Age-related differences during visual search: the role of contextual expectations and cognitive control mechanisms.

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In visual search, the cognitive system controls the contextual information available by inhibiting irrelevant information to successfully orient attention towards the search target. As cognitive control is reduced in older adults they often experience more difficulties in such tasks. In two eye-tracking experiments, we investigated the interplay between contextual expectations and cognitive control during visual search in naturalistic scenes. A younger and an older group of participants had to find a target object varying in consistency with the search scene (e.g., a basket of bread vs a clothes iron in a restaurant scene) after being primed with contextual information either congruent or incongruent with it (e.g., a restaurant vs a bathroom), and administered as a scene (Experiment 1) or a word (Experiment 2, which included a scrambled word as neutral prime). Participants also completed two cognitive control tasks (Stroop and Flanker) to assess their cognitive control. Older adults had greater difficulty than younger adults with inconsistent objects, especially when primed with congruent information (Experiment 1), or a scrambled word (neutral condition, Experiment 2). Congruent expectations boost distractor objects which have to be suppressed when the semantics of the target object violates them. Neutral primes acted as low-level perceptual distractors that increased the attentional load of participants and needed to be suppressed. Higher cognitive control, especially in older participants, improved the search accuracy in these experimental conditions, but it did not mediate the eye-movement responses. These results shed new light on the links between cognitive control and visual attention in ageing.

Keywords: visual search; cognitive ageing; contextual expectations; cognitive control; eye-tracking.

1 Introduction

2 Cognitive ageing has been linked to degraded performance in a variety of visual
3 tasks such as driving, face recognition, or searching for a target among distractors
4 (Bédard et al., 2006; Burton-Danner, Owsley, & Jackson, 2001; Foster, Behrmann, &
5 Stuss, 1995; Hahn, Carlson, Singer, & Gronlund, 2006; Potter, Greal, Elliott, & Andres,
6 2012). Older adults, for example, take longer to identify a target object (e.g., more
7 saccades, Watson, Maylor, & Bruce, 2005) spend significantly more time processing it
8 (e.g., longer gaze duration; Williams, Zacks, & Henderson, 2009), and display a worse
9 performance than younger adults when asked to remember, or search for a target
10 embedded within other distractor objects (see Zanto & Gazzaley, 2014 for a review).

11 Beyond a generalised slowing of cognitive processing (e.g., Salthouse, 1994,
12 2012), most research on ageing points at cognitive control mechanisms to explain the
13 difficulties often experienced by healthy older adults (e.g., Gazzaley, Cooney, Rissman,
14 & D'Esposito, 2005). In visual search, in fact, irrelevant features of distracting objects
15 have to be actively inhibited to orient attention towards the target object, and this
16 operation relies on cognitive control that is assumed to be impaired in older adults (e.g.,
17 Foster et al., 1995, Schwarzkopp, Mayr, & Jost, 2016; but see Monge & Madden, 2016
18 for an alternative explanation based on perceptual degradation).

19 The inhibitory mechanism underlying top-down cognitive control has been
20 labelled as proactive, a slow and effortful mechanism that acts globally to mitigate
21 interference before perceptual processing, which has been shown to be affected by ageing
22 (e.g., Mayr, 2001). Proactive control has been distinguished from the reactive control
23 which is instead a fast and automatic mechanism that acts contingent to stimulus onset
24 (e.g., Braver, Gray, & Burgess, 2007), and it is spared by ageing (e.g., Bugg, 2014).

Another related hypothesis for the difficulties experienced by older adults in visual search is that they may over-rely upon top-down contextual information to compensate for age-related decline in cognitive processing (e.g., Lindenberger & Mayr, 2014; Madden, 2007). Neider and Kramer (2011), for example, found that the overt allocation of attention in older adults was guided more prominently by the spatial association between the context of a pseudo-realistic scene and the target of the search (e.g., searching for a jeep on the ground), as compared to younger adults.

The interplay between proactive control mechanisms and access to contextual information during the visual search has been examined, mostly in young adults, by using contextual cueing paradigms (e.g., Chun, 2000). Chun, Chun, & Jiang, 1998 found that young observers were faster in searching the letter T among Ls distractors when repeatedly exposed to particular spatial layouts of the letters; and older adults seem to equally benefit from this pre-activation (e.g. Howard, Dennis, Howard, Yankovich, & Vaidya, 2004; Madden, Whiting, Cabeza, & Huettel, 2004; Whiting, Madden, Pierce, & Allen, 2005; but see Smyth & Shanks, 2011, for impaired learning of contextual information in older adults). Other studies on young adults have extended the findings of contextual cueing in visual search from arrays of visual objects to photo-realistic scenes, and corroborated the evidence that the pre-activation of a scene facilitates search within it (e.g., Hollingworth, 2007).

Nevertheless, naturalistic visual scenes provide additional top-down contextual information (e.g., a restaurant vs. a bathroom scene) which is combined with the information of the search target (e.g., a basket of bread) to guide overt attention to locations (e.g., a table) that are more likely to contain it (e.g., Bar, 2004; Eckstein, Drescher, & Shimozaki, 2006; Madden, 2007; Neider & Zelinsky, 2006). Moreover, the way objects are processed depends on their semantic relationship with the embedding

scene context. Objects that are semantically inconsistent with the scene (e.g., a clothes iron versus a basket of bread in a restaurant) tend to attract earlier fixations than consistent ones (e.g., Belke, Humphreys, Watson, Derrick, Meyer, & Telling, 2008; LaPointe & Milliken, 2016; Loftus & Mackworth, 1978; Underwood, Humphreys, & Cross, 2007); and once identified, they require a more effortful processing (e.g., longer fixation duration, Cornelissen & Võ, 2017; Henderson, Weeks, Phillip a., & Hollingworth, 1999; Võ & Henderson, 2011; but see Wu, Wick, & Pomplun, 2014 for a review of open controversies in the literature).

The use of more realistic scenes in studies investigating visual search on older adults is restricted to a few exceptions such as the study by Neider and Kramer (2011) briefly mentioned above. Note, however, that this study did not employ a contextual cueing paradigm, which entails the pre-activation of contextual information before the visual search. Therefore, it is yet to be understood how the pre-activation of contextual information would mediate visual search mechanisms in older adults, especially when such information may, or may not, be in conflict with the contextual information available during the actual search task (e.g., the information of the scene context or the semantics of the target object). In theory, the cognitive system should resort on top-down control mechanisms to suppress irrelevant - or conflicting - information; and cognitive ageing is known to hinder these mechanisms. Thus, a contextual cueing paradigm would make possible to explicitly test the involvement of cognitive control mechanisms in visual search, while helping to shed light onto age-related differences.

