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# Differential Effects of Aging on Executive and Automatic Inhibition

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# Differential Effects of Aging on Executive and Automatic Inhibition

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One of the major accounts of cognitive aging states that age effects are related to a deficiency of inhibitory mechanisms (Hasher & Zacks, 1988). Given that inhibition has traditionally been associated with the frontal cortex, and that the frontal cortex deteriorates early with age (Raz, 2000), this is consistent with the frontal hypothesis of aging (West, 1996). However, not all inhibitory processes require executive control, and so they are not all equally supported by the frontal cortex. As a consequence, one would expect dissociations between inhibitory tasks in the sense of a greater susceptibility of executive/frontal inhibition to aging. Based on Nigg's (2000) working inhibition taxonomy, we tested this hypothesis by combining inhibitory paradigms with different levels of executive control within the same participants. The results showed that age affects Stroop interference but not negative priming (Experiment 1) and stop signal responsiveness but not negative priming (Experiment 2). These findings

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suggest that tasks with a high executive (or effortful) inhibitory control are more sensitive to aging than tasks with a lower executive (more automatic) inhibitory control. The results are discussed in relation to the inhibitory and frontal accounts of aging.

One of the major accounts of cognitive aging suggests that an important cause of age changes in cognition is a decline in the efficiency of inhibitory processes that may be critical in selecting information for further processing (Hasher & Zacks, 1988; Hasher, Zacks, & May, 1999). However, several studies have shown that age declines in inhibitory processes are far from universal (Connelly & Hasher, 1993; Kramer, Humphrey, Larish, Logan, & Strayer, 1994; Langley, Vivas, Fuentes, & Bagne, 2005; Zacks & Hasher, 1997), and researchers have subsequently claimed the existence of a family of different types of inhibitory processes (e.g., Harnishfeger, 1995; Friedman & Miyake, 2004; Nigg, 2000; Hasher et al., 1999).

Despite the theoretical proposal of multiple inhibitory processes, there has been no systematic attempt to look at the specific effects of age on these types of inhibition with reference to theoretical models proposed in the literature. In that context, the aim of the present study was to explore whether inhibitory deficits associated with normal aging can be interpreted in a theoretical framework distinguishing the concepts of *executive* and *automatic* inhibition proposed by Nigg (2000). According to Nigg (2000; also see Friedman & Miyake, 2004; Harnishfeger, 1995), inhibitory tasks vary in relation to the level of executive control required, from very automatic inhibitory processes to very controlled suppression. More specifically, executive inhibition tasks are defined as requiring the ability to deliberately inhibit dominant or prepotent stimuli or responses when necessary. Executive inhibition is constrained to the conscious, controlled and deliberate suppression of irrelevant stimuli or responses. A prototypical task of this kind is the Stroop task, in which one needs to consciously inhibit or override the tendency to produce a more dominant or automatic response (i.e., name the color word). *Automatic* inhibition tasks are defined as involving inhibition processes that occur without awareness of the participant. It occurs when irrelevant information is automatically and simultaneously activated in conjunction with relevant information, and is “suppressed by the cognitive system prior to conscious awareness” (Wilson & Kipp, 1998, p. 98). It seems to be an involuntary residual after-effect of the processing of the relevant information. It is also known as “reactive inhibition” and it occurs in phenomena such as negative priming (NP).

Following Nigg’s (2000) distinction and given that older adults are known to have more difficulties on executive than on automatic processes (Hasher & Zacks, 1979; Jennings & Jacoby, 1993; Salthouse, Toth, Hancock, & Woodard, 1997; Titov & Knight, 1997), the prediction is that aging should affect executive inhibition to a greater extent than automatic inhibition. Kramer et al. (1994) provided evidence supporting this view in their seminal study of fractionation of inhibitory mechanisms. Whereas older adults had more difficulty than younger in a response-stopping paradigm and in the Wisconsin Card Sorting Task (WCST), both groups produced equivalent NP effects, response compatibility. and inhibition of return. Kramer et al. interpreted their results as a dissociation between inhibitory tasks requiring the involvement of executive or frontal mechanisms (arguably WCST and stopping a strong response) and inhibitory tasks not involving these mechanisms (arguably NP and inhibition of return). However, the range of inhibitory tasks used by Kramer et al. differed in many respects including the nature of the stimuli, instructions, and the type of inhibitory process required. Much stronger evidence for specificity of age deficits in executive inhibition would be provided if the same group of young and older adults were examined in paradigms sharing materials and procedure but differing only in the level of executive control required by the task. This was the aim of the current study.

We selected for this purpose the tasks that are proposed by Nigg (2000) as requiring executive (Stroop and stop signal) and automatic (NP) inhibition. Under the hypothesis that *executive* inhibition is more sensitive to aging than *automatic*, the effects of age should be significant on the Stroop interference effect but not on the NP effect (Experiment 1), and on stop signal responsiveness but not on NP (Experiment 2). These methodological manipulations should provide a key factor in the understanding of some of the inconsistencies relating to the inhibitory hypothesis of aging (Hasher & Zacks, 1988), and should therefore have strong theoretical implications.

## EXPERIMENT 1: STROOP AND NEGATIVE PRIMING EFFECTS IN AGING

The Stroop effect refers to the observation that people are slower to name the ink color of incongruent color words (e.g., the word “red” written in green ink) than a colored patch (e.g., a red patch) or a string of colored letters (e.g., xxxx printed in green ink). This Stroop effect is usually explained in terms of the requirement to intentionally inhibit or suppress the dominant process of reading a word. Negative priming (NP) was first observed by Dalrymple-Alford and Budayr (1966) in the context of the Stroop effect. Dalrymple-Alford and Budayr reported that interference in the Stroop test was increased when the ignored word on any one trial became the attended color on the next trial, relative to sequences where successive words and colors were unrelated. According to recent accounts (Tipper, 1985, 2001), NP arises due to inhibition of the ignored distractor on trial n that results in a longer time to reach the activation necessary to permit accurate response production for the same stimulus when it appears as the target on trial n + 1. According to Tipper, NP is a means of observing an inhibitory process that is assumed to be a normal component of selective attention. The representation of the distractor on trial n becomes associated with inhibition, which in turn, impairs processing of that same item when it becomes the target in trial n + 1. In that sense, the slowness in response times due to NP is considered as a sign of ”healthy” processing of any information presented to participants, even when presented as irrelevant for the task at hand. Whereas the Stroop effect is considered the result of strong interference that has to be consciously dealt with, NP occurs as the result of a relatively automatic and unintentional side-effect of a mechanism that suppresses irrelevant mental representations (Nigg, 2000).

Recent evidence of independence between these two types of processes has been provided by Catena, Fuentes, and Tudela (2002) who showed that NP and Stroop interference could be dissociated (one appearing in the absence of the other) using the same materials. The aim of this experiment was to provide some experimental evidence of age dissociations between Stroop and NP effects using comparable materials in the same young and older participants. Following our hypothesis of a greater effect of aging on inhibitory tasks with high executive control, a greater effect of aging was predicted in the Stroop effect than in the NP effect when testing the same participants. Therefore, the prediction was an age × inhibition condition interaction showing a negative effect of aging in the (*executive*) Stroop condition only.

## METHOD

### Participants

A total of 60 people participated in this experiment. Thirty young adults between the ages of 18 and 25 ($M = 20.0$, $SD = 1.5$) from the University of Plymouth participated as part of course requirements and 30 older adults over the age of 60 ($M = 73.8$, $SD = 5.7$) from the local community volunteered to participate in the study. The average National Adult Reading Test (NART, Nelson & Willison, 1991) scores were 27.8 ($SD = 5$) for the older and 15.4 ($SD = 3.6$) for the younger adults, respectively. These scores were significantly different [$t(58) = 9.2$; $p < .001$], indicating higher verbal intelligence in the older adults.

Each subject gave his or her informed consent to participate in the study and the protocol was approved by the University of Plymouth Human Ethics Committee.

