1 Age-related differences during visual search: the role of contextual expectations and cognitive

2 control mechanisms†.

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1 **Age-related differences during visual search: the role of contextual**

2 **expectations and cognitive control mechanisms.**

3 During the visual search, cognitive control mechanisms activate to inhibit distracting information

4 and efficiently orient attention towards contextually relevant regions likely to contain the search

5 target. Cognitive ageing is known to hinder cognitive control mechanisms, however little is known

6 about their interplay with contextual expectations, and their role in visual search. In two eye-

7 tracking experiments, we compared the performance of a younger and an older group of participants

8 searching for a target object varying in semantic consistency with the search scene (e.g., a basket

9 of bread vs. a clothes iron in a restaurant scene) after being primed with contextual information

10 either congruent or incongruent with it (e.g., a restaurant vs. a bathroom). Primes were administered

11 either as scenes (Experiment 1) or words (Experiment 2, which included scrambled words as neutral

12 primes). Participants also completed two inhibition tasks (Stroop and Flanker) to assess their

13 cognitive control. Older adults had greater difficulty than younger adults when searching for

14 inconsistent objects, especially when primed with congruent information (Experiment 1), or a

15 scrambled word (neutral condition, Experiment 2). When the target object violates the semantics

16 of the search context, congruent expectations or perceptual distractors, have to be suppressed

17 through cognitive control, as they are irrelevant to the search. In fact, higher cognitive control,

18 especially in older participants, was associated with better target detection in these more

19 challenging conditions, although it did not influence eye-movement responses. These results shed

20 new light on the links between cognitive control, contextual expectations and visual attention in

21 healthy ageing.

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1 **Introduction**

2 Cognitive ageing has been linked to degraded performance in a variety of visual tasks such

3 as driving, face recognition, or searching for a target among distractors (Bédard et al., 2006;

4 Burton-Danner, Owsley, & Jackson, 2001; Foster, Behrmann, & Stuss, 1995; Hahn,

5 Carlson, Singer, & Gronlund, 2006; Potter, Grealy, Elliott, & Andres, 2012). Older adults

6 take longer to identify a target object (e.g., more saccades; Watson, Maylor, & Bruce,

7 2005), spend more time processing it (e.g., longer gaze duration; Williams, Zacks, &

8 Henderson, 2009), and display a worse performance than younger adults when asked to

9 remember or to search for a target embedded within other distractor objects (see Zanto &

10 Gazzaley, 2014 for a review).

11 Beyond a generalised slowing of cognitive processing (e.g., Salthouse, 1994, 2012), most

12 research on ageing points to cognitive control mechanisms to explain the difficulties often

13 experienced by healthy older adults (e.g., Gazzaley, Cooney, Rissman, & D'Esposito,

14 2005). In visual search, for example, irrelevant information within the visual context has

15 to be inhibited to orient attention towards the target object efficiently, and this operation

16 relies on cognitive control that can be impaired in older adults (e.g., Foster et al., 1995,

17 Schwarzkopp, Mayr, & Jost, 2016; but see Monge & Madden, 2016 for an alternative

18 explanation based on perceptual degradation). Braver, Gray, and Burgess (2007) suggest a

19 dual account of cognitive control mechanisms by distinguishing between proactive and

20 reactive control. Proactive control refers to a slow and effortful mechanism that acts

21 globally to mitigate interference before perceptual processing, which is mostly affected by

22 ageing (e.g., Mayr, 2001). Reactive control is instead a fast and automatic mechanism that

23 acts contingent on stimulus onset, and seems spared by ageing (e.g., Bugg, 2014).

1   The interplay between proactive control and access to contextual information during the

2   visual search has been examined, mostly in young adults, by using contextual cueing

3   paradigms (e.g., Chun, 2000). Chun and Jiang (1998) found that young observers were

4   faster in searching a target letter T among Ls distractors when previously and repeatedly

5   exposed to a specific spatial layout of the letters; and older adults seem to equally benefit

6   by this pre-activation (e.g. Howard, Dennis, Howard, Yankovich, & Vaidya, 2004;

7   Madden, Whiting, Cabeza, & Huettel, 2004; Whiting, Madden, Pierce, & Allen, 2005; but

8   see Smyth & Shanks, 2011, for impaired learning of contextual information in older adults).