Moreover, the use of naturalistic scenes as visual cues should promote the activation of both high-level (conceptual) information (i.e., the semantic category of the scene) as well as, low-level (perceptual) information (e.g., the spatial layout of the objects). This boost on both conceptual and perceptual information may imply an added

cost to cognitive processing if such information is irrelevant to the search task, and thus, it has to be suppressed. When young adults perform a visual search after being cued with contextual information (e.g., Brockmole, Castelhana, & Henderson, 2006; Chun, 2000; Hollingworth, 2009) they display facilitated processing only when the contextual prime and the search scene varied in the local context surrounding the target. However, there is no evidence of facilitated processing when the scenes had different spatial layouts despite being conceptually related (e.g., two different libraries) or if the prime scene and the search scene differed in low-level features, such as the colour (e.g., Goujon, Brockmole, & Ehinger, 2012). Thus, in order to discriminate whether contextual effects associated to visual cueing relate to their conceptual or perceptual nature, they have to be compared with a simple conceptual condition as provided, for example, by linguistic information (i.e., words).

In sum, the age-related difficulties observed in previous literature have been mostly explained either as an over-reliance of older adults on contextual information, or, as a reduced capacity of suppressing such information when irrelevant. The current eye-tracking study employs a contextual cueing paradigm, using both visual (scenes) and linguistic cues (words), and aims to: (a) understand how the pre-activation of top-down contextual information (conceptual and perceptual) modulates the identification of a target object embedded in a naturalistic scene during a visual search task, (b) examine whether and how cognitive control mechanisms are involved and (c) uncover the impact of cognitive ageing on it.

The overarching goal of our study is to disentangle ageing effects that may be associated with the over-reliance of older adults on contextual information from those effects that may instead be linked to an impairment on cognitive control mechanisms.

The present study

We report two eye-tracking visual search experiments with younger and older adults. In these experiments, participants are initially prompted with a target cue word, then briefly primed with contextual information, either a visual scene (e.g., a picture of a restaurant, Experiment 1) or a category word (e.g., the word “restaurant”, Experiment 2). Then, they are presented with a search scene where they have to find the target object, which can be either consistent or inconsistent with it (e.g., a basket of bread versus an iron); see Figure 1 for an example of the experimental design. The primed information can be either congruent or incongruent with the search scene (or also neutral, but only in Experiment 2). In a trial of Experiment 1, for example, a participant may be exposed to a restaurant scene, and then have to search for a clothes iron in another restaurant scene that is visually different (i.e., it is not the same scene, and they differ in low-level visual features). This experimental condition has a prime scene conveying categorically congruent information and a target object which is inconsistent with the search scene. The same structure applies to Experiment 2, where we replace prime scenes with prime words conveying categorical information, and add a ‘neutral’ priming condition operationalised as a scrambled mask of a context word. In this way, in the neutral prime condition participants are still primed with low-level information, but such information does not convey any high-level categorical meaning, and hence it is semantically neutral for the search task.

 INSERT FIGURE 1 HERE

We compare the performance of the younger and the healthy older group on three critical measures of the search task: (a) response accuracy, which is the proportion of correctly detected target objects; and on correct trials only (b) the time to first fixation, which is the time it takes for a participant to look at the target object for the first time from scene onset, and points at the speed of target identification; and (c) the total fixation time, which is the sum of all fixations allocated to the target object, and points at the processing effort required to correctly recognize the target of the search. Each group was also assessed on general cognitive abilities using the Montreal Cognitive Assessment Test (MoCA; Portuguese Version normed by Freitas, Simões, Alves, & Santana, 2011). This step was necessary to screen older participants for potential neurodegenerative diseases.

Furthermore, in order to look for evidences about the involvement of cognitive control during visual search, we correlate the behavioural performances of our younger and older participants on visual search with their individual performance on Stroop and Flanker tasks, which have often been used in previous literature to tap into cognitive control mechanisms (see Rey-Mermet & Gade, 2017 for a recent review). This analysis represents an essential addition to previous research on ageing, which has mostly looked at group analysis of responses on the same task to tap into cognitive control mechanisms. Our aim instead is to link the responses on classic cognitive control tasks (e.g., Stroop and Flanker) with the responses on the visual search and obtain direct evidence for, or against, interdependent mechanisms, e.g., lower cognitive control may lead to worsening accuracy in the visual search task. We also use this final analysis to directly compare the

influence of the two types of contextual priming (conceptual and perceptual) on cognitive control and visual search performances.

In both experiments, we predict participants to be faster at identifying the target object when inconsistent with the search scene. This prediction stems from previous literature finding that inconsistent objects are prioritised over consistent objects because they violate the contextual fit of the scene (e.g., LaPointe & Milliken, 2016; Loftus & Mackworth, 1978). Going beyond this literature, we predict that, if older participants rely more on top-down contextual expectations, they should be less accurate at detecting inconsistent objects as they violate the context of the scene, mainly, when the information of such context is boosted through priming. Moreover, if their poorer performance in visual search stems from their inability to suppress conflicting information, older individuals with better cognitive control should be more accurate in this condition.

Recall that if the prime scene belongs to the same semantic category as the search scene, it does not facilitate the search task as much as a scene from another category, because the local context matters more than the global context (e.g., Brockmole et al., 2006).

Also, the contextual gist of a scene (e.g., a restaurant scene) is acquired very quickly, and hence, a representation of the possible objects and their spatial layout is also rapidly created (e.g., Henderson & Ferreira, 2004). Thus, we may expect that searching in a restaurant scene after being primed with a different restaurant scene should be facilitated relative to being primed with a pool hall scene. However, the two scenes differ in their low-level features. Thus, the participants may find it harder to disengage from the specific spatially-guided expectations created when primed with the same category (restaurant) than to discard the irrelevant information of an unrelated category prime (pool hall). This hypothesis would also be consistent with the finding that (visually) conflicting stimuli disrupt perceptual identification more than irrelevant stimuli (e.g.,

Vallesi, Stuss, McIntosh, & Picton, 2009). As a result of this rationale, we also expect older participants to require a more extended allocation of overt attention to identifying the target object when inconsistent with the scene correctly, or when primed with congruent information, as again, their capacity to resolve conflicting information is reduced.

A similar logic may apply to prime words, but now the critical comparison being between neutral and incongruent (or congruent) priming. The neutral priming condition, operationalised as a scrambled mask of a context word, is a perceptual distractor which may likely interfere with the retention of the target identity more than both congruent or incongruent prime words that can instead be visually processed, and ignored if irrelevant. So, we expect all participants to have a worsen detection performance when the prime is neutral, especially when the object to look for is inconsistent with the scene context. As predicted for Experiment 1, older adults may find this condition particularly hard because their capacity to suppress irrelevant information - coming from the perceptual nature of a neutral prime and the semantic inconsistency of the object - is reduced. However, if cognitive control is genuinely involved in helping the suppression of such irrelevant information, we expect older participants with higher cognitive control performance to be better at correctly detecting the target in this condition.