### Materials and Design

The materials were adapted from the standardized Stroop test (Golden, 1978). Following Vakil, Manovich, Ramati, and Blachstein (1996) and Van der Linden et al. (1999), we used four white laminated A4 sheets of paper with 100 stimuli on them. Each sheet contained a different condition. Four conditions were presented to each participant: word reading, color naming, Stroop interference and NP. Each stimulus was either a 5 × 15 mm rectangle or a color word (red, yellow, purple, green, blue, and orange). In the word reading condition 100 names of colors printed in black ink were presented and participants were asked to read aloud the words. In the color naming condition, 100 colored rectangles were displayed and participants were required to name their color. In the interference condition, 100 words were written in an incongruent ink color, that is, the word and its ink color were different. The color word (to ignore) on trial n was never the same as the ink color (to attend to) on trial n + 1. Participants were asked to name the ink color and not the word. In the NP condition the stimuli were similar to those in the Stroop interference condition with the exception that the color word (to ignore) in trial n was the same as the ink color (to attend to) on trial n + 1. On each sheet, a first row of 10 stimuli was always used for practice. There were a total of 10 rows × 10 stimuli on each page, and participants were asked to process the stimuli across rows from left to right, and from the top row to the bottom row. RTs were measured by the means of a stopwatch that was triggered by the experimenter when the participant read or named the first test stimulus and stopped when the participant read or named the last stimulus on the sheet. Errors were also counted, but as their occurrence was rare (most participants produced no errors, with the maximum percent errors being 3.9%) and with no differences between groups, these data were not analyzed further.

Speed of processing was measured by using the Digit Symbol test (DS) (WAIS, Wechsler, 1997). The DS test comprises a code table showing the digits one to nine each paired with a symbol and rows of double boxes each with a digit in the top box and nothing in the lower box. The participant's task is to fill with the appropriate symbol as many lower boxes as possible in 90 sec. The dependent measure is the number of boxes correctly filled.

## Procedure

Before performing the experimental task, participants performed the Digit Symbol test (DS). The order of administration of the four word reading/ink naming conditions was controlled following a Latin square procedure: Seven younger and 8 older participants received order 1 (reading, naming, interference, and NP), 8 younger and 7 older participants received order 2 (naming, interference, NP, and reading), 7 younger and 8 older participants received order 3 (interference, NP, reading, and naming) and 8 younger and 7 older participants received order 4 (NP, reading, naming, and interference). Before performing the task, older adults were asked to complete a general health questionnaire and then performed the Mini Mental State Exam (MMSE) to assess the presence or absence of dementia (cut off score = 25). No older participants had to be excluded on this basis (*M* = 28.46; *SD* = 1.13; minimum = 27). After performing the task, the experimenter asked whether participants had realized the link between consecutive trials in the NP condition.

## RESULTS

None of the participants reported having spotted the link between consecutive trials in the NP condition. We also confirmed that, as expected, older participants were cognitively slower than the younger participants as indicated by the results on the Digit Symbol task: there was a significant effect of aging [Student $t(58) = 7.55$; $p < .001$] revealing better scores in the young participants ($M = 69.07$; $SD = 8.79$) than in the older adults ($M = 51.3$; $SD = 9.4$).

Table 1 shows the time taken to complete the four conditions in the Stroop task by the two groups of participants. The Stroop effect (the difference in RT between the interference and color naming conditions) was 35.03 sec ($SD = 8.2$) and 59.8 sec ($SD = 23.92$) in younger and older participants respectively. Analyses of variance showed that this effect was significant in the younger [$F(1, 29) = 545.67$, $MSE = 33.74$; $p = .0001$] and in the older [$F(1, 29) = 187.46$, $MSE = 286.16$; $p = .0001$] groups. The NP effect (the difference in RT between the negative priming and interference conditions) was 11.62 sec ($SD = 11.15$) and 7.77 sec ($SD = 15.4$) in younger and older participants, respectively. Analyses of variance revealed that the NP effect was significant in the younger [$F(1, 29) = 32.97$, $MSE = 62.28$; $p < .001$] and in the older [$F(1, 29) = 7.59$, $MSE = 119.26$; $p = .01$] groups. In order to look at the effects of aging on these effects, a 2 (younger vs older) × 2 (Stroop vs NP) repeated measures ANOVA showed a significant effect of group [$F(1, 57) = 12.1$, $MSE = 3280$, $p < .001$], an effect of inhibition type [$F(1, 58) = 184.5$, $MSE = 427.2$, $p < .001$], and an interaction between group and inhibition type [$F(1, 58) = 26.55$, $MSE = 6143$, $p < .001$]. The analysis of the interaction (Student-$t$) showed that younger and older adults differed in the size of the Stroop effect [$t(58) = 5.36$; $p < .001$] but not in the NP effect [$t(58) = 1.11$; $p = .27$]. The correlation between age and Stroop effect was significant after partialing out the effect of speed of processing (with DS score as the measure for the effect of speed of processing) (*partial* $r = .37$; $p < .01$).

Table 2 shows number of errors for the two groups of participants for the four conditions. We distinguished between self corrected (participants realised they had committed an error and corrected their response) and uncorrected errors. A 2 (group) × 4 (condition) × 2 (type of error) repeated measures ANOVA

TABLE 1
*Mean* (*SD*) Time Taken to Complete Each of the Four Conditions in the Stroop Task by Younger and Older groups in Experiment 1

| *Group* | *Reading* | *Naming* | *Interference* | *Negative Priming* |
|---|---|---|---|---|
| Younger | 42.10 (10.90) | 60.37 (12.15) | 95.41 (15.75) | 107.03 (21.97) |
| Older | 46.40 (8.77) | 76.93 (20.51) | 136.73 (31.64) | 144.5 (33.49) |

TABLE 2
Number of Errors *(Mean* and *SD*) Committed for Reading, Naming, Interference, and Negative Priming Conditions in Experiment 1 for Younger and Older Groups

| *Group* | *Reading* | *Naming* | *Interference* | *Negative Priming* |
|---|---|---|---|---|
| Younger—Cor Errors | 0.2 (0.61) | 1.3 (1.46) | 2.00 (1.53) | 3.46 (2.37) |
| Older—Cor Errors | 0.16 (4.46) | 1.40 (1.03) | 2.40 (2.41) | 2.86 (2.37) |
| Younger—Non Cor Errors | 0.13 (0.34) | 0.36 (0.66) | 1.63 (3.45) | 0.60 (1.54) |
| Older—Non Cor Errors | 0.00 (0.00) | 0.66 (1.76) | 1.46 (3.60) | 0.96 (2.53) |

Cor = self corrected; Non Cor = uncorrected.

showed no effect of group [$F(1, 58)= .01$; $MSE = .1$; $p = 912$]. There was an effect of condition [$F(3, 174)= 26.98$; $MSE = 91.2$; $p = .0001$] showing that there were fewer errors in the reading and naming conditions than in the interference and negative priming conditions. The number of errors committed in the Stroop and the negative priming conditions were equivalent. The effect of type of error was also significant [$F(1, 58)= 25.84$; $MSE = 119$; $p = .0001$], indicating that there were more self corrected errors than uncorrected. The group did not interact with the condition [$F(3, 174)= .21$; $MSE = .7$; $p = .89$] nor with the type of error [$F(1, 58)= .01$; $MSE = .5$; $p = .751$]. The triple interaction (group × condition × type of error) was not significant either [$F(3, 174)= 1.28$; $MSE = 3.1$; $p = .284$].

## DISCUSSION

In this study, in which inhibition was measured within subjects and using the same stimuli, aging affected the Stroop *executive* inhibition cost but not the NP *automatic* inhibition cost. Also, and importantly in the face of some studies failing to detect NP effects in older participants, a significant effect of NP was found in both younger and older participants in this study, that is, RTs were longer for the NP condition than for the interference condition. This demonstrates that the task was sensitive to the effect of NP and that a lack of sensitivity could be ruled out as a potential explanation for the absence of interaction between age and NP. The number of errors was minimal and showed no differences associated with age.

