppression mechanism takes place). To do so, the same ANOVA performed previously (Section 1, generation of conflict) including Bin, Conflict type, Congruence, Age group and Manipulated conflict was carried out, but with RTs as a dependent factor. There was a significant interaction between Bin, Conflict type, Congruence and Age group, $F(4,236) = 7.54$, $p < .001$, $\eta_p^2 = 0.11$. As shown on Fig. 4, both age groups were differentially influenced by bin. In the older group, there was a significant change across

[3] To rule out the possibility that the previous results were due to overall differences between age groups in reaction times, the same analysis were performed but using proportional reaction times as a dependent factor (i.e., each reaction time of each subject was divided by the general mean of that subject). Once again, a congruence by age group interaction was observed, $F(1,61) = 7.05$, $p = .01$, $\eta_p^2 = 0.10$, with larger congruence effects for older adults (0.09) than for younger ones (0.06).

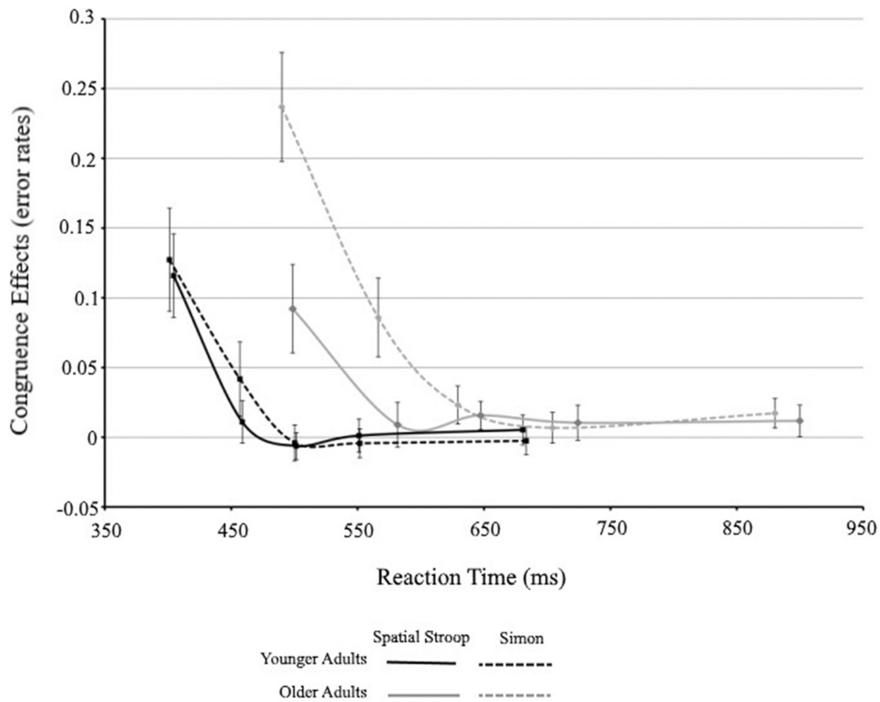

Fig. 2. Congruence effects on error rates (incongruent-congruent trials) as a function of response speed for the factorial combination of conflict type and age group (Simon-younger adults; Simon-older adults; Spatial Stroop-younger adults; Spatial Stroop-older adults). The mean standard errors have been added for each bin.