Experiment 1

Design

In a 2x2x2 experimental design, the congruency of the Prime scene (Congruent, Incongruent) with the search scene is crossed with the semantics of the target Object of

the search (Consistent, Inconsistent) within-participants, along with a between-participant Group (Younger and Older) condition (see Figure 1 for the experimental design).

Material

We used 42 experimental scenes, 42 filler scenes and 84 prime scenes, all naturalistic images, i.e., photographs. Four different versions of each experimental scene are construed: two types of Object consistency (Consistent – Inconsistent) counterbalanced in two locations (Left - Right) within the scene to avoid the development of systematic search strategies. We had, therefore, a total of 168 unique items, which were divided into four lists following a Latin-Square design. Primes and fillers scenes were selected from open-access databases (e.g., Flickr’s “The Commons”). Prime scenes were selected according to their contextual congruency with respect to the experimental scenes while ensuring that they would never contain the target object (refer to Appendix A for the norming of the material).

Participants

We recruited 53 native speakers of Portuguese in two groups: a younger group of 32 undergraduate students (28 F; Age = 21.4 ± 5.71) and an older group of 21 participants (17 F, Age = 67.4 ± 4.97) from Universities of the Third Age with no reported history of neuropsychological deficits. All participants had normal or corrected-to-normal vision. The younger participants were awarded course credits, and the older participants were paid 15 Euro for taking part in the experiment. This study was approved by the Ethics Committee of the Department of Psychology, University of Lisbon, before data collection.

Eye-tracker setup

Visual stimuli were presented on a 19-inch LG Flatron L194ws LCD screen with a 60Hz refresh rate, 55cm away from participants' eyes, subtending 29.3° of visual angle. Eye movement data were recorded using an SMI IVIEW X HI-SPEED eye-tracker (SensoMotoric Instruments, Teltow, Germany) at a sampling rate of 1,250Hz. Only the participants' dominant eye (assessed using a parallax test) was tracked. Chin rest and forehead support were used to stabilise the head position. A Logitech Cordless Rumblepad 2 controller was used to record the target detection responses. The experiment was developed using Experiment Center 3.2.

 INSERT FIGURE 2 HERE

Procedure

Each trial started with a written cue (500ms) prompting the participant with the target object to be searched. Then, a fixation cross appeared in the centre of the screen, displayed until it was fixated for 1000ms, after which the prime scene was presented for 250ms followed by a scrambled mask of the same scene for another 250ms. The mask was applied to reduce the perceptual activation of the prime scene before the search scene (Enns & Lollo, 2000). After the search scene appeared, the participants had to state whether they did, or did not, see the cued target object by pressing a response button on a cordless joypad (see Figure 2 for an example trial).

The target object was always present in the experimental trials and always absent in the filler trials. This distribution guarantees a balanced 50-50 distribution of yes/no responses. At the beginning of each experimental session, participants were familiarised

with the task through four practice trials. A 15-point calibration procedure was performed at the beginning of the experiment and repeated every 10 trials (on 8-points) to ensure accurate tracking. The calibration was accepted when the deviation error was below 0.8° and 1.2° degrees of visual angle for the x and y-axis, respectively. On average, the younger group displayed a $0.61^\circ \pm 0.42^\circ$ visual angle deviation error on the x-axis and $0.72^\circ \pm 0.58^\circ$ on the y-axis while the older group displayed a $0.82^\circ \pm 0.60^\circ$ error on the x-axis and $1.12^\circ \pm 0.79^\circ$ on the y-axis.

At the end of the visual search task, each participant was asked to respond to the MoCA test (30 points maximum score) and performed a computerised version of the Stroop (64 randomised trials, 32 Congruent and 32 Incongruent) and Flanker (64 randomised trials, 32 Congruent – 32 Incongruent) tasks, implemented using E-Prime (Psychology Software Tools, Pittsburgh, PA).

The eye-tracking session lasted 30 minutes on average which together with the cognitive control tasks and the MoCA totalled approximately an hour of testing.

Analysis

Data pre-processing and dependent measures of search performance: Raw gaze data was initially pre-processed into fixations and saccades using BeGaze 3.2 (SMI Instruments), and further analysed using R 3.4.4 (R Core Team, Vienna, Austria). Of the 2,226 total trials (i.e., 42 scenes and 53 participants), we excluded 8 items (108 trials) as participants could not correctly identify the target object above the 50% chance level, and an additional 45 trials (by participant and experimental condition) because the response times were 2.5 SDs above the mean. Of these 2,073 trials, we retained the 1,504 trials in which the target object was fixated. For these trials, we considered the response accuracy to the visual search task, and on correct trials (i.e., 1,454) the eye-movement measures for

the two main stages of target detection: identification and processing. For the identification stage, we computed the time to the first fixation of the target object from scene onset. For the processing stage, we considered the total fixation time on the object, which is the sum of all fixations on the target during the trial.

Statistical analysis: We used linear-mixed effects modelling (LME) as implemented by the lme4 (vs 1.1-18-1) package in R to analyse our dependent measures (Bates, Mächler, Bolker, & Walker, 2015). We adopted the LME approach as it allows the simultaneous modelling of by-participant and by-item random effects. This approach is advantageous for two main reasons: (1) it captures the intrinsic variability of the random variables when estimating the coefficients for the fixed effects, and hence it takes into account the individual differences between, for example, the participants; and (2) it avoids data aggregation: a practice which leads to less precise estimates when correlations are unequal across repeated measures and may yield biased estimates especially with small samples (Muth et al., 2016). The predictors, centred to reduce co-linearity, were: Prime (Congruent = -.5, Incongruent = .5), Object (Consistent = -.5, Inconsistent = .5) and Group (Older = -.6, Younger = .4). Our random effects were Participant (53) entered as a between-participant variable, as participants are nested into their age group, and Scene (42). In ageing research, a well-known phenomenon is that the behavioural responses of older participants are consistently slower than those of the younger participants (e.g., Salthouse, 1994). It becomes, therefore, crucial to normalise the time-dependent responses so that their general slowing does not obscure any effect arising from the experimental condition of interest due to ageing. We followed the approach proposed by Faust, Balota, Spieler, & Ferraro, 1999, whereby we z-scored the time-dependent eye-movement measures of time to first fixation and total time of fixation independently for