The present data add to the growing body of evidence showing that NP effects can be observed in older adults (Buchner & Mayr, 2004; Gamboz & Russo, 2004;
Q2 Gamboz, Russo, & Fox, 2000; Grant & Dagenbach, 2000; Kieley & Hartley, 1997;
Q3,Q4 Kramer et al., 1994; Langley et al., 1998; Little & Hartley, 2000; Schooler et al., 1997; Sullivan & Faust, 1993; Vakil et al., 1996; Van der Linden et al., 1999; see

Gamboz et al., 2002 for a recent meta-analysis confirming this evidence). These results may stand in contrast to some of the early studies on NP and aging showing significant differences between young and older participants (Connelly & Hasher, 1993; Hasher, Stoltzfus, Zacks, & Rypma, 1991; McDowd & Oseas-Kreger, 1991; Stoltzfus, Hasher, Zacks, Ulivi, & Goldstein, 1993; Tipper, 1991) when using different NP tasks. More specifically, while we used Stroop stimuli with a constant NP manipulation between consecutive trials, most of the earlier studies investigating NP and aging (e.g., Hasher et al.'s) used displays of two letters (e.g., one red-target, one green-distractor), where the NP manipulation took place within pairs of trials (prime and probe). It has also been suggested (Amieva, Phillips, Della Sala, & Henry, 2004; Buchner & Mayr, 2004) that the generally small size of the NP effect, together with the increased variability of performance in older individuals, might explain the lack of NP effect in some studies. In their article, Buchner and Mayr (2004) discussed these and other factors that may explain the lack of NP effects found in older adults in some studies. We refer the interested reader to that study for a detailed discussion of how the interaction between the size of the NP effect and the size of the sample can give rise to a statistically non-significant NP effect in older adults. The aim of Experiment 2 was to provide convergent evidence with the dissociations between *executive* and *automatic* inhibition observed in Experiment 1 using different tasks. On this occasion, NP was investigated using a computerized task where distractor and target stimuli (displays of a green and a red letter) were presented on individual consecutive trials. The number of participants was increased by almost 50% in order to increase the power to detect possible age effects on NP. The effects of aging on NP were contrasted to Q5 the effects of aging on the stop signal task (Logan, 1984), a task where people have to deliberately withhold a response and that has been described as measuring the ability to consciously inhibit a dominant response (Logan, 1994; Friedman & Miyake, 2004; Nigg, 2000). As opposed to Experiment 1, where Stroop and NP measures were not totally independent, NP and stopping time are independent measures. The prediction was that aging would affect stop signal performance, but would leave the NP effect unaffected.

As in Experiment 1, speed of processing was also measured in order to statistically examine the effects of speed of processing on the age differences (Salthouse, 1996).

## EXPERIMENT 2: STOP SIGNAL, NP, AND AGING

In a typical stop signal task (e.g., Logan, Cowan, & Davis, 1984), participants have to execute a choice reaction time task in response to a target (Go condition) except in those trials where, at variable SOAs, a tone stopping signal (No-Go condition) follows the target. Usually, only 25% of trials involve a stop signal, in order to prime the participant to respond to the stimulus in the majority of trials.

One important methodological factor in the stop signal test is the control of the interval between the onset of the target stimulus and the appearance of the stop signal (e.g. tone). Studies that have failed to observe systematic age-related differences in inhibition in children for example, use fixed stop signal delays (e.g., Jennings, van der Molen, Pelham, Brock, & Hoza, 1997; Oosterlaan & Sergeant, 1998; Schachar & Logan, 1990), whereas studies that have shown an age-related increase in inhibitory problems in older adults, as measured by the stopping speed, used a dynamic tracking algorithm for setting the stop signal delay (see Method section for a description of this measure; Bedard et al., 2002; Ridderinkof, Band, & Logan, 1999; Williams et al., 1999). The present study therefore used a tracking algorithm that monitored the performance of the participant on every trial in order to control the duration of the interval between the onset of the stimulus and the stop signal.

As for the previous combination of paradigms used in Experiment 1, no studies have so far investigated the effects of aging on NP and stop signal performance within the same group of participants and using the same materials (see however the study by Kramer et al. [1994] showing specific effects of aging on the stop signal task when using different materials for the stop signal and the NP tasks). Following our hypothesis we expected an effect of aging on the *executive* inhibitory task (measured by the stop signal paradigm) but we expected no effect on the *automatic* inhibitory task (measured by the NP paradigm). If the results confirm the prediction, they will provide added support for the hypothesis of age dissociations between inhibitory mechanisms requiring different levels of attentional or executive control.

## METHOD

### Participants

A total of 89 new people participated in this experiment, comprising 46 young adults between the age of 18 and 39 ($M = 24.3$, $SD = 4.5$), and 43 older volunteers over the age of 60 ($M = 68.4$, $SD = 9.4$). The younger participants were students at the University of Plymouth and participated as part of a course requirement. The older participants were recruited from the local community and participated in exchange for a small monetary reward. The mean Mill Hill Vocabulary test scores were 25.25 ($SD = 4.1$) for the older adults and 17.34 ($SD = 2.9$) for the younger adults [$t(44) = 8.7$; $p < .001$], indicating higher levels of verbal intelligence in the older group. Before performing the computerized paradigms, older adults were asked to complete a general health questionnaire and to perform the Mini Mental State Exam (MMSE) to assess the presence or absence of dementia (cut off score = 25). No participants had to be excluded on this basis ($M = 29.1$; $SD = 1.3$; $min = 26$). Participants also performed the Digit Symbol test (DS) (WAIS, Wechsler,

1997) to assess their speed of processing. Each subject gave his or her informed consent to participate in the study and the protocol was approved by the University of Plymouth Human Ethics Committee.

## MATERIALS AND DESIGN

Each participant performed both the stop signal task and the NP task. The order of these tasks was counterbalanced among participants (50% of the younger and older adults performed the NP task first).

### Negative Priming

Stimuli were presented on a computer screen, at a distance of 57 cm from the participant. Stimulus presentation was programmed using E-Prime. Stimuli consisted of two letters overlapped in the center of the screen. The two letters, one green and one red, were fitted in a 100 × 100 pixel square (5 cm × 5 cm window). The background was white. A set of 10 capital letters were used (the five vowels and the 5 consonants K, L, N, R, and S). At the beginning of each trial a fixation cross was presented for a random duration of 300, 400, or 500 msec and followed by the two overlapping letters which were presented for 500 msec. The letters were followed by a white screen presented for 1,500 msec to allow for longer than 500 msec RTs. Participants were asked to decide whether the red letter was a vowel or a consonant, and to press the corresponding response key (keys Z and M for consonant and vowel respectively for 50% of the participants). The green letter was always to be ignored. Participants' RT and accuracy were recorded. The need for accuracy and speed were equally emphasized in the instructions that participants read.

After a 40-trial practice session, participants pressed the space bar to start the experimental session. The experimental session consisted of two blocks presented in a fixed order among participants and separated by a short break. Each block consisted of 180 stimuli divided into 4 sub-blocks of 45 stimuli presented in a fixed order. Two of these sub-blocks were NP sub-blocks (where the distractor on trial n becomes the target on trial n+1 in all trials) and 2 sub-blocks were control sub-blocks (where the distractor on trial n is different from the target on trial n+1 in all trials). The order of sub-blocks and trials within the sub-blocks was fixed. At the end of the task the experimenter asked participants whether they had noticed any relationship between consecutive trials.