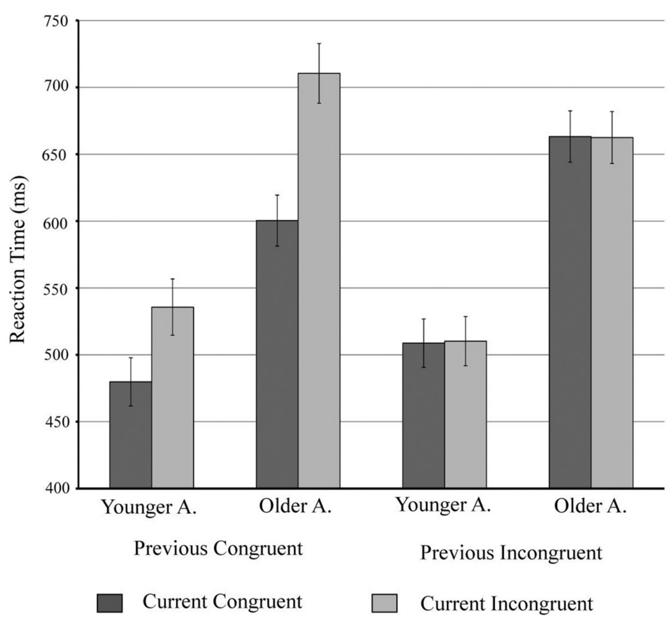

Fig. 3. Reaction times for congruent and incongruent current trials as a function of Age group (Younger Adults and Older Adults) and Previous Congruence (± standard error of the mean).

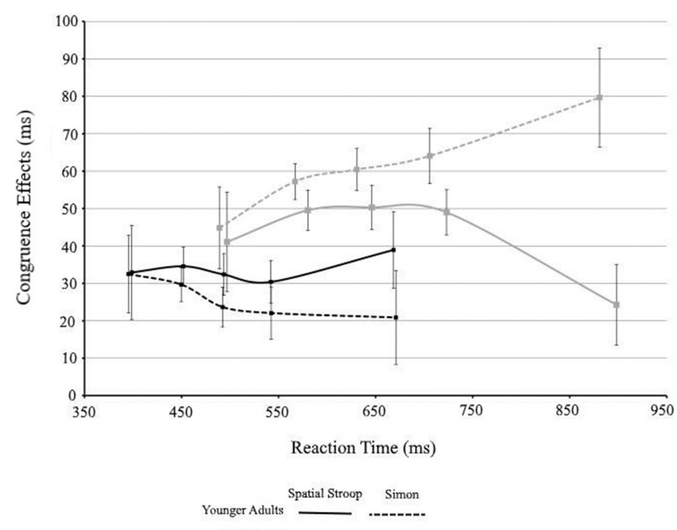

Fig. 4. Congruence effects on reaction times (incongruent-congruent trials) as a function of response speed for the factorial combination of conflict type and age group (Simon-younger adults; Simon-older adults; Spatial Stroop-younger adults; Spatial Stroop-older adults) (the standard error of the mean has been added for each bin).

bins for Simon conflict ($F(4,112) = 3.63$, $p = .008$, $\eta_p^2 = 0.11$; 46 ms and 78 ms for bins one and five respectively). However, for Spatial Stroop conflict, the reduction of congruence effects observed across bins did not reach significance ($F(4,112) = 1.82$, $p = .06$; 40 ms and 21 ms for bins one and five respectively). In the younger group, variations of congruence effects across bins were smaller and not significant ($F(4,128) = 1.02$, $p = .40$, and 33 ms and 22 ms for bins one and five respectively regarding Simon conflict type; $F < 1$, and 33 ms and 39 ms for bins one and five regarding Spatial Stroop conflict type).

3.3.3. *Proactive control*

Finally, proactive control focusing on proportion congruent effects was analysed. To study PC effects in contexts where they are not confounded with SC effects, the analyses focused on conflict type alternation trials (where no SC effects are observed). An ANOVA including Proportion of congruence, Manipulation of conflict type (manipulated vs. neutral), Congruence, Age group, and Manipulated conflict was performed, with the last two variables as between-participant factors. As expected, a significant Proportion of congruence by Congruence interaction was observed, $F(1,61) = 7.46$, $p = .008$,