9   Other studies on young adults have extended the findings of contextual cueing in visual

10   search from arrays of visual objects to photo-realistic scenes, and largely corroborated the

11   evidence that the pre-activation of a scene facilitates search (e.g., Hollingworth, 2007).

12   However, they are facilitated only when the cue scene and the search scene vary in the local

13   context surrounding the target but not when they instead vary in the global context (e.g.,

14   Brockmole, Castelhano, & Henderson, 2006; Chun, 2000; Hollingworth, 2009). When the

15   scenes have different spatial layouts despite being conceptually related (e.g., two different

16   libraries) or if the cue scene and the search scene differ in low-level features, such as colour,

17   there is also no benefit (e.g., Goujon, Brockmole, & Ehinger, 2012).

18   Realistic scenes provide rich contextual information (e.g, a restaurant) that combined with

19   the information about the search target (e.g., a basket of bread) is used by the cognitive

20   system to guide overt attention to locations (e.g., a table) that are more likely to contain it

21   (e.g., Bar, 2004; Eckstein, Drescher, & Shimozaki, 2006; Madden, 2007; Neider &

22   Zelinsky, 2006). When the contextual relation between the scene and the objects is

23   disrupted, such as a restaurant scene with a clothes iron in it, then this inconsistent object

24   may be prioritized, e.g., attract earlier fixations compared to a consistent object (e.g., Belke,

1 Humphreys, Watson, Derrick, Meyer, & Telling, 2008; LaPointe & Milliken, 2016; Loftus

2 & Mackworth, 1978; Underwood, Humphreys, & Cross, 2007); and once identified, it will

3 require a more effortful processing (e.g., longer fixation duration, Cornelissen & Võ, 2017;

4 Henderson, Weeks, Phillip a., & Hollingworth, 1999; Võ & Henderson, 2011; but see Wu,

5 Wick, & Pomplun, 2014 for a review of open controversies in the literature).

6 Very little research in cognitive ageing has looked at possible differences in visual search

7 strategies between younger and older adults associated with contextually richer visual

8 contexts. One exception is the study by Neider and Kramer (2011), who found that older

9 adults relied more than younger adults on the spatial associations between the context of a

10 pseudo-realistic scene and the target of the search (e.g., searching for a jeep on the ground)

11 to guide their overt attention. Older adults may, in fact, over-rely on contextual information

12 to compensate for the age-related decline in cognitive processing (e.g., Lindenberger &

13 Mayr, 2014; Madden, 2007). Note, however, that Neider and Kramer (2011) did not

14 explicitly manipulate contextual expectations using cueing, nor examined their interplay

15 with explicit measures of cognitive control.

16 The current visual search eye-tracking study employs a contextual cueing paradigm to

17 precisely investigate how the pre-activation of contextual information may differently

18 modulate the identification of a target object embedded in (and consistent or inconsistent

19 with) a naturalistic scene in older and younger adults. Our main aim is to investigate the

20 inhibitory cognitive control strategies adopted by the two age groups to cope with irrelevant

21 information promoted by the type of priming and the semantics of the target object. Our

22 main goal is to seek for direct evidence for (or against) the role of cognitive control in

23 visual search while highlighting possible age-related differences.

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2   INSERT FIGURE 1 HERE

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5 **The present study**

6 We report two eye-tracking visual search experiments in which participants (an older and

7 a younger group) are initially prompted with a target cue word and then briefly primed with

8 contextual information, either a visual scene (e.g., a picture of a restaurant, Experiment 1)

9 or a category word (e.g., the word "restaurant", Experiment 2). Then, they are presented

10 with a search scene where they have to find the target object, which can be either consistent

11 or inconsistent with it (e.g., a bread basket versus an iron); see Figures 1 and 2 for the

12 experimental design and an example of a trial. The primed information can be either

13 congruent or incongruent with the search scene (or also neutral, but only in Experiment 2).