### Stop Signal

The material and design used for the stop signal were identical to those used for the NP paradigm, with the only difference described later. A stop signal (a 1,000 Hz tone) was given on 25% of the trials in a pseudo randomized sequence. The interval between the onset of the visual stimulus and the tone was varied trial by trial according to the participant's response accuracy. To compute the interval between the stimulus onset and the Stop Signal tone we used the tracking algorithm described by Logan, Schachar, and Tannock (1997). The Stop Signal Delay (SSD), defined as the interval between the onset of the visual stimulus and the presentation of the Tone (No-Go signal), was initially set at 250 msec. Then, the SSD was varied dynamically after every No-Go trial, depending on the participants' accuracy. If the participant succeeded in suppressing the response on the previous No-Go trial, the SSD was increased by 50 msec on the following trial. In this way inhibiting the response in the subsequent trial should become more difficult. If the participant failed to inhibit the response on the previous No-Go trial, the SSD was decreased by 50 msec. In this way, inhibiting the response on the following trial should be made easier. This online tracking algorithm was to allow the adjustment of the interval between stimuli and No-Go signal so that participants managed to successfully inhibit a potent response on 50% of the No-Go trials (a detailed description of the race model underlying this technique can be found in Logan, 1994). Based on the race model (Logan, 1994), the latency of the stop process (Stop Signal RT or SSRT) is estimated from the start and finish of the stop process. The start of the stop process is under experimental control by the interval between the onset of the stimulus and the tone in the No-Go trials (Stop Signal Delay or SSD), but the finish time has to be inferred from the observed Go RT distribution. In other words, SSRT measure the time it takes to suppress the ongoing or planned response in the No-Go trials (e.g., Bedard et al., 2002; Ridderinkhof, Band, & Logan, 1999; Williams et al., 1999) and is calculated by subtracting the Stop Signal Delay from the Go RTs.

During the practice session participants were presented with the No-Go tone but they were instructed to ignore it. In the experimental session, participants were asked to desist from responding whenever they heard the stop signal. They were told that the tone was presented in an unpredictable way and that sometimes it would be difficult to stop the response and sometimes not. In order to prevent participants from applying a strategy of ”waiting for a possible stop-signal,” by which they could try to trade speed of responding for accuracy of inhibition, instructions emphasized that speed of response was crucial, and that the probability of making errors was high. Participants were advised not to worry if they were unable to inhibit their response.

## RESULTS

The Digit Symbol results showed a significant effect of aging [$t(43) = 8.7$; $p < .001$] revealing better scores (faster speed of processing) in the young participants ($M = 65.98$; $SD = 11.25$) than in the older adults ($M = 49.83$; $SD = 9.73$).

## Negative Priming

Table 3 presents results observed in both the NP and stop signal tasks. Seven (5 young and 2 older) participants were excluded from the analyses because they realized the link in the NP sub-blocks between distractors and targets on consecutive trials. RTs were analyzed using a 2 (Young vs Older adults) × 2 (NP vs. Control condition) repeated measures ANOVA. This analysis showed an effect of age [$F$ (1, 79) = 40345, $MSE$ = 404548; $p < .0001$] confirming that older adults were globally slower than younger adults. There was also a significant effect of condition [$F$ (1, 79) = 14042, $MSE$ = 2694; $p < .0001$] showing that RTs were longer in the NP condition than in the Control condition, which shows the existence of a significant NP effect. However, there was no Group × Condition interaction [$F$ (1, 79) = 0.328, $MSE$ = 63; $p > .05$] that is, the effect of NP was equivalent in the two age groups.

## Stop Signal

Mean SSRT was 408 ms ($SD$ = 113.32) for older adults and 306 ms ($SD$ = 75.98) for younger adults. A simple ANOVA on SSRTs showed a significant effect of age [$F$(1, 87) = 25.096, $MSE$ = 230503.3 $p = .0001$ indicating that the older adults took longer to successfully stop an ongoing response. The correlation between age and SSRT effect was significant when controlling for the effect of speed of processing (score in the digit symbol task) (*partial* $r = .191$; $p < .05$).

Results also showed that older adults were slower than younger in the Go trials, [$F$(1, 87) = 42.147, $MSE$ = 725843.2; $p < .0001$]. Correlations between age and response latency on Go trials were significant after controlling for speed of processing (*partial* $r = .356$; $p < .001$), which indicates that an additional factor other than general speed of processing (perhaps a ”waiting strategy” that will be discussed later) was at play in the performance of older adults. Following this finding, in order to analyze possible age effects on accuracy in the No-Go trials, the slowing

TABLE 3
*Mean* (*SD*) RT and Accuracy in NP and Stop Signal (Go and Stop Trials) Tasks for Younger and Older Groups in Experiment 2

| | *Negative Priming* | | *Stop Signal* | |
|---|---|---|---|---|
| | *Control* | *NP* | *Go Trials* | *No Go Trials (SSRTs)* |
| Younger—RT (ms) | 509 (60) | 516 (60) | 582 (98) | 306 (76) |
| Older—RT (ms) | 609 (76) | 618 (78) | 762 (159) | 408 (113) |
| Younger—accuracy (%) | .91 (.03) | .90 (.04) | .91 (.09) | .56 (.14) |
| Older—accuracy (%) | .97 (.05) | .96 (.03) | .95 (.1) | .68 (.18) |

down in RTs observed in the Go condition in the older adults was controlled by calculating partial correlations between age and accuracy in the No-Go trials, which showed no correlation (*partial* $r = -.089$; $p > .05$). A regression analysis also showed that accuracy levels depended greatly on the RTs in the Go trials ($R^2 = .525$; $p < .001$).

## DISCUSSION

This second experiment confirms our hypothesis of age dissociations between *executive* and *automatic* inhibition. Aging affected the ability to withhold the strong response in the stop signal task (*executive* inhibition), but did not affect NP (*automatic* inhibition). In this context it is important to notice that, as in Experiment 1, the absence of an interaction between age and condition in the NP task was observed in presence of a significant NP effect for the older as well as the younger adults (RT in NP condition minus RT in control condition).

The way in which the difficulty of withholding a response manifested itself in the older adults deserves some attention. First, the crucial finding was that the speed of inhibiting a response as measured by SSRTs was significantly slower in the older than in the younger participants, even after controlling for the general role of speed of processing (Salthouse, 1996). This result confirms previous findings by Bedard et al. (2002), Kramer et al. (1994), May and Hasher (1998), and Williams et al. (1999). Second, we observed that older adults were also slower in the Go trials, and again after controlling for speed of processing. This result indicates that, despite all the preventive measures that we adopted (warning participants that they should not wait to see whether there would be a tone or not before giving their response, using the tracking algorithm, repeating the instructions verbally when necessary, etc.), older adults may have adopted the strategy of waiting to see whether there would be a stop signal or not before giving their response. This may reflect conservative behavior in older adults who may have tried to compensate for their difficulty in inhibiting responses, despite being clearly instructed not to do so. Similar results were observed in patients with Alzheimer's disease by Amieva et al. (2002).

## GENERAL DISCUSSION

The aim of the present study was to test the hypothesis that aging affects *executive* inhibition to a greater extent than *automatic* inhibition, following the distinction that we borrowed from Nigg (2000). To this aim we selected tasks described by Nigg and other researchers (Hashnifeger, 1995; Friedman & Miyake, 2004) as tapping into executive or automatic inhibition and combined them into paradigms with closely matched stimuli but different executive control levels within the same experiments. The results have shown negative effects of age on the Stroop and stop signal tasks, both thought to reflect *executive* inhibition. Importantly, our index of *automatic* inhibition in two negative priming paradigms with the same stimuli and response requirement were not affected significantly by age. It is also important to note that the effects of aging on *executive* inhibition could not be statistically explained in terms of general slowing in older adults as shown by partial correlation analyses.