$\eta_p^2 = 0.11$, with larger congruence effects in the high PC condition ($F(1,61) = 150.43$, $p < .001$, $\eta_p^2 = 0.71$; 54 ms) compared to the low PC condition ($F(1,61) = 167.10$, $p < .001$, $\eta_p^2 = 0.73$; 44 ms). As shown on Fig. 5, age did not modulate this interaction (Proportion of congruence x Congruence x Age group, $F < 1$) as both groups showed very similar proportion congruent effects. Although the Proportion of congruence x Congruence x Manipulation of conflict type interaction did not reach significance ($F(1,61) = 1.94$, $p = .169$), PC effects were only significant for the conflict where proportion congruence manipulation took place ($F(1,61) = 6.17$, $p = .016$, $\eta_p^2 = 0.09$; 16 ms PC effect) and not for the condition where the proportion of congruence was neutral ($F(1,61) = 0.65$, $p = .42$; 4 ms PC effects). Interestingly, these specific PC effects were not modulated by either Age group (Proportion of congruence x Congruence x Manipulation of conflict type x Age, $F < 1$) or Manipulated conflict (Proportion of congruence x Congruence x Manipulation of conflict type x Manipulated conflict, $F < 1$).

For error rates, no proportion congruent effects were observed, since the interaction between Proportion of congruence and Congruence was not significant ($F < 1$).

4. Discussion

To draw comprehensive conclusions about how cognitive control deteriorates with aging and thus be able to develop accurate approaches, it is important to consider the different processes involved in cognitive control separately. For this reason, the present study explored the impact of healthy aging on generation of conflict, conflict detection and control implementation subprocesses. Importantly, a single paradigm was used including only interference tasks to avoid using various tasks that may influence the processes to be studied in different ways. Results indicated that older adults experience higher generation of conflict, but only when stimulus-response conflict is involved, and higher conflict detection for both conflict types. Regarding control implementation subprocesses, older adults only showed difficulties in reactive control within the same trial and only for stimulus-response conflict type.

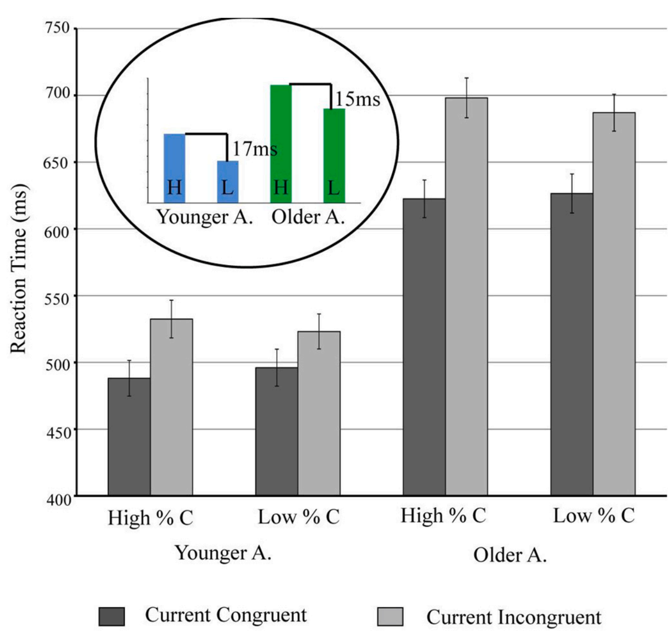

Fig. 5. Reaction times for congruent and incongruent trials as a function of proportion congruence conditions (High % C and Low % C for high and low proportion congruence conditions respectively), for older and younger adult groups and only including conflict-type alternation trials. Bars represent ± standard error of the mean. Blue and green colour bars represent congruence effects (ms) as a function of high (H) and low (L) proportion congruent conditions; the numerical value of the overall PC effects for older and younger adults is also shown. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

As in previous studies, larger congruence effects for older compared to younger adults were observed (i.e., Puccioni & Vallesi, 2012) but which are the specific deficits underlying them? As mentioned above, older adults showed greater *generation of conflict* but only for the Simon conflict type. Specifically, group differences in the automatic response capture were analysed and showed greater congruence effects for older than for younger adults in early bins but only for the Simon conflict type. Both groups showed similar congruence effects for the Spatial Stroop conflict type. These findings suggest that older adults captured more task-irrelevant information than younger adults, but only for the Simon conflict type.