14 In a trial of Experiment 1, for example, a participant may be exposed to a restaurant scene,

15 and then have to search for a clothes iron in a different restaurant scene that is visually

16 distinct (i.e., it is not the same scene, and they differ in low-level visual features). In this

17 example, the experimental condition has a prime scene conveying contextually congruent

18 information and a target object that is inconsistent with the search scene. The same

19 structure applies to Experiment 2, in which we replace prime scenes with prime words

20 conveying contextual information, and add a 'neutral' priming condition operationalised

21 as a scrambled word, carrying no lexical meaning.

22 We compare the performance of a younger and a healthy older group on three critical

23 measures of the search task: (a) response accuracy, which is the proportion of correctly

1 detected target objects; and on correct trials only (b) the time to first fixation, which is the

2 time it takes for a participant to look at the target object for the first time from scene onset,

3 and points at the speed of target identification; and (c) the total fixation time, which is the

4 sum of all fixations allocated to the target object, and points at the processing effort

5 required to correctly recognize the target of the search. Each group is assessed on general

6 cognitive abilities using the Montreal Cognitive Assessment Test (MoCA; Portuguese

7 Version normed by Freitas, Simões, Alves, & Santana, 2011). This step is necessary to

8 screen older participants for potential cognitive impairment resulting from

9 neurodegenerative disease. In the analysis, we use linear-mixed effect modelling to capture

10 the variability in baseline performance across our participants better, and z-score all time-

11 related variable to account for general-slowing of the older group (see Method for more

12 details). Furthermore, we test both younger and older participants on two classic tests of

13 executive control, the Stroop and the Flanker tasks (see Rey-Mermet & Gade, 2017 for a

14 recent review). A summary measure of the participants' performance on these two tasks,

15 obtained using Principal Component Analysis, is then correlated with the measures of

16 visual search discussed above. We do so to obtain direct evidence for, or against,

17 interdependent mechanisms such as lower cognitive control leading to worsening accuracy

18 in the visual search task. This analysis represents an essential addition to previous research

19 on ageing, which has often argued about impairment of cognitive control mechanisms in

20 older adults without seeking for cross-validation across tasks. In this final analysis, we use

21 the data from both Experiment 1 and Experiment 2 to obtain a greater statistical power (i.e.,

22 more participants) as well as to compare the influence of the two types of contextual

23 priming (scenes vs words) on visual search performance.

1   *Our predictions*

2   In both experiments, we expect participants to be faster at identifying the target object when

3   it is inconsistent with the search scene. This prediction stems from previous findings which

4   revealed that as the semantic information of objects may be processed in extra-foveal

5   vision, inconsistent objects that violate the contextual fit of the scene attract attention

6   earlier than consistent objects (e.g., LaPointe & Milliken, 2016; Loftus & Mackworth,

7   1978). Going beyond this literature, if older participants rely more on contextual

8   expectations, then we expect them to find it more difficult to detect inconsistent objects

9   than consistent objects, as they violate the contextual expectations of the scene by

10   definition. Furthermore, we expect this difficulty to increase when the context is boosted

11   through priming. Critically, if the poorer performance in visual search also stems from the

12   inability of older adults to suppress irrelevant information (Lustig & Jantz, 2015; Zanto &

13   Gazzaley, 2014), those older adults with better cognitive control should be better able to

14   act upon irrelevant information, and consequently be more accurate.

15   In terms of eye-movement responses, one may intuitively expect that searching for an

16   object in a restaurant scene after being primed with another restaurant scene should be

17   facilitated relative to searching after being primed with an unrelated scene such as a pool

18   hall. However, the two restaurant scenes crucially differ in the spatial layout of objects,

19   which is acquired very quickly (e.g., Henderson & Ferreira, 2004), as well as in low-level

20   visual features. Thus, the participants may find it actually harder to disengage from specific

21   spatially-guided expectations created when primed with the same category (e.g., restaurant)

22   than to supress the irrelevant information of a conceptually unrelated scene (e.g., pool hall).