each participant. Effectively, this strategy makes sure that the mean response between the two age groups is the approximately same (i.e., no main effect of Group), and that any true difference between the two groups should emerge as an interaction between the Group variable and the experimental variable of interest (e.g., Prime in our study). We visualise the response accuracy and the time-dependent attentional measures already z-scored but provide the reader with plots of the same measures without any transformation as supplementary material. We also considered the order of trials (accounting for learning strategies) as a covariate and controlled for it by residualizing it against each DVs in a linear regression model ($DV \sim Order$, in R syntax), and then taking the residuals obtained as the DVs for further analyses. This ensured that this incidental covariate did not influence the effects of our experimental conditions (Prime and Object) on each DV analysed. Our initial models had a full fixed-effect structure (i.e., all main effects and interactions) with a maximal random-effect structure (i.e., random variables are included both as intercepts and uncorrelated slopes (Barr, Levy, Scheepers, & Tily, 2013). Then, in order to have models that are parsimonious in the number of parameters (Matuschek, Kliegl, Vasishth, Baayen, & Bates, 2017), we reduced them utilising the step function of the R package lmerTest (vs 3.0-1; Kuznetsova, Christensen, Bavay, & Brockhoff, 2014). This method performs a backward selection of the model, both on the random and fixed effect structure, which iteratively removes terms that do not significantly improve the model fit (thresholds of $p < 0.1$ for random effects and $p < 0.08$ for fixed effects to include marginally significant results). The tables report the coefficients, standard errors, and t-values of only those predictors that were significant after model selection. We derived p-values for the fixed effects in the LME models from F-tests based on Satterthwaite approximation of the effective degrees of freedom. We also report the

standardised β s, i.e., coefficients that have been normalised so that they are all on the same scale and therefore their size can be compared directly.

The results are organised into two paragraphs: (a) “*General cognitive abilities and cognitive control*”, in which we compare the performance of the two groups on the MoCA, and on the Stroop and Flanker tasks and (b) “*Visual search analysis*”, in which we compare the two groups on the visual search task.

 INSERT TABLE 1 HERE

Results

General cognitive abilities and cognitive control

We assessed the general cognitive ability of the younger and the older participants with the MoCA, and their cognitive control mechanisms with the Stroop and Flanker tasks (see Table 1 for mean and standard errors of these measures). On the MoCA, the older group was significantly worse than, the younger group ($t [30.3] = -4.43, p < 0.001$). For the Stroop task, on a total of 3,520 trials, we excluded 41 trials for the younger group and 73 trials for the older group because they were either below 1% or above the 99% of the RT distribution of their age group. A mixed ANOVA analysis of the accuracy revealed a significant main effect of Congruency, with less accurate performances in incongruent than congruent trials [$F(1,51) = 4.6; p = 0.03$], and a marginal interaction between Group and Congruency, with older adults performing worse in incongruent trials [$F(1,51) = 3.57; p = 0.06$], and no main effect of Group. On the response time, we found significant main effects of Group, with older adults being slower than young adults

[$F(1,51) = 111.38$; $p < 0.0001$], and Congruency, with longer response times for incongruent than congruent trials [$F(1,51) = 91.37$; $p < 0.0001$]. We also found a significant two-way interaction between Group and Congruency with older adults being slower than younger adults in incongruent trials [$F(1,51) = 21.96$; $p < 0.0001$]. For the Flanker task, on a total of 3,520 trials, we excluded 41 trials for the younger group and 30 trials for the older group that were either below 1% or above the 99% of the RT distribution. We only found a main effect of Congruency on the accuracy, with less accurate performance in incongruent than congruent trials [$F(1,51) = 327.85$; $p < 0.0001$]; while for the response time, we found significant main effects of Group, with older adults being slower than younger adults [$F(1,51) = 30.49$; $p < 0.0001$]; and Congruency, with incongruent trials responded to slower than congruent trials [$F(1,51) = 6.4$; $p = 0.01$]. We did not find a significant interaction between Congruency and Group. These results largely confirm previous literature by showing increased difficulty in inhibiting incongruent information, especially by older participants. It must be noted, however, that this age-related interaction manifested in the Stroop rather than the Flanker task (e.g., Spieler, Balota, & Faust, 1996).

 INSERT FIGURE 3 AND TABLE 2 HERE

Visual search analysis

Response Accuracy: On response accuracy (Figure 3, upper panel), we found significant main effects of Prime, with lower accuracy when the prime scene and the search scene were semantically congruent, and Group, with younger participants being more accurate than older participants (refer to Table 2 for the model output). We also observed

significant two-way interactions between Prime and Object, with lower accuracy for inconsistent objects in congruently primed scenes; and between Object and Group, with older participants committing more errors when the object was inconsistent with the scene, primarily when the prime scene was semantically congruent with the search scene (three-way interaction Prime, Object and Group).

Time to the first fixation and total fixation time on the object: On the time to the first fixation to the target object (Figure 3, middle panel), we only found a main effect of Object, with inconsistent objects located faster than consistent objects. When looking at the total fixation time on the object (Figure 3, lower panel), we found that inconsistent objects were processed for longer than consistent objects during a trial (main effect of Object), especially by older participants (interaction Object, Group). Older participants also looked at the target object for longer when the prime scene and the search scene were contextually congruent (interaction Prime, Group).

Discussion

Inconsistent objects were harder to be correctly identified by the older group, mainly when the visual prime was congruent with the search scene. Overall, congruent priming impaired response accuracy, regardless of the age group. We argue that congruent priming may increase the activation of distractor objects, given the shared context between the prime scene and the search scene. This increased contextual activation may make target detection even harder because the spatial layout of objects must also be reassessed when the visual search begins. This finding is consistent with Brockmole et al. (2006) who observed that the repeated priming of a scene did not facilitate visual search when the scenes differed in the spatial layout. Furthermore, older

participants displayed a worsen detection performance than younger adults because they may over-rely on contextual expectations, and have more difficulties suppressing them.

Concerning the eye-movement data, we found that inconsistent objects were looked at earlier than consistent objects. They were also looked at for longer, especially by older participants. These results are in line with previous research (e.g., Belke et al., 2008; LaPointe & Milliken, 2016; Henderson et al., 1999; Williams et al., 2009). This result supports the idea that the semantics of objects be partly extracted in extra-foveal vision, as indexed by the earlier identification time for inconsistent objects, although the integration of information violating the context of the scene requires more effortful processing, as indexed by the longer fixation time. Moreover, older participants found the object-scene integration even more effortful when primed with a congruent scene. Arguably, this condition requires them to re-orient visual attention as the two scenes share the same semantic category but have different spatial layouts.

In sum, we applied contextual priming to a visual search task and manipulated the congruency between a prime scene and a search scene. The repeated cueing of contextual information was usually found to improve visual search (e.g., Chun, 2000). We contrasted semantically congruent and incongruent primes and found instead that congruent cueing was detrimental for the correct detection of the search target. This was probably due to increased activation of distractor objects and an additional cost due to ‘different’ spatial layout, especially for inconsistent objects which are unexpected within the scene context. The older group was more susceptible to these effects, which is in line with the idea that older adults rely more on contextual expectations than younger adults to compensate for a cognitive decline (Gazzaley & D’Esposito, 2007; Lindenberger & Mayr, 2014). As we shall see in the final analysis of our study, older adults with better cognitive control were also better capable of finding inconsistent targets.