The previous literature does provide evidence for such dissociation if one combines the results from different studies. Numerous studies, for example, have shown a significant effect of age on the standard Stroop effect (e.g., Cohn, Dustman, & Bradford, 1984; Spieler, Balota, & Faust, 1996; West & Alain, 2000). On the other hand, there is an increasing number of studies showing that the magnitude of the NP effect is equivalent for older and younger adults (Buchner & Mayr, 2004; Gamboz & Russo, 2004; Gamboz, Russo & Fox, 2000; Grant & Dagenbach, 2000; Kramer et al., 1994; Langley et al., 1998; Schooler et al., 1997; Sullivan & Faust, 1993; see Gamboz et al., 2002 for a recent meta analysis). More specifically, some studies have shown an equivalent NP effect in older and younger participants when using Stroop stimuli (Kieley & Hartley, 1997; Little & Hartley, 2000; Vakil et al., 1996). What is new in our study, however, is that it looks at the effects of aging using these paradigms with identical stimuli in a within-subjects paradigm where only the degree of executive control varies in order to investigate differential effects of aging on them. This methodology presents the unique advantage of testing specifically the hypothesis of dissociations between *executive* and *automatic* inhibition by eliminating some alternative potential interpretations of age-related differences in performance. More specifically, it seems unlikely that the specific age effects on the Stroop condition can be explained in terms of task difficulty as young and older adults committed the same number of errors in Stroop and NP conditions.

Before addressing the theoretical implications of these findings, we outline some caveats on the present study. The first concerns the purity of NP as an inhibitory measure. It has been suggested that, in addition to inhibition, additional cognitive factors such as episodic memory are involved in NP (e.g., Neill, 1997). More specifically, when the target was presented as a distracter in the previous trial, its retrieval conflicts with a response to the stimulus as a target on the current trial, slowing RT (Neill & Valdes, 1992; Neill, Valdes, Terry, & Gorfein, 1992). Other non-inhibitory processes may be important at the stage of response selection, such as temporal discrimination (Milliken, Joordens, Merikle, & Seiffert, 1998). Despite the evidence that Tipper (2001) has recently shown in defense of the inhibitory account of NP and the neuropsychological studies showing evidence in favor of the inhibitory view (McDonald et al., 2005; Metzler & Parkin, 2000) some possible contribution of episodic retrieval (or other non inhibitory) processes to the

NP effect in Experiment 2 cannot be ruled out completely. In his attempt at integrating the inhibition and episodic retrieval views of NP, Tipper pointed out that inhibitory processes are likely more relevant during and immediately subsequent to the processing of the prime stimulus, whereas retrieval processes would become more relevant at the time of probe presentation. More important for our study, however, is the fact that our method (no repetition of targets on successive trials) favors an inhibitory mechanism, rather than an episodic memory mechanism (Kane et al., 1997). The crucial point is that our measure of NP represents at least partially inhibitory processes at work.

A second consideration is the degree to which NP reflects an *automatic* inhibitory mechanism. In the current taxonomies available (Nigg, 2000; but also see Harnishfeger, 1995; Friedman & Miyake, 2004), NP is classified into the automatic inhibition category. However, there is some evidence that NP may require some attentional resources. Engle, Conway, Tuholski, and Shisler (1995) observed that the size of NP decreased as work load (number of words to be remembered) increased. However, two important theoretical issues must be noted here. First, although Hasher and Zacks (1979), and Posner (1978) defined automatic processes as being effortless, unconscious, and involuntary, it is rarely the case for all three features to hold simultaneously (see Carr, 1992; Neumann, 1984; for reviews). Second, by classifying NP into the *automatic* category, it is not implied that NP requires no attentional resources at all. In fact, the definition of automaticity does not Q9 imply that automatic processing is completely uncontrolled and free of resource demands (see Logan, 1980; Tzelgov, 1999; Tzelgov, Henik, & Berger, 1992; for examples of control of automatic processing, and Kahneman & Chajczyk, 1983; Paap & Ogden, 1981; Spinks, Zhang, Fox, Gao, & Tan, 2004, for indications of the sensitivity of automatic processes to resources). In any case, the crucial point for the current study is that clearly NP requires less attentional control than resistance to interference in the Stroop test or withholding the response in the stop signal task. The fact that none of the participants included in the analyses realized the link between distractor and consecutive target in our NP tasks provides strong evidence for the argument that the inhibitory processes involved were outside conscious awareness. Grant and Dagenbach's (2000) results showing normal NP effects in older adults with reduced working memory also argue in favor of a relative independence between the NP effect and the availability of executive-processing resources.

As in the majority of aging studies, our older adults showed higher levels of vocabulary than their younger counterparts—might crystallized intelligence be mediating the pattern of age effects found in NP? In order to look for possible effects of crystallized ability on NP we first calculated correlations between vocabulary and NP. In Experiment 1, there was a significant correlation between vocabulary scores and NP effect ($r = -.293$; $p < .05$). We then calculated a partial correlation between age and NP to investigate the possibility that the higher vocabulary scores in the older group could explain the lack of effect of age on NP. The result showed no correlation between age and NP after controlling for vocabulary scores (*partial* $r = .147$; $p = .27$), ruling out the hypothesis that the lack of age effect on NP is mediated by the high vocabulary scores of the older participants. In order to control for possible effects of verbal abilities on NP in Experiment 2 we also calculated the correlations between vocabulary and NP, and the result showed no correlation ($r = -.114$; $p > .05$). These analyses suggest that the lack of age effect on NP cannot be explained by the high levels of vocabulary observed in our older participants.

In a final cautionary note, it is worth mentioning that, as a general criticism to the construct of inhibition, it has been suggested that, with the exception of the Stop Signal task, where inhibitory mechanisms have been offered to explain cognitive performance, non-inhibitory mechanisms (stimulus feature mismatch between previous and current items in the case of negative priming) could accomplish the same goal (MacLeod, Dodd, Sheard, Wilson, & Bibi, 2003). Other authors (e.g., Harnishfeger, 1995) have also argued that the concept of inhibition is problematic due to the lack of consistency among theoretical definitions. The main question is that the existence of a single inhibition process that applies to all the different paradigms currently employing the term seems unlikely. The existing evidence points instead to many different and independent processes that might merely share an operating characteristic of interference suppression. We must, however, point out that our study follows this line of thought and is an attempt to break down the inhibition construct into different processes aimed at *resisting interference* through different levels of attentional control.

We turn now to the theoretical implications of our study. Utilizing specific experimental manipulations with tasks differing only in the level of executive control required by the inhibitory aspect of the task, we observed dissociations indicating specific effects of aging on the *executive* inhibitory tasks. The present results provide new support for both the presence of age dissociations for inhibitory mechanisms and the need to fractionate the cognitive processes involved in different inhibitory tasks (also see Connelly & Hasher, 1993; Friedman & Miyake, 2004). Additionally, the current results provide evidence for the hypothesis of greater effects of aging on *executive* (or intentional or effortful) than on *automatic* (or unintentional) inhibition, which is in line with the original hypothesis put forward by Hasher and Zacks (1979) as applied to memory processes, that is, that age affects to a greater extent processes requiring executive attention. It is worth noting that although automatic inhibition in the present study was assessed in both studies using an NP paradigm, other studies have shown evidence of robust automatic inhibition in old age. For example, inhibition of return (IOR) effects, that is, slowed responding to a target stimulus presented in the same location as a previous stimulus (a phenomenon that is outside the participants' consciousness) are not influenced by age (Connelly & Hasher, 1993; Faust & Balota, 1997; Hartley & Kieley, 1995; Langley, Fuentes, Hochhalter, Brandt, & Overmier, 2001; Langley et al., 2005; McCrae & Abrams, 2001; Poliakoff, Coward, Lowe, & O'Boyle, 2007).

Following the evidence provided in the current study, it may be suggested that a theoretical integration of the two frameworks of Hasher and Zacks (1979, 1988) would have a higher predictive value than the theoretical framework of the inhibitory hypothesis alone (Hasher & Zacks, 1988). The two principles of this theoretical integration would be (a) there is a continuum of attentional requirements among inhibitory processes, and processes at either end of this continuum can be referred to as *automatic*/effortless and *executive*/effortful inhibitory processes, (b) there is a variable capacity limit to attention and this declines with age. The combination of these two principles yields the prediction that older adults will show a greater decrease in performance on inhibition tasks requiring high levels of attentional control.