Older adults also showed higher *conflict detection* than young adults. Specifically, results showed that older adults had increased congruence effects after congruent trials, indicating that they recorded higher levels of conflict. This finding corroborates those of previous studies that showed higher sensitivity to response conflict levels in older compared to younger adults (i.e., Czernochowski et al., 2010; Nessler, Friedman, Johnson, & Bersick, 2007). This was indicated by increased amplitude in a medial frontal negativity (MFN) event-related potential (ERP) component, associated with response conflict detection.

Regarding *control implementation*, older adults only showed difficulties in *reactive control within trials*. The findings indicated that there were differences between groups in the suppression effect, once again restricted to Simon conflict type. Specifically, older adults showed normal suppression effects for Spatial Stroop conflict (i.e., almost no differences between congruent and incongruent trials in late bins) but increased congruence effects for Simon conflict in late bins. Surprisingly, younger adults did not seem to show much modulation of the congruence effect by bins. The reason could be that the early automatic response capture of task-irrelevant information is actually resolved pretty fast, as shown by the quick reduction of congruence effects from bin one to bin two in error rates. Therefore, there is not much to be suppressed in late bins.

As regards *reactive control across trials*, also measured with sequential congruent effects, there were no differences between age groups, as congruence effects after incongruent trials were similarly reduced in both groups. To the extent that a reduction in congruence effects after incongruent trials indicates the effectiveness of attentional bias toward task-relevant information due to encountering conflict and implementing control in the previous trial, the results indicate that older adults do not show any deficit in reactive control implementation across trials. Interestingly, both increased conflict induction after a congruent trial and increased automatic reactive implementation of control after an incongruent trial (so that both groups end up completely overcoming the interference) can be considered as priming of automaticity (the former) or priming of control (the latter) (Egner, 2014; King, Korb, & Egner, 2012). It can be concluded that more automatisms are used with increasing age. Thus, participants' responses are more dependent on the previously experienced situation.

Likewise, there were no differences between young and older adults in *proactive control* implementation as measured by PC effects. The results replicate previous findings from a study that also manipulated the proportion of congruent trials (Bélanger, Belleville, & Gauthier, 2010). In that study, healthy older adults showed a proactive conflict resolution comparable to that of younger adults (understood as the strategy developed in contexts where incongruent trials are frequent and which, in turn, enhances task-relevant processing). However, in that study PC effects were not dissociated from SC effects as in the present study, in which PC effects were tested in situations where SC effects were absent (Torres-Quesada et al., 2014). In fact, various studies (Braver, Paxton, Locke, & Barch, 2009; Paxton, Barch, Racine, & Braver, 2008; Paxton, Barch, Storandt, & Braver, 2006) have found a higher tendency of older adults to rely on reactive control mechanisms rather than on proactive ones. Does it mean that they show proactive impairments? The same authors argue that older adults do not show any proactive impairments since, after task-strategy training, participants switched to a conflict resolution strategy, changing from a reactive one to a proactive one after intense training (Paxton et al., 2008). Therefore, it seems that, regardless of the paradigm, older adults can show proactive control adjustments. However, differences between studies might be due to the task being used or to the fact that older adults do not use proactive control by default. Given that this control strategy is more demanding, they might rely by default on reactive mechanisms, and only use proactive mechanisms when either task demands, motivation or training clearly call for their activation. In addition, studies showing a greater tendency to use reactive than proactive control processes in older adults (Braver et al., 2009; Paxton et al., 2006; Paxton et al., 2008) used tasks based on working memory processes. By contrast, in the present study and that of Bélanger et al. (2010), the task used was based on interference tasks, that is, attentional cognitive control. Although tightly related, working memory and attentional cognitive control performance might involve some subprocesses that are differentially affected by age. Nevertheless, future research is needed to clarify the differences between interference and working memory tasks regarding the use of proactive vs. reactive control in older adults.