As already discussed, a visual scene is a cue that conveys not only high-level conceptual information but also low-level information such as the spatial layout of the objects. So, although the prime scenes were all different in their low-level properties with respect to the search scene, and hence could not systematically bias target detection across experimental conditions, it remains to be examined how purely conceptual priming would affect search performance. Moreover, it would be essential to examine the case where participants are primed with information that does not convey any conceptual meaning, and it is hence “neutral” with respect to both the scene context and the semantics of the target object, and therefore acts as a perceptual distractor instead. In Experiment 2, we address these questions by using words instead of picture primes and by including a neutral prime condition consisting of a scrambled word.

Experiment 2

Design

The 2x2x3 design of Experiment 2 mostly followed that of Experiment 1. The only difference was that instead of using Prime scenes, we now used Prime words (i.e. the word “Restaurant” instead of the picture of a restaurant), and included a neutral condition along with the congruent and incongruent conditions. The other experimental conditions were the same as in Experiment 1 with a within-participant Object condition (Consistent, Inconsistent) and a between-participant Group condition (Older, Younger; see Figure 1 for the experimental design).

Material

We used 62 experimental scenes and 62 filler scenes, all naturalistic images and used written words to indicate the conceptual context to be primed. Additionally, we added a neutral prime condition, consisting of a scrambled version of the incongruent or congruent word prime. Compared to Experiment 1, we added 20 experimental trials to account for the neutral prime condition, along with a further 20 filler trials to maintain the even balance between target-present and target-absent trials. The additional experimental and filler images were selected from a database used by Coco, Nuthmann, & Della Sala, 2017, a study also investigating object consistency using naturalistic images (refer to Appendix A for the norming of the material).

Participants

We recruited two new groups of native speakers of Portuguese: a younger group of 24 undergraduate participants (15 F; Age = 24 ± 7.2) and an older group of 24 participants (16 F, Age = 66.6 ± 4) with no recorded history of neuropsychological deficits. All participants had normal or corrected-to-normal vision. As in Experiment 1, the younger participants were awarded course credits, and the older participants were paid 15 Euro for taking part in the experiment.

Procedure

The procedure of Experiment 2 was identical to that of Experiment 1: Participants were shown a written target object cue for 500ms, followed by a fixation cross displayed until the participant looked at it for 1000ms. Then, they were shown a prime word for 250ms, followed by a scrambled mask of the word for an additional 250ms. When the prime was neutral, and hence it was already a scrambled word, we show a different mask

to appear visually different. Then, the search scene was displayed until participants decided the presence or absence of the cued target object (see Figure 2 for a visualisation of the trial run). Participants were instructed using precisely the same protocol as for Experiment 1. We also used the same eye-tracking calibration procedure and the same cordless joypad to log in their responses. The calibration was accepted when the deviation error was below 0.8° and 1.2° degrees of visual angle for the x and y-axis, respectively. On average, the younger group displayed a $0.34^{\circ} \pm 0.17^{\circ}$ visual angle deviation error on the x-axis and $0.31^{\circ} \pm 0.16^{\circ}$ on the y-axis while the older group displayed a $0.48^{\circ} \pm 0.37^{\circ}$ error on the x-axis and $0.36^{\circ} \pm 0.26^{\circ}$ on the y-axis. Participants also undertook the MoCA and the same computerised version of the Stroop and Flanker tasks.

Analysis

As in Experiment 1, raw gaze data was pre-processed into fixations and saccades using BeGaze 3.7 and further analysed using R 3.4.4 (R Core Team, Vienna, Austria). Of the 2,976 total trials (i.e., 62 scenes and 48 participants), we excluded 9 items (120 trials) as participants could not correctly identify the target object above the 50% chance level, and an additional 75 trials (by participant and experimental condition) because the response times were 2.5 SDs above the mean. Of these 2,781 trials, we retained the 2,419 trials in which the target object was fixated. We considered the same dependent measures of Experiment 1: (a) response accuracy to the visual search task, and on correct trials (i.e., 2,302), (b) the time to the first fixation of the target object from scene onset, and (c) the total fixation time on the object. We used the same modelling approach of Experiment 1 to analyse our data, and hence we refer the reader to that section for the details. The only fundamental difference in the analysis of Experiment 2 is that the Prime variable has now

three factorial levels instead of two, i.e., Congruent, Incongruent and Neutral. We have chosen Neutral as the reference level and compared Congruent and Incongruent against it.

 INSERT TABLE 3 HERE

Results

General cognitive abilities and cognitive control

On the MoCA, the older group is significantly worse than, the younger group ($t[44.7] = -2.23$, $p < 0.03$; refer to Table 3 for a summary of the measures). For the Stroop task, on a total of 3,520 trials, we excluded 34 trials for the younger group and 67 trials for the older group as they were either below 1% or above 99% of the RT distribution of their age group. A mixed ANOVA analysis of the accuracy revealed only a significant main effect of Congruency, with less accurate performance in incongruent than congruent trials [$F(1,46) = 7.4$; $p = 0.01$]. On the response time, we found significant main effects of Group, with older adults being slower than younger adults [$F(1,46) = 38.76$; $p < 0.0001$], and Congruency, with longer response times for incongruent than congruent trials [$F(1,46) = 132.7$; $p < 0.0001$]. We also found a significant two-way interaction between Group and Congruency with older adults being slower than younger adults in incongruent trials [$F(1,46) = 4.12$; $p < 0.05$]. For the Flanker task, on a total of 3,520 trials, we excluded 33 trials for the younger group and 36 trials for the older group as they were either below 1% or above the 99% of the RT distribution. Regarding accuracy, we only found a significant main effect of Congruency, with less accurate performance in incongruent than congruent trials [$F(1,46) = 1628.05$; $p < 0.0001$]; and on the response time, we found significant main effects of Group, with older adults being slower than

younger adults [$F(1,46) = 26.6$; $p < 0.0001$], and Congruency, with incongruent trials responded to slower than congruent trials [$F(1,46) = 14.74$; $p < 0.0001$]. We did not find a significant interaction between Congruency and Group. These results are in line with what observed in Experiment 1.

 INSERT FIGURE 4 AND TABLE 4 HERE

Visual search analysis

Response Accuracy: On response accuracy (Figure 4, upper panel), we found significant main effects of Group, with younger participants being more accurate than older participants, and of Prime, whereby incongruently primed trials were performed more accurately than neutral trials. We also observed a significant three-way interaction between Prime, Object and Group, whereby older adults were less accurate on detecting inconsistent objects when primed with neutral information, as opposed to incongruently primed (refer to Table 4 for the model output).