An alternative potential explanation of the reported results is that age differences increase whenever task difficulty increases. This explanation can be seen as reflecting general capacity models of aging, whereby increasing the number of cognitive components in a task increases the size of the age effect, possibly due to generalized slowing acting on all cognitive processes equally (e.g., Salthouse, 1996). It has been argued that, for example, such "age × complexity" interactions in relation to Stroop performance can be interpreted in terms of more general cognitive slowing (Verhaeghen & De Meersman, 1998; but see West & Alain, 2000). Tasks that require *executive* inhibition will be relatively complex compared to *automatic* tasks, so it becomes difficult to distinguish between explanations based on executive processing and those based on complexity. The difficulty with a complexity-based argument is that there is no independent measure of complexity, beyond response latency or error rate. Whichever of these two measures is used as a proxy for complexity, the current data are not compatible with an explanation in terms of an age × complexity interaction. For instance, the young group have a SSRT (No-Go trials) of 306 msec per trial, while the reading time in the Stroop test is 420 msec per trial (42 sec for 100 trials). Yet it is the former task, with the quicker responses, which show the greater age effect. In addition, partialling out speed does not remove the age differences in executive tasks. Similarly, error rates did not vary across age on the Stroop interference condition, yet there is a robust age effect on RT. Further, in our experiments, there is evidence that age differences in the measure most often used as a proxy for general processing speed cannot explain the pattern of age effects on inhibitory tasks. Finally, an explanation of our results purely in terms of difficulty of the task would predict a higher number of errors in the Stroop condition than in the NP condition. This was, however, not the case. All in all, our data seem to indicate that an additional factor other than difficulty must be at play in our experiments. As argued by Amieva et al. (2004) in the context of inhibition in dementia, we suggest that the concept of automatic/controlled processing provides a clearer, more testable, and more objective way of classifying tasks than the concept of complexity.

To what extent are our results consistent with the frontal hypothesis of aging (Raz, 2000; West, 1996)? Although not perfect, the equivalence between executive and frontal processes is typically high in the sense that most executive processes require frontal involvement. The tasks used in the present study to evaluate executive inhibition have consistently shown frontal correlates when performed in neuroimaging studies. For example, the brain areas that are involved in the conflict resolution necessary to perform the Stroop task seem to show a consistent locus in the anterior cingulate and prefrontal cortex (e.g., George et al., 1994; Kerns et al., 2004; MacDonald, Cohen, Stenger & Carter, 2000). The same applies to the stop signal task (e.g. Aron, Fletcher, Bullmore, Sahakian & Robbins, 2003; Rubia et al., 2001). However, although there may be some frontal activations when people are performing the automatic inhibition task used in our study, the brain areas that seem to be more involved are more posterior (e.g., the inferior parietal lobe and the left temporal lobe for NP, Mayr, Niedeggen, Buchner, & Pietrowsky, 2003; Steel et al., 2001; Thai, Hodgson, Andrés, & Guerrini, 2007). Altogether, these results seem to support the idea of a specific effect of aging on inhibitory processes supported by the frontal lobes. However, some authors have argued that it is unlikely that a simple frontal aging hypothesis can capture the full complexity of cognitive changes that accompany aging (Band, Ridderinkhof, & Segalowitz, 2002; Greenwood, 2000). Finally, given the current practical difficulty in assessing the view, namely, the lack of appropriate evidence to determine the exact frontal or non frontal region(s) responsible for inhibitory phenomena of interest (Andrés, 2003; Kok, 1999), we suggest bringing into play the current study as a starting point and to use the more conservative *executive/automatic* taxonomy until further evidence is provided.

To sum up, we found clear evidence that older adults show impaired ability to inhibit behavior, where the task required *executive*, effortful inhibition. In contrast, there were no age differences in *automatic* inhibitory processes. The current results provide an advance on previous literature because this dissociation in age effects was shown within the same sample, in two separate types of experimental task. Further, the *automatic* and *executive* inhibitory tasks were matched as far as possible on task stimuli and response demands. We conclude that inhibitory tasks can be placed on a continuum from highly automatic to highly executive, and that the effects of normal aging on inhibition will increment as the need for control of the inhibitory process increases.

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## REFERENCES

Amieva, H., Lafont, S., Auriacombe, S., Le Carret, N., Dartigues, J. F., Orgogozo, J. M., et al. (2002). Inhibitory breakdown and dementia of the Alzheimer type: A general phenomenon? *Journal of Clinical and Experimental Neuropsychology, 24*, 503–516.

Amieva, H., Phillips, L. H., Della Sala, S., & Henry, J. D. (2004). Inhibitory functioning in Alzheimer's disease. *Brain, 127*, 949–964.

Andrés, P. (2003). Frontal cortex as the central executive of working memory: Time to revise our view. *Cortex, 39,* 871–895.

Q10 Arbuthnott, K. D. (1995). Inhibitory mechanisms in cognition: Phenomena and models. *Current Psychology of Cognition, 14*, 3–45.

Aron, A. R., Fletcher, P. C., Bullmore, E. T., Sahakian, B. J., & Robbins, T. W. (2003). Stop-signal inhibition disrupted by damage to right inferior frontal gyrus in humans. *Nature Neuroscience, 6,* 115–116.

Band, G. P. H., Ridderinkhof, K. R., & Segalowitz, S. (2002). Explaining neurocognitive aging: Is one factor enough? *Brain and Cognition, 49*, 259–267.

Bedard, A.-C., Nichols, S., Barbosa, J., Schachar, R. J., Logan, G. D., & Tannock, R. (2002). The development of selective inhibitory control across the life span. *, 21*, 93–111.

Buchner, A., & Mayr, S. (2004). Auditory negative priming in younger and older adults. *The Quarterly Journal of Experimental Psychology, 57A*, 769–787.

Q11 Q12 Burgess, P. W. (1997). Theory and methodology in executive function research. In P. Rabbitt (ed.), *Methodology of frontal and executive function* (pp. 81–16). Hove, U.K.: Psychology Press.

Carr, T. H. (1992). Automaticity and cognitive anatomy: Is word recognition automatic. *American Journal of Psychology, 105,* 201–237.

Catena, A., Fuentes, L., & Tudela, P. (2002). Priming and interferente effects can be dissociated in the stroop task: New evidence in favor of the automaticity of word recognition. *Psychonomic Bulletin and Review, 9,* 113–118.

Q13 Collette, F., & Van der Linden, M. (2002). Brain imaging of the central executive component of working memory. *Neuroscience and Biobehavioral Reviews, 26,* 105–125.

Cohn, N. B., Dustman, R. E., & Bradford, D. C. (1984). Age-related decrements in Stroop Color Test performance. *Journal of Clinical Psychology, 40*, 1244-1250.

Q14 Connelly, S. L., & Hasher, L. (1993). Aging and the inhibition of spatial location. *Journal of Experimental Psychology: Human Perception and Performance, 19*, 1238–125**.**

Q15 Craik, F., & Jennings, J. M. (1992). Human memory. In F. Craik & T. Salthouse (eds.), *The handbook of aging and cognition* (pp. 51–119). Mahwah, N.J.: Lawrence Erlbaum Associates.

Q16 Dalrymple-Alford, E. C., & Budayr, B. (1966). Examination of some aspects of the Stroop color-word test. *Perceptual and Motor Skills, 23*, 1211–1214.

Engle R. W., Conway, A. R. A., Tuholski, W. W., & Shisler, R. J. (1995). A resource account of inhibition. *Psychological Science, 6,* 122–125.

Faust, M. E., & Balota, D. A. (1997). Inhibition of return and visuospatial attention in healthy older adults and individuals with dementia of the Alzheimer type. *Neuropsychology, 11*, 13–29.

Q17 Folstein, M. F., Folstein, S. E., & McHugh, P. R. (1975). "Mini-mental state": A practical method for grading the cognitive state of patients for the clinician. *Journal of Psychiatric Research, 12*, 189–198.

Friedman, N. P., & Miyake, A. (2004). The relations among inhibition and interference control functions: A latent variable analysis. *Journal of Experimental Psychology: General, 133,* 101–135.