23   This hypothesis would be consistent with studies showing that visual search is not

24   facilitated when the cue scene and the search scene differ in spatial layout (e.g., Brockmole

1 et al. 2006), and that (visually) conflicting stimuli disrupt perceptual identification more

2 than irrelevant stimuli (e.g., Vallesi, Stuss, McIntosh, & Picton, 2009). Therefore, we

3 expect older participants to require a more extended allocation of overt attention than

4 younger participants to correctly identify the target object when it is inconsistent with the

5 scene, or when primed with congruent information, as they have a reduced capacity to

6 resolve conflicting information.

7 The above logic may apply as well to prime words, with the critical comparison now being

8 between neutral and incongruent (or congruent) priming. The neutral priming condition, a

9 scrambled mask of a context word (i.e., carrying no lexical meaning), is a perceptual

10 distractor which may likely interfere with the retention of the target identity to a greater

11 degree than both congruent or incongruent prime words that can instead be processed and

12 ignored if irrelevant. We thus expect participants to display a reduced detection

13 performance when the prime is neutral, especially when the target object is inconsistent

14 with the scene context. In line with our predictions of Experiment 1, older adults may find

15 this condition particularly hard due to their reduced capacity to suppress irrelevant

16 information stemming from the perceptually disruptive nature of the neutral prime, which

17 is a scrambled word that can disrupt their retention of the target object cue, and the semantic

18 inconsistency of the object.

1   **Experiment 1**

2   *Methods*

3   *Participants*

4   We recruited 53 native speakers of Portuguese in two groups: a younger group of 32

5   undergraduate students (28 F; Age = 21.4 ± 5.71) and an older group of 21 participants (17

6   F, Age = 67.4 ± 4.97) from Universities of the Third Age with no reported history of

7   neuropsychological deficits. All participants had normal or corrected-to-normal vision. The

8   younger participants were awarded course credits, and the older participants were paid 15

9   euros for taking part in the experiment. This study was approved by the Ethics Committee

10   of the Department of Psychology, University of Lisbon, before data collection.

11   *Design, stimuli and procedure*

12   In a 2x2x2 experimental design, we crossed the congruency between the Prime scene and

13   the search scene (Congruent, Incongruent) with the semantics of the target Object with

14   respect to the search scene (Consistent, Inconsistent) within-participant, and had a Group

15   condition (Younger, Older) between-participants (see Figure 1 for a visualisation of the

16   design).

17   We used 42 experimental scenes, 42 filler scenes and 84 prime scenes, all naturalistic

18   images, i.e., photographs. Four different versions of each experimental scene were created,

19   with the two types of Object consistency (consistent, inconsistent) counterbalanced in two

20   locations (left, right) within the scene to avoid the development of systematic search

21   strategies. We, therefore, had a total of 168 unique items, divided into four lists following

22   a Latin-Square design. Prime and filler scenes were selected from open-access databases

1   (e.g., Flickr's "The Commons"). The prime scenes were selected according to their

2   contextual congruency with respect to the experimental scenes while ensuring that they

3   would never contain the target object (refer to Appendix A for the norming of the material).

4   Visual stimuli were presented on a 19-inch LG Flatron L194ws LCD screen with a 60Hz

5   refresh rate, 55cm away from participants' eyes, subtending 29.3º of visual angle. Eye

6   movement data were recorded using an SMI IVIEW X HI-SPEED eye-tracker

7   (SensoMotoric Instruments, Teltow, Germany) at a sampling rate of 1,250Hz. Only the

8   participants' dominant eye (assessed using a parallax test) was tracked. Chin rest and

9   forehead support were used to stabilise the head position. A Logitech Cordless Rumblepad

10   2 controller was used to record the target detection responses. The experiment was

11   developed using Experiment Center 3.2.

12   --------------------------------

13   INSERT FIGURE 2 HERE

14   --------------------------------

15   Each trial started with a written cue (500ms) prompting the participant with the search

16   target. A fixation cross then appeared in the centre of the screen, displayed until it was

17   fixated for 1000ms, after which the prime scene was presented for 250ms followed by a

18   scrambled mask of the same scene for another 250ms. The mask was applied to reduce the

19   perceptual activation of the prime scene before the search scene (Enns & Lollo, 2000).

20   After the onset of the search scene, the participants had to state whether they did, or did

21   not, see the target object by pressing a response button on a cordless joypad (see Figure 2

22   for an example trial).