Time to first fixation and total fixation time on the object: On time to first fixation to the target object (Figure 4, middle panel), we found a main effect of Object, whereby inconsistent objects were looked at faster than consistent objects, especially when primed with incongruent as opposed to neutral information (interaction Prime and Object). When looking at the total fixation time on the object (Figure 4, lower panel), we only observed a significant two-way interaction between Prime and Object, whereby inconsistent

objects were looked at for longer than consistent objects when the participants were primed with a neutral prime as compared to a congruent prime.

Discussion

In this follow-up experiment, we tested the effect of conceptual cueing on the pre-activation of contextual information during the visual search. The experimental design also included the priming of information that did not carry any high-level information, i.e., a scrambled mask of a word, defined as ‘neutral’ priming.

We found that older people were less accurate at detecting the target object than younger people. Moreover, the neutral priming hampered the detection of the target more than the incongruent priming condition. This effect was particularly prominent in the older adults, and especially for inconsistent objects. Inconsistent objects were looked at earlier than consistent objects, mainly when the priming was incongruent (relative to neutral). They were also looked at for longer time when the priming was neutral as opposed to congruent priming.

The finding that stands out in this follow-up experiment is the disrupting effect due to the neutral priming condition. As said above, we operationalised the neutral prime condition as a scrambled visual mask of a possible context word. We speculate that such a cue, carrying no task-relevant information, acted as a perceptual distractor, likely increasing the attentional load on participants, especially for older participants (e.g., Lustig, Hasher, & Tonev, 2006). This increased load must be successfully dealt with for a target to be correctly identified especially when such a target is unexpected within the scene context.

This result may also be read in parallel with what seen with the congruent visual priming of Experiment 1. A congruent scene prime created a high-level conceptual

overlap with the search scene, but it also triggered a low-level perceptual distraction due to differences in the spatial layout of such scenes that had to be resolved. A neutral word prime also created a low-level perceptual distraction, as compared to an incongruent prime, that had to be resolved. Thus, this result seems to indicate that the increased difficulty of older adults may not only relate to the inhibition of irrelevant conceptual information, but also to the inhibition of irrelevant perceptual information.

The results reported so far show that cognitive ageing mediates the access and use of contextual information as well as the attentional strategies adopted by younger and older adults to accomplish the search task. As amply reviewed, most literature on ageing supports the idea that cognitive control is directly involved in top-down mechanisms (e.g., Gazzaley & D'Esposito, 2007), in which contextual information plays a prominent role (Gilbert & Li, 2013). However, theoretical claims about cognitive control are often made by looking at group analysis of the responses from a single task. In order to assess more precisely the role played by cognitive control we need to investigate how and to what extent the responses of our participants on the search task correlate with their responses on tasks known to tap into cognitive control (e.g., the Stroop and Flanker). Additionally, in order to allow for more certain claims about the influence of prime type (scene vs word) on visual search performance, we must draw a direct comparison between the two.

Effects of cognitive control and prime information type on the visual search

We pooled together the data from Experiment 1 and Experiment 2 to examine how visual search performance relates to cognitive control, type of primed information, and may vary as a result of cognitive ageing. We excluded the neutral priming condition from this analysis as the two datasets can only be compared on the same levels of

1 congruency, i.e., Congruent and Incongruent prime. Then, we computed by-participant
 2 aggregated measures on the visual search task and the Stroop and Flanker tasks. For the
 3 visual search task, we aggregated each of the three dependent variables (DV) discussed
 4 above (i.e., response accuracy, time to first fixation and total time of fixation, z-scored).
 5 We took the mean on each of the four experimental conditions (crossing Object,
 6 Consistent vs Inconsistent and Prime, Congruent vs Incongruent) for each participant
 7 (i.e., 404 data points: 101 participants; 53 from Experiment 1 and 48 from Experiment 2
 8 * 4 conditions). For the Stroop and Flanker tasks, instead, we used Principal Component
 9 Analysis (PCA) to obtain a unique independent variable of the cognitive control of each
 10 participant. As Friedman & Miyake (2004) highlighted, inhibition-related processes may
 11 be more than a single unitary construct, and different cognitive control tasks may tap into
 12 different aspects of response inhibition. Moreover, responses collected in any such tasks
 13 never reflect pure inhibition as they involve other cognitive processes (i.e., task
 14 impurity). In this study, we were not interested in discriminating among the different
 15 types of inhibition, but rather on using a robust measure of the overall cognitive control
 16 capacity of each participant that in turn could be used as a predictor of search
 17 performance. For this reason, we applied PCA to the two DVs of accuracy and response
 18 times (on correct trials only) of the Stroop and Flanker tasks described above. This lead
 19 to inputting 8 variables in the PCA: 2 DVs * 2 tasks * 2 types of the trial (i.e., Congruent
 20 and Incongruent). We ran the PCA independently for each age group. This assured that
 21 the first component of the PCA could not just reflect baseline differences between
 22 younger and older adults (e.g., overall slower responses in the older adults), because the
 23 groups were kept separate, and hence the PCA should genuinely index the cognitive
 24 control of each participant within his/her age group.

Moreover, by applying PCA over the two tasks (Stroop and Flanker), we also partly countered the problem of task impurity, as our aggregated measure of cognitive control was estimated out of the participant performance in two different tasks (see Appendix B for more details on the PCA decomposition). Statistical inference was then obtained using linear mixed-effects modelling with the same approach described above. The only difference was the addition of prime Type (Word = -.5, Scene = .5) as fixed effect predictor in the model, and that we only had Participants (101 levels) as the random effect, nested into their respective age Group.

INSERT FIGURE 5 AND TABLE 5 HERE

Response Accuracy: On response accuracy (Figure 5, upper panel), we found significant main effects of Group, with younger participants being more accurate than older participants, and of Cognitive Control, whereby the participants that better performed at the Stroop and Flanker were also better at detecting the target object in the search task (refer to Table 5 for the model output). We observe that older participants had greater difficulty than younger participants when they had to find an inconsistent target object and were primed with congruent information (three-way interaction between Prime, Object and Group). However, older participants with better cognitive control, were also better at detecting inconsistent targets when primed with a congruent scene (four-way interaction).

Time to first fixation and total fixation time on the object: On time to the first fixation to the target object (Figure 5, middle panel), we confirm the main effect of Object,

whereby inconsistent objects were looked at faster than consistent objects. Especially when the participants received an incongruent prime, and it was a scene (refer to Table 5 for the model output). As for the total fixation time on the object (Figure 5, lower panel), we found that an inconsistent object is looked at for longer, especially by older participants and when the information primed was a visual scene (two and three-way interactions). Moreover, older participants looked at the target object for longer when it was inconsistent; they had been primed with congruent information, and the information of the prime was a scene. We have not found any significant effect of cognitive control on eye-movement responses.