Gamboz, N., & Russo, R. (2004). Age differences in negative priming, episodic memory and frontal lobe tasks: A single inhibitory deficit? *Brain impairment, 5,* 126–137.

Gamboz, N., Russo, R., & Fox, E. (2002). . *Psychology and Aging, 17*, 525–531.

George, M. S., Ketter, T. A., Parekh, P. I., Rosinsky, N., Ring, H., Casey, B. J., et al. (1994). Regional brain activity when selecting a response despite interference: A H$^2$15 O PET study of the Stroop and emotional Stroop. *Human Brain Mapping, 1*, 194–209.

Golden, C. J. (1978). *Stroop color and word test: A manual for clinical and experimental uses*. Wood Dale, IL: Stoelting Company.

Grant, J. D., & Dagenbach, D. (2000). Further considerations regarding inhibitory processes, working memory, and cognitive aging. *American Journal of Psychology, 113*, 69–94.

Greenwood, P. M. (2000). The frontal aging hypothesis evaluated. *Journal of the International Neuropsychological Society, 6*, 705–726.

Harnishfeger, K. (1995). The development of cognitive inhibition. Theories, definitions, and research evidence. In F. K. Dempster & Ch. J. Brainerd (eds.), *Interference and inhibition in cognition* (pp. 176–206). London: Academic Press.

Hartley, A. A., & Kieley, J. M. (1995). Adult age differences in the inhibition of return of visual attention. *Psychology and Aging, 10*, 670–683.

Hasher, L., & Zacks, R. T. (1979). Automatic and effortful processes in memory. *Journal of Experimental Psychology: General*, *108*, 356–388.

Hasher, L., & Zacks, R. T. (1988). Working memory, comprehension, and aging: A review and a new view. In G. H. Bower (ed.), *The psychology of learning and motivation, 22* (pp. 193–225). Orlando, FL: Academic Press.

Hasher, L., Stoltzfus, E. R., Zacks, R. T., & Rypma, B. (1991). Age and inhibition. *Journal of Experimental Psychology: Learning, Memory and Cognition, 117,* 163–169.

Hasher, L., Zacks, R. T., & May, C. P. (1999). Inhibitory control, circadian arousal, and age. In D. Gopher & A. Koriat (eds.), *Attention and performance XVII, Cognitive regulation of performance: Interaction of theory and application* (pp. 653–675). Cambridge, MA: MIT Press.

Q18 James, W. (1890). *The principles of psychology.* New York: Holt.

Jennings, J. M., & Jacoby, L. (1997). An opposition procedure for detecting age-related deficits in recollection: Telling effects of repetition. *Psychology and Aging, 12,* 352–361.

Jennings, J. R., van der Molen, M. W., Pelma, W., Broca, K., & Hoza, B. (1997). Inhibition in boys with attention deficit hyperactivity disorder as indexed by heart rate change. *Developmental Psychology, 33,* 308–318.

Q19 Kane, M. J., Bleckley, M. K., Conway, A. R. A., & Engle, R.W. (2001). A controlled-attention view of working-memory capacity. *Journal of Experimental Psychology: General, 130,* 169–183.

Kahneman, D., & Chajczyk, D. (1983). Test of automaticity of reading: Dilution of the Stroop effect by color-irrelevant stimuli. *Journal of Experimental Psychology: Human Perception and Performance, 9,* 497–509.

Kerns, J. G., Cohen, J. D., MacDonald, A.W., Cho, R.Y., Stenger, V. A., & Carter, C. S. (2004). Anterior cingulate conflict monitoring and adjustments in control. *Science, 303*, 1023–1026.

Kieley, J. M., & Hartley, A. A. (1997). Age-related equivalence of identity suppression in the Stroop color-word task. *Psychology and Aging, 12,* 22–29.

Kok, A. (1999). Varieties of inhibition: Manifestations in cognition, event-related potentials and aging. *Acta Psychologica, 101,* 129–158.

Kramer, A. F., Humphrey, D. G., Larish, J. F., Logan, G., & Strayer, D. (1994). Aging and inhibition: Beyond a unitary view of inhibitory processing in attention. *Psychology and Aging, 9*, 491–512.

Langley, L., Fuentes, L., Hochhalter, A., Brandt, J., & Overmier, J. (2001). Inhibition of return in aging and Alzheimer's disease: Performance as a function of task demands and stimulus timing. *Journal of Clinical and Experimental Neuropsychology, 23*, 431–446.

Langley, L., Vivas, A., Fuentes, L., & Bagne, A. G. (2005). Differential age effects on attention-based inhibition: Inhibitory tagging and inhibition of return. *Psychology and Aging, 20*, 356–360.

Q20,21 Little, D. M equivalent in older and younger adults. *Psychology and Aging, 15*, 9–17.

Logan, G. D. (1980). Attention and automaticity in Stroop and priming tasks: Theory and data. *Cognitive Psychology, 12,* 523–553.

(1984). On the ability to inhibit simple and choice reaction time responses: A model and a method. *Journal of Experimental Psychology: Human Perception and Performance, 10*, 276–291.

Q22 Logan, G. D. (1994). On the ability to inhibit thought and action: A users' guide to the stop signal paradigm. In D. Dagenbach & T. H. Carr (eds.), *Inhibitory processes in attention, memory, and language*. San Diego: Academic Press.

Logan, G. D., Schachar, R. J., & Tannock, R. (1997). Impulsivity and inhibitory control. *Psychological Science*, *8*, 60–64.

MacDonald, A. W., Cohen, J. D., Stenger, V. A., & Carter, C. S. (2000). Dissociating the role of the dorsolateral prefrontal and anterior cingulate cortex in cognitive control. *Science, 288,* 835–1838.

MacLeod, C. M., Dodd, M. D., Sheard, E. D., Wilson, D. E., & Bibi, U. (2003). In opposition to inhibition. B. H. Ross (ed.), *The Psychology of Learning and Motivation, 43*, 163–206.

May, C. P., & Hasher, L. (1998). Synchrony effects in inhibitory control over thought and action. *Journal of Experimental Psychology: Human Perception and Performance, 24*, 363–379.

Mayr, S., Niedeggen, M., Buchner, A., & Pietrowsky, R. (2003). ERP correlates of auditory negative priming. *Cognition, 90*, B11–B21.

McCrae, C., & Abrams, R. (2001). Age-related differences in object- and location-based inhibition of return of attention. *Psychology and Aging, 16*, 437–449.

McDonald, C., Bauer, R., Filoteo, J., Grande, L., Roper, S., & Gilmore, R. (2005). Attentional inhibition in patients with focal frontal lobe lesions. *Journal of Clinical and Experimental Neuropsychology, 27*, 485–503.

McDowd, J. M., & Oseas-Kreger, D. M. (1991). Aging, inhibitory processes, and negative priming. *Journal of Gerontology: Psychological Sciences, 46,* 340–345.

Metzler, C., & Parkin, A. J. (2000). Reversed negative priming following frontal lobe lesions. *Neuropsychologia, 38,* 363–379.

Neill, W. T. (1997). Episodic retrieval in negative priming and repetition priming. *Journal of Experimental Psychology: Learning, Memory, and Cognition, 23*, 1291–1305.

Neill, W., & Valdes, L. (1992). . *Journal of Experimental Psychology: Learning, Memory, and Cognition, 18*, 327–334.

Neill, W., Valdes, L., Terry, K., & Gorfein, D. (1992). Persistence of negative priming: II. Evidence for episodic trace retrieval. *Journal of Experimental Psychology: Learning, Memory and Cognition*, *18*, 993–1000.

Q23 Nelson, H. E., & Willison, J. (1991). *National Adult Reading Test (NART) Test Manual* (2nd ed.). Windsor: NFER-Nelson.

Neumann, O. (1984). Automatic processing: A review of recent findings and a plea for an old theory. In W. Prinz & A. F. Sanders (eds.), *Cognition and automatic processing* (pp. 255–293). Berlin: Springer-Verlag.