1   The target object was always present in the experimental trials and always absent in the

2   filler trials. This distribution guarantees a balanced 50-50 distribution of yes/no responses.

3   At the beginning of each experimental session, participants completed four practice trials

4   to familiarise with the task. A 15-point calibration procedure was performed at the

5   beginning of the experiment and repeated every 10 trials (on 8-points) to ensure accurate

6   tracking. The calibration was accepted when the deviation error was below $0.8º$ and $1.2º$

7   degrees of visual angle for the x and y-axis, respectively. On average, the younger group

8   displayed a $0.61º \pm 0.42º$ visual angle deviation error on the x-axis and $0.72º \pm 0.58º$ on the

9   y-axis while the older group displayed a $0.82º \pm 0.60º$ error on the x-axis and $1.12º \pm 0.79º$

10   on the y-axis.

11   At the end of the visual search task, each participant responded to the MoCA test (30 points

12   maximum score) and performed a computerised version of the Stroop (64 randomised

13   trials, 32 Congruent and 32 Incongruent) and Flanker (64 randomised trials, 32 Congruent

14   – 32 Incongruent) tasks, implemented using E-Prime (Psychology Software Tools,

15   Pittsburgh, PA). The eye-tracking session lasted for about 30 minutes, which together with

16   the cognitive control tasks and the MoCA totalled approximately to an hour of testing.

17   ***Analyses***

18   Raw gaze data were initially pre-processed into fixations and saccades using BeGaze 3.2

19   (SMI Instruments), and further analysed using R 3.4.4 (R Core Team, Vienna, Austria). Of

20   the 2,226 total trials (i.e., 42 scenes and 53 participants), we excluded 8 items (108 trials)

21   because participants could not correctly identify the target object above the 50% chance

22   level, and an additional 45 trials (by participant and experimental condition) because the

23   response times were 2.5 SDs above the mean. Of these 2,073 trials, we retained the 1,504

1   trials in which the target object was fixated. For these trials, we considered the response

2   accuracy to the visual search task, and on correct trials (i.e., 1,454) the eye-movement

3   measures for the two main stages of target detection: identification and processing. For the

4   identification stage, we computed the time to the first fixation of the target object from

5   scene onset. For the processing stage, we considered the total fixation time on the object,

6   which is the sum of all fixations on the target during the trial.

7   We used linear-mixed effects modelling (LME) as implemented by the `lme4 (vs 1.1-`

8   `18-1)` package in `R` to analyse our dependent measures (Bates, Mächler, Bolker, &

9   Walker, 2015). We adopted the LME approach as it allows the simultaneous modelling of

10   by-participant and by-item random effects. This approach is advantageous for two main

11   reasons. First, it captures the intrinsic variability of the random variables when estimating

12   the coefficients for the fixed effects, and hence it takes into account the individual

13   differences between, for example, the participants. Second, it avoids data aggregation, a

14   practice which leads to less precise estimates when correlations are unequal across repeated

15   measures and may yield biased estimates, especially with small samples (Muth et al.,

16   2016). The predictors used for the LME analysis, centred to reduce co-linearity, were:

17   Prime (Congruent = -.5, Incongruent = .5), Object (Consistent = -.5, Inconsistent = .5) and

18   Group (Older = -.6, Younger = .4), and our random effects were Participant (53; entered as

19   a between-participant variable, as participants are nested into their age group), and Scene

20   (42). In ageing research, a well-known phenomenon is that time-related responses of older

21   participants are consistently slower than those of the younger participants (e.g., Salthouse,

22   1994). It becomes, therefore, crucial to normalise them so that the general slowing does

23   not confound effects genuinely arising from the experimental conditions of interest. We

24   followed the approach proposed by Faust, Balota, Spieler, & Ferraro, 1999, whereby we z-

1   scored the time-dependent eye-movement measures of time to first fixation and total time

2   of fixation independently for each participant. Effectively, this strategy makes sure that the

3   mean response between the two age groups is approximately the same (i.e., no main effect

4   of Group), and that any true difference between the two groups should emerge as an