Discussion

Regarding the relationship between cognitive control, prime type and ageing in visual search, we corroborate most results observed in the separate analysis of the experiments but also obtained novel insights. We confirmed that younger participants displayed a better performance than older participants on the search task, but now we also found that, regardless of the age group, a better cognitive control helped participants to be more accurate in their search. We also replicated that older adults had greater difficulty in suppressing congruent information when the object to be found was inconsistent with the context, mainly when the priming information was a scene. To this result, we added that a better cognitive control helped the performance of older adults in this condition.

On the eye-movement measures, we confirmed that older adults had greater difficulty in locating an inconsistent object when primed with congruent information, mainly if the prime was a scene. Once the inconsistent object was found, they also spent significantly more time than younger adults attending at it. However, we found no involvement of cognitive control on the attentional responses of either the younger or the

1 older group. The results from the response accuracy lend support to the idea that older
2 adults do have greater difficulty in suppressing irrelevant information than younger
3 adults, and that cognitive control is involved in the resolution of such conflicts. This
4 difficulty increases when the prime is a scene, as the conflict is not only conceptual but
5 also perceptual and the spatial layout of objects must also be reassessed when the visual
6 search begins. However, despite having found ample evidence that such difficulty also
7 resonates in the eye-movement responses, we could not relate this finding to cognitive
8 control as externally measured by the Stroop and Flanker tasks. This suggests that classic
9 tasks indexing cognitive control may not reflect all types of inhibitory mechanisms and
10 that additional top-down cognitive mechanisms may be at work during the overt
11 allocation of attention during unconstrained exploration of naturalistic scene information.

13 **General Discussion**

14 Research on healthy ageing has shown that, beyond a general slowing of
15 cognitive processing (e.g., Salthouse, 2012), older adults become over-reliant on top-
16 down information (e.g., Gazzaley & D'Esposito, 2007; Lindenberger & Mayr, 2014); and
17 experience difficulties in suppressing it when irrelevant to the task at hand (e.g., Lustig &
18 Jantz, 2015; Zanto & Gazzaley, 2014).

19 Visual search tasks require an active inhibition of the features of distractor objects
20 to locate the target efficiently. The inhibition of irrelevant information is a costly
21 cognitive operation, which for older adults may be even more challenging due to their
22 reduced cognitive control (e.g., Lustig et al., 2006, Zanto & Gazzaley, 2014,
23 Schwarzkopp et al., 2016).

24 Most ageing research on visual search has focused on object arrays (e.g., Potter et
25 al., 2012) rather than more naturalistic scenes (but see Neider & Kramer, 2011).

Moreover, little attention was usually paid to the relationship between top-down contextual information, which is key to scene understanding (e.g., Torralba, Oliva, Castelhana, & Henderson, 2006) and cognitive control mechanisms, which are fundamental to selective attention (e.g., Lavie, Hirst, De Fockert, & Viding, 2004), especially in the context of cognitive ageing.

In order to better examine this relationship, in this study, we proposed that top-down contextual information can be pre-activated before a search task to bias the participants towards expectations (conceptual and perceptual) that may support (or hinder) the search for the target. When these expectations are such that they could hinder the search, they have to be suppressed to maximise its efficiency. As said, the inhibition of irrelevant information is a cognitive control operation that is assumed to be impaired in older adults, and hence they would experience more difficulties in detecting a target violating contextual expectations that are irrelevant, or even misleading, to the search. Moreover, if cognitive control is genuinely involved in the visual search, we could measure it using classic tasks, such as Stroop and Flanker, and correlate it with the measures of performance observed in the search task.

We tested these hypotheses on two different groups of younger and older adults who performed a visual search task after being primed with contextual information (a scene or a word) that was either congruent, incongruent or neutral (only in Experiment 2) for the context of the search scene. The semantic relationship between the target object and the search scene was also manipulated so that it was either consistent or inconsistent with it. We also correlated the search performance of our participants with their performance on the Stroop and Flanker tests as represented using Principal Component Analysis, while comparing the effect of prime types (i.e., scenes vs words).

When the prime was a scene (Experiment 1), older adults were slower and less accurate than younger adults at identifying objects that were inconsistent with the search scene (e.g., a clothes iron in a restaurant). Critically, this detrimental effect on target detection was more prominent when the context of the scene was pre-activated through cueing (e.g., the exposure to a prime restaurant scene before searching in a different scene of a restaurant). This pre-activated congruent context reinforced expectations regarding the presence of consistent, rather than inconsistent, objects (conceptual overlap), as well as boosted expectations for a specific spatial layout of the objects building the scene. In other words, by visually priming a congruent context, we increased the expectation for consistent objects, thereby making an inconsistent object more likely to be considered as a distractor and hence ignored, while the spatial layout of the objects between the prime and the search scene had also to be re-assessed. Arguably, this process of attentional re-orienting due to conflicting information is detrimental to perceptual identification (e.g., Vallesi et al., 2009). Younger adults were better able to suppress the violation of such expectations and maintain an efficient search in this condition. Older adults instead were lesser able to do so, due to their reduced cognitive control ability.

When participants were primed with simple conceptual information via words rather than picture cues, the older group still performed best when searching for inconsistent objects after being incongruently primed, although this time, the critical comparison was between incongruent and neutral priming. It is possible that both the congruent condition for the visual primes and the neutral word conditions tax participants' cognitive control mechanisms in similar ways: they both involve the suppression of distracting perceptual information. In Experiment 1, the distracting information was the different spatial layout for contextually congruent scenes (i.e., they mostly share the same objects but were placed differently). In Experiment 2, the distracting information was

1 instead the scrambled word prime which increased the attentional load to retain
2 information about the target identity and hence acted as a perceptual distractor. More
3 research on the effect of perceptual distractors during scene viewing in contextual cueing
4 paradigms is needed. In particular, the spatial dependency of objects in the scene is a
5 crucial factor when attention is allocated during scene understanding (e.g., Brockmole &
6 Henderson, 2006; Wu, Wang, & Pomplun, 2014). Therefore, it would be relevant in
7 future work to establish how a more systematic manipulation in the spatial configuration
8 of objects between the prime scene and the search scene, and not just their semantic
9 association, would modulate object recognition and identification.

10 In both experiments, we observed that greater cognitive control was linked to
11 higher accuracies in trials with inconsistent objects, both for visual and word primes, and
12 when the primes were congruent or neutral, respectively. Proactive control has been
13 proposed as a mechanism that acts upon prior expectations. We posit that the difficulty
14 experienced by our older participants in inhibiting the irrelevant pre-activated contextual
15 information may be due to compromised proactive control. In future studies, it would be
16 essential to examine whether changes in the proportion of congruent and incongruent
17 contextual priming (e.g., 75% vs 25%, and vice-versa) may provide a different impact on
18 target detection. We could expect that greater congruent priming may lead to a further
19 decrease in the detection of inconsistent targets.