Nigg, J. T. (2000). On inhibition/disinhibition in developmental psychopathology: Views from cognitive and personality psychology and a working inhibition taxonomy. *Psychological Bulletin, 126*, 200–246.

Q24 Nigg, J., Butler, K. M., Huang-Pollock, C., & Henderson, J. (2002). Inhibitory processes in adults with persistent childhood onset ADHD. *Journal of Consulting and Clinical Psychology, 70,* 153–157.

Q25 Norman, D. A., & Shallice, T. (1980). Attention to action: Willed and automatic control of behavior. Center for Human Information Processing (Technical report No. 99). Reprinted in revised form. In
Q26 R. J. Davidson, G. E. Schartz and Shapiro (eds.), *Consciousness and self-regulation. Advances in research* (1986), 4 (pp. 1–18). New York and London: Plenum Press.in

Oosterlaan, J., & Sergeant, J. A. (1998). Response inhibition and response re-engagement attention-deficit/hyperactivity disorder, disruptive, anxious and normal children. *Behavioral and Brain Research, 94*, 33–43.

Paap, K. R., & Ogden, W. G. (1981). Letter encoding is an obligatory but capacity demanding operation. *Journal of Experimental Psychology: Human Perception and Performance, 7,* 518–528.

Park, D. C., & Hedden, T. (2001). Working memory and aging. In M. Naveh-Benjamin, M. Mos-
Q27 covitch, & H. L. Roediger (eds.), *Perspectives on human memory and cognitive aging: Essays in*
Q28 *honour of Fergus Craik*. East Sussex, U.K.: Psychology Press.

Poliakoff, E., Coward, R., Lowe, C., & O'Boyle, D. (2007). The effect of age on inhibition of return is independent of non-ocular response inhibition. *Neuropsychologia, 45*, 387–396.

Posner, M. I. (1978). *Chronometric explorations of mind*. Hillsdale, N.J.: Erlbaum.

Q29 Raven, J. C., Raven, J., & Court, J. H. (1988). *Mill Hill Vocabulary Scale*. Oxford: Oxford Psychology Press.

Raz, N. (2000). Aging of the brain and its impact on cognitive performance: Integration of structural and functional findings. In F. I. M. Craik and T. A. Salthouse (eds.), *Handbook of aging and cognition—II* (pp. 1–90). Mahwah, N.J.: Erlbaum.

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

Rubia, K., Russell, T., Overmeyer, S., Brammer, M. I., Bullmore, E. T., Sharma, T., Simmons, A., et al. (2001). Mapping motor inhibition: Conjunctive brain activations across different versions of go/no go and stop tasks. *Neuroimage, 13,* 250–261.

Salthouse, T. (1996). The processing-speed theory of adult age differences in cognition. *Psychological Review, 103,* 403–428.

Salthouse, T., Toth, J. P., Hancock, H. E., & Woodard, J. L. (1997). Controlled and automatic forms of memory and attention: Process purity and the uniqueness of age-related influences. *Journal of Gerontology: Psychological Sciences, 52B,* 216–228.

Schachar, R. J., & Logan, G. D. (1990). Impulsivity and inhibitory control in normal development and childhood psychopathology. *Developmental Psychology*, *26*, 710–720.

Schneider, W., & Chen, J. M. (2003). Controlled and automatic processing: Behavior, theory, and biological mechanisms. *Cognitive Science, 27*, 525–559. (1997). Continued inhibitory capacity throughout adulthood: Conceptual negative priming in younger and older adults. *Psychology and Aging, 12*, 667–674.

Q30 Shallice, T. (1988). *From neuropsychology to mental structure*. Cambridge: Cambridge University Press.

Q31 Shallice, T., & Burgess, P. (1996). The domain of supervisory processes and temporal organization of behaviour. *Philosophical Transactions of the Royal Society of London: Biological Science, 351*, 1405–1411.

Shiffrin, R. M., & Schneider, W. (1977). Controlled and automatic human information processing II.
Q32 Perceptual learning, automatic attending, and a general theory. *Psychological Review, 84*, 127–190.

Spieler, D. H., Balota, D. A., & Faust, M. E. (1996). Stroop performance in healthy younger and older adults and in individuals with dementia of the Alzheimer's type. *Journal of Experimental Psychology—Human Perception and Performance*, *22*, 461–479.

Spinks, J. A., Zhang, J. X., Fox, P. T., Gao, J. H., & Tan, L. H. (2004). More workload on the central executive of working memory, less attention capture by novel visual distractors: Evidence from an fMRI study. *Neuroimage, 23,* 517–524.

Steel, C., Haworth, E., Peters, E., Hemsley, D., Sharma, T., Gray, J., et al. (2001). Neuroimaging correlates of negative priming. *Neuroreport, 12*, 3619–3624.

Stoltzfus, E. R., Hasher, L., Zacks, R. T., Ulivi, M., & Goldstein, D. (1993). *Journal of Gerontology: Psychological Sciences, 48,* 179–188.

Sullivan, M., & Faust, M. (1993). Evidence for identity inhibition during selective attention in old adults. *Psychology and Aging, 8,* 589–598.

Thai, N. J., Hodgson, T., Andrés, P., & Guerrini, Ch. (2007). Functional MRI study of negative priming: Implications for frontal disinhibition. Paper presented at the International Society of Magnetic Resonance in Medicine (ISMRM). Berlin.

Tipper, S. (1985). The negative priming effect: Inhibitory priming by ignored objects. *Quarterly Journal of Experimental Psychology A, 37*, 571–590.

Tipper, S. (1991). Less attentional selectivity as a result of declining inhibition in older adults. *Bulletin of the Psychonomic Society, 29*, 45–47.

Tipper, S. (2001). Does negative priming reflect inhibitory mechanisms? A review and integration of conflicting views. *Quarterly Journal of Experimental Psychology, 54,* 321–343.

Titov, N., & Knight, R. (1997). Adult age differences in controlled and automatic memory processing. *Psychology and Aging, 12*, 565–573. (1997). Specifying the relations between automaticity and consciousness: A theoretical note. *Consciousness and Cognition, 6*, 441–451.

Tzelgov, J., Henik, A., & Berger, J. (1992). Controlling Stroop effect by manipulating expectation for color related stimuli. *Memory & Cognition, 20,* 727–735.

Van der Linden, M., Hupet, M., Feyereisen, P., Schelstraete, M. A., Bestgen, Y., Bruyer, R., et al. (1999). Cognitive mediators of age-related differences in language comprehension and verbal memory performance. *Aging, Neuropsychology and Cognition*, *6*, 32–55.

Vakil, E., Manovich, R., Ramati, E., & Blachstein, H. (1996). The Stroop Color-Word task as a measure of selective attention: Efficiency in the elderly. *Developmental Neuropsychology*, *12*, 313–325.

Verhaeghen, P., & De Meersman, L. (1998). Aging and the Stroop effect: A meta-analysis. *Psychology and Aging, 13,* 120–126.

Q33 Vitkovitch, M., Bishop, S., Dancey, Ch., & Richards, A. (2002). Stroop interference and negative priming in patients with multiple sclerosis. *Neuropsychologia, 40*, 1570–1576.

Wechsler, D. (1997). *WAIS-III administration and scoring manual.* San Antonio, TX: Psychological Corporation.

West, R. L. (1996). An application of prefrontal cortex function theory to cognitive aging. *Psychological Bulletin, 120,* 272–292.

West, R., & Alain, C. (2000). Age-related decline in inhibitory control contributes to the increased Stoop effect observed in older adults. *Psychophysiology, 37*, 179–189.

Williams, B. R., Ponesse, J. S., Russell, J. S., & Logan, G. D. (1999). Development of inhibitory control across the life span. *Developmental Psychology, 35*, 205–213.

Wilson, S. P., & Kipp, K. (1998). The development of efficient inhibition: Evidence from directed-forgetting tasks. *Developmental Review, 18*, 86–123.

Zacks, R., & Hasher, L. (1997). *Journal of Gerontology: Psychological Sciences, 52B,* 274–283.