A result worth discussing is the fact that older adults showed both a higher automatic response capture and a lower suppression effect only for the Simon conflict. Observing stronger congruence effects for Simon than for Spatial Stroop conflict is a typical finding and may be related to the different nature of Simon and Spatial Stroop interference (i.e., different dimensional overlap; see Kornblum et al., 1990). Conflict in Simon tasks is based on task-irrelevant dimensions. The task-irrelevant target location activates the ipsilateral response, thus triggering a motor conflict in incongruent conditions. By contrast, the Spatial Stroop task only involves perceptual interference between the location and direction of the target. That is, it seems that when the task-irrelevant dimension involves the automatic response (Simon task), older adults show a larger capture than when the task-irrelevant dimension is perceptual, and therefore the automatic response activation is not directly involved. To account for that vulnerability to Simon conflict, one could argue that, since both conflicts are located in different brain areas, the neural substrate related to Simon conflict may be more deteriorated with age. Specifically, Egner, Delano, and Hirsch (2007) showed that Simon conflict was mainly related to pre-supplementary motor area activity while Stroop activations were related to more parietal locations. Apart from the frontal-lobe hypofunction hypothesis (i.e., Braver & Barch, 2002; West, 1996), cognitive processes supported by the prefrontal cortex experience an earlier and greater decline compared to processes requiring non-frontal regions. Moreover, neuroimaging literature has also shown that the differential pattern of brain activations across age groups particularly concerns the frontal lobes. In fact, many studies have shown an under-recruitment of frontal regions with aging (e.g., Gutches, Kensinger, & Schacter, 2007; Vallesi, McIntosh, & Stuss, 2009). Therefore, since Simon conflict has a more frontal location than Stroop conflict, it is not surprising to find age-related deficits, possibly due to frontal function decline. Another plausible explanation is related to the degree of inhibitory control involved in each conflict type. Previous studies have shown that aging deficits in inhibitory control might depend on the degree to which such control is needed (e.g., Andrés, Guerrini, Phillips, & Perfect, 2008). Simon conflict takes place at the time of the response while Spatial Stroop conflict arises at early stages of processing. Considering this, Simon conflict likely involves stronger inhibitory control since the inhibition has to take place at the same time that the conflict is occurring, with almost no time to prepare the inhibition of the motor response. Future research should explore all these possibilities in depth.

It is important to highlight some limitations of this study. The first limitation is its relatively small sample size, which reduces the generalizability and reliability of the results. Yet, sensitivity analysis showed that, with the sample size, the minimum effect sizes that could have been detected were smaller than those observed in most critical analyses. Second, different tests were used for each population of older adults to control for neuropsychological and age-related deficits, as each university had its own pool of participants selected on the basis of different cognitive test scores. It would be more accurate if all participants completed the same tests. Similarly, neurological deficits and other possible problems (i.e., depression) were controlled through self-declared statements. It would be more accurate to monitor these deficits on the basis of specific tests or clinical history. Third, the results are limited to the cognitive control processes defined previously and to the experimental task used. Finally, in the present study it is not possible to talk about age as a process, as it is not a longitudinal study and only two different age groups were compared. It will be important to explore these processes in a longitudinal study.

5. Conclusions

In summary, results showed that older adults seemed more sensitive to task-irrelevant information since they showed larger early response capture to it and larger conflict detection experiences. Moreover, they showed deficits only in on-line reactive control implementation when it took place at the time of the response, that is, when understood as the suppression of the automatic response activation by task-irrelevant information (i.e., reactive control implementation within trials). However, they did not show any deficit in control implementation when it took place across trials, understood as the benefit of just having resolved conflict, which also enhances task-relevant information. Interestingly, older adults did not show any impairment of proactive control defined as the strategy developed in highly frequent incongruent trial contexts.

Ethical approval

Approval was obtained from the ethics committee of University of Granada. The procedures used in this study adhere to the tenets of the Declaration of Helsinki.

Informed consent

Informed consent was obtained from all individual participants included in the study.

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Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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