5   interaction between the Group variable and the experimental variable of interest (e.g.,

6   Prime in our study).

7   Here we present the response accuracy and the time-dependent attentional measures

8   already z-scored (but refer to the Supplementary Material S2 and S3 for plots of the same

9   measures without any transformation). We also considered the order of trials (accounting

10 for learning strategies) as a covariate and controlled for it by residualizing it against each

11 of the dependent variables (DVs) in a linear regression model (DV ~ Order, in R syntax),

12 and then taking the residuals obtained as the DVs for further analyses. This approach

13 ensures that the effects of our experimental predictors (Prime and Object) on each DV

14 analysed are cleaned from this incidental covariate. Our initial models had a full fixed-

15 effect structure (i.e., all main effects and interactions) with a maximal random-effect

16 structure (i.e., random variables are included both as intercepts and uncorrelated slopes;

17 Barr, Levy, Scheepers, & Tily, 2013). Then, in order to have models that were

18 parsimonious in the number of parameters (Matuschek, Kliegl, Vasishth, Baayen, & Bates,

19 2017), we reduced them utilising the step function of the R package lmerTest (vs 3.0-

20 1; Kuznetsova, Christensen, Bavay, & Brockhoff, 2014). This method performs a backward

21 selection of the model, both on the random and fixed effect structure, iteratively removing

22 terms that do not significantly improve the model fit (thresholds of $p < 0.1$ for random

23 effects and $p < 0.08$ for fixed effects to include marginally significant results). Table 1

24 reports the coefficients, standard errors, and t-values only for those predictors that were

1   significant after model selection. We derived p-values for the fixed effects in the LME

2   models from F-tests based on Satterthwaite approximation of the effective degrees of

3   freedom. We also report the standardised βs, i.e., coefficients that have been normalised to

4   be directly comparable

5   ***Results***

6   Results are organised into two sections: (a) "General cognitive abilities and cognitive

7   control", in which we compare the performance of the two groups on the MoCA and the

8   Stroop and Flanker tasks, and (b) "Visual search analysis", in which we compare the two

9   groups on the visual search task.

10   --------------------------------

11   INSERT TABLE 1 HERE

12   --------------------------------

13   *General cognitive abilities*

14   We assessed the general cognitive ability of the younger and the older participants with the

15   MoCA, and their cognitive control mechanisms with the Stroop and Flanker tasks (see

16   Table 1 for mean and standard errors of these measures). On the MoCA, the older group

17   was significantly worse than the younger group (t [30.3] = -4.43, p < 0.001).

18   For the Stroop task, on a total of 3,520 trials, we excluded 41 trials for the younger group

19   and 73 trials for the older group because they were either below the 1st or above the 99th

20   percentile of the RT distribution for their age group. A mixed ANOVA analysis of the

1   accuracy revealed a significant main effect of Congruency, with less accurate performances

2   in incongruent than congruent trials [$F_{(1,51)}$= 4.6; $p = 0.03$], and a marginal interaction

3   between Group and Congruency, with older adults performing worse in incongruent trials

4   [$F_{(1,51)}$= 3.57; $p = 0.06$], and no main effect of Group. On the response time, we found

5   significant main effects of Group, with older adults being slower than young adults

6   [$F_{(1,51)}$= 111.38; $p < 0.0001$], and Congruency, with longer response times for

7   incongruent than congruent trials [$F_{(1,51)}$= 91.37; $p < 0.0001$]. We also found a significant

8   two-way interaction between Group and Congruency with older adults being slower than

9   younger adults in incongruent trials [$F_{(1,51)}$= 21.96; $p < 0.0001$].

10   For the Flanker task, on a total of 3,520 trials, we excluded 41 trials for the younger group

11   and 30 trials for the older group that were either below the 1st or above the 99th percentile

12   of the RT distribution. We only found a main effect of Congruency on the accuracy, with

13   less accurate performance in incongruent than congruent trials [$F_{(1,51)}$= 327.85; $p <$

14   0.0001]. For the response time, we found significant main effects of Group, with older

15   adults being slower than younger adults [$F_{(1,51)}$= 30.49; $p < 0.0001$]; and Congruency,

16   with incongruent trials responded slower than congruent trials [$F_{(1,51)}$= 6.4; $p = 0.01$]. We

17   did not find a significant interaction between Congruency and Group.

18   These results largely confirm previous literature by showing increased difficulty in

19   inhibiting incongruent information, especially by older participants. It must be noted,

20   however, that this age-related interaction manifested in the Stroop but not in the Flanker

21   task highlights a difference on the underlying inhibitory mechanisms they tap on (e.g.,

22   Spieler, Balota, & Faust, 1996).

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1   INSERT FIGURE 3 AND TABLE 2 HERE

2   -------------------------------

3 *Visual search analysis*

4 On response accuracy (Figure 3, upper panel), we found significant main effects of Prime,

5 with lower accuracy when the prime scene and the search scene were semantically

6 congruent, and Group, with younger participants being more accurate than older

7 participants (refer to Table 2 for the model output). We also observed significant two-way

8 interactions between Prime and Object, with lower accuracy for inconsistent objects in

9 congruently primed scenes; and between Object and Group, with older participants

10 committing more errors when the object was inconsistent with the scene, primarily when

11 the prime scene was semantically congruent with the search scene (three-way interaction

12 between Prime, Object and Group).

13 On time to the first fixation to the target object (Figure 3, middle panel), we only found a

14 main effect of Object, with inconsistent objects located faster than consistent objects. When

15 looking at the total fixation time on the object (Figure 3, lower panel), we found that

16 inconsistent objects were looked at for longer than consistent objects (main effect of

17 Object), especially by older participants (interaction Object, Group). Older participants

18 also looked at the target object for longer when the prime scene and the search scene were

19 contextually congruent (interaction Prime, Group).

20 **Discussion**

21 In Experiment 1, all participants had greater difficulty in correctly identifying the target

22 object when the prime scene and the search scene conveyed the same contextual

1   information (i.e., they were two restaurant scenes), and especially so when the target object

2   was inconsistent with such contextual information. We argue that congruent priming may

3   make target detection harder because: (a) the spatial layout of objects between the prime

4   scene and the search scene must be reassessed, which is consistent with Brockmole et al.

5   (2006) who observed no search benefit when scenes differed in global spatial layout; and

6   (b) the activation of distractor objects consistent with the search context is further increased

7   with respect to an inconsistent object, hence making it an even less likely target. In line

8   with this reasoning, older adults had greater difficulties than younger adults to find an

9   inconsistent object, especially when the prime scene and the search scene shared the same

10   contextual information. Such difficulty may be explained by their over-reliance on

11   contextual expectations, and by their reduced capacity to suppress it when these are

12   irrelevant. In fact, as we shall see later in the section "*Individual differences in cognitive*

13   *control and their impact on visual search*", older adults with better cognitive control were

14   also more capable of finding inconsistent targets.

15   Concerning the eye-movement data, we found that the older participants looked earlier and

16   for longer at inconsistent objects than at consistent objects. These results support the

17   finding that the semantics of objects are, at least partly, accessed in extra-foveal vision

18   (e.g., Belke et al., 2008; LaPointe & Milliken, 2016) and that the integration of object

19   information violating the scene context requires a more effortful processing (e.g.,

20   Henderson et al., 1999; Williams et al., 2009). In addition to bolstering previous literature,

21   we add that older participants display an even more effortful processing than younger

22   adults to integrate object-scene information when the object is inconsistent, or when primed

23   with a congruent scene. Arguably, this happens because they are required to resolve the

1 conflict generated by the two scenes having different spatial layouts while sharing the same

2 semantic context.

3 A visual scene is a cue that conveys not just conceptual, but also perceptual information

4 about the context. It remains to be understood whether, and to what extent, a purely

5 conceptual prime would impact on search performance. Moreover, it would be essential to

6 examine the case where participants are primed with information that acts as a purely

7 perceptual distractor, and it is hence "neutral" for both the scene context and the semantics

8 of the target object. In Experiment 2, we address these questions by using words instead of

9 scenes as the priming cue, and by including a neutral prime condition consisting of a

10 scrambled word that does not convey any conceptual meaning.