20 When looking at eye-movement responses, we found that inconsistent objects
21 were fixated earlier, especially when using a word prime that was incongruent, rather
22 than neutral. Older participants looked at the target objects for longer when congruently
23 primed with a scene, and when the target of the search was inconsistent with it. The more
24 effortful attentional processing of the older adults to detect the target object is in line with
25 previous literature (e.g., Williams et al., 2009). In fact, the violation of object-scene

information is known to be associated with more complex behavioural and neural processing because the inconsistency has to be resolved for the integration between object and scene information to happen (e.g., Coco, Araujo, & Petersson, 2017; Coco, Malcolm, & Keller, 2014; Mudrik, Lamy, & Deouell, 2010). Here, we contribute to this literature by showing an additional effort experienced by older participants in processing target objects that violate the context of the scene. Future research should better examine the mechanisms of object-scene integration in cognitive ageing by perhaps applying contextual cueing to other tasks where short-term memory is involved (e.g., change-detection). In such a task, we may expect that the recognition of a changed inconsistent object may be more difficult for older participants if the prime and search scene share the same context.

Although our data suggest that, at least for accuracy in the search task, a higher cognitive control improves visual search performance, we cannot explain the whole pattern of results only through this factor. Firstly, cognitive control capacity modulated the detection of the target also for the younger group, suggesting that this capacity plays a role regardless of age differences. Secondly, although we found group differences in the attentional patterns between older and younger adults, we did not find any effect of cognitive control on any of the eye-movement measures analysed. It could be possible that the Stroop and Flanker tasks point at a more general type of cognitive control that it is not fine-grained enough to explain age-related differences on overt-attention. Our study, therefore, highlights the importance of collecting more, and perhaps, more refined measures of cognitive control to better examine its multi-faceted role in tasks involving top-down processing, such as visual search.

In sum, in this study, we have shown that the pre-activation of top-down contextual information mediates the detection of a target object during visual search in

naturalistic scenes. This pre-activation yielded different outcomes for older and younger adults, and strongly varied with the semantic fit of such a target with the context, and the type of cueing administered. We have also shown potential links between cognitive control and search efficiency, although such a finding was restricted to the detection accuracy rather than to the overt allocation of attention of our younger and older groups.

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Appendix A: Norming the experimental material.

Experiment 1: The experimental material was normed in three phases. First, 10 undergraduate students (6 female, age = 21.5 ± 1.43) were asked to name 8 objects they would expect in each of the 7 indoor contexts chosen (i.e., Bathroom, Church, Kitchen, Bedroom, Office, Restaurant, Waiting Room). 198 unique objects were produced overall and the 8 most mentioned ones, for each context, were selected as consistent targets. The 8 inconsistent objects, instead, were chosen from a pool of objects never mentioned by any of the interviewees. Second, a new group of 20 students (12 female, age = 21.2 ± 1.23) was asked to rate the consistency of the objects within their respective contexts on a 6-point Likert scale (from *very unlikely* to *very likely*). We retained the 6 objects with the highest (consistent) and lowest (inconsistent) scores (e.g., Soap – Bathroom: mean = 5.9 ± 0.31 ; Flashlight – Bathroom: mean = 1.3 ± 0.67). Finally, a new group of 12 students (6 female, age = 22.5 ± 1.87) was asked to rate on a 6-point Likert scale: (a) the contextual congruency between the prime scene and the search scene, (b) the likelihood that each scene would be a representative example of its corresponding context, (c) the consistency of the target object with respect to the search scene and (d) the association between each target object and its referring word cue. We show that: (a) the difference between congruous and incongruous prime scenes is statistically significant ($M = 5.4$ vs 1.5 , $t(489) = 44$, $p < 0.001$); (b) both prime scenes and the search scenes are considered as typical examples of their context ($M = 5$ for both, $t(503) = 0.167$, $p = 0.87$); (c) consistent objects are rated as more likely to be in the search scene than inconsistent objects ($M = 5.1$ vs 1.7 , $t(470) = 28$, $p < 0.001$); and (d) the target objects are rated as highly identifiable by the word cue (mean = 5.3 ± 1.7).

Experiment 2: The additional 20 experimental scenes added in Experiment 2 to accommodate the effect size of the design for the additional Neutral priming condition have been taken from a

larger dataset of a recent study by Coco, Nuthmann and Della Sala, 2017. These photographs were created following exactly the same logic. Each scene contained a critical object that was either consistent or inconsistent with the context of the scene and the position of the object was counterbalanced left and right within the scene. Eight participants were asked to assess the consistency of the object and its linguistic denotation. Each participant saw the experimental scene and a box with a crop of the critical object along its side. He/she was asked to: (a) write down the name for the critical object shown, and (b) to respond to the question “How likely is it that this object would be found in this room?” using a six-point Likert scale (1-6). On the subset of 20 scenes used in this experiment we obtained a mean naming agreement of 96.8%. Furthermore, consistent objects were judged as significantly more likely (5.78 ± 0.57) to appear in the scene than inconsistent objects (1.88 ± 1.11), as confirmed with an independent-samples Kruskal-Wallis H test ($\chi^2(1) = 129.2$, $p < .001$).

Appendix B: Correlation and Principal Component Analysis for the cognitive control tasks.

Conceptually, Principal Component Analysis (PCA) is used to reduce the dimensionality of variables that are likely correlated, and hence can be “compressed” into a smaller dimensionality, i.e., fewer variables. In particular, PCA finds the directions where most of the variance of the data spread, with each component being one of these new dimensions (i.e., the axes). Figure 1B shows the correlation of the responses for the Flanker and the Stroop tasks, for the older and younger group separately (left side), as well as, the two components of the PCA computed on those (right side), for the two different experiments. We find that both in Experiment 1 and in Experiment 2 a substantial amount of the variance is already taken by the first component. In particular, the first component of the PCA explains 89% of the variance in the younger group and 70% in the older group for the participants of Experiment 1, and 86% of the variance for the younger group and 87% for the older group in Experiment 2. These results suggest that the first component of the PCA can be confidently used as a predictor for the cognitive control of each participant. Moreover, by running the PCA separately for the younger and the older group, we make sure that its first component is not just accounting for the baseline difference in reaction time and performance of the two groups, but genuinely capture differences in the cognitive control of each individual within his/her reference group.

Figure 1B: Correlation and Principal Component Analysis on cognitive control tasks; On the left, we show the Pearson correlation matrix for the 2 different measures of response accuracy and time, for the 2 conditions of stimulus Congruency (i.e., Congruent and Incongruent) for the 2 cognitive control task examined (i.e., Flanker and Stroop), separately by age group (Older, top; Younger; bottom). The colour palette indicates the strength of the correlation from blue (-1) to red (1). On the right, we show the results from the corresponding Principal Component Analysis as a bi-plot, each dot here represents an individual participant. Finally, the **A** panel shows the results of Experiment 1, whereas the **B** panel the results of Experiment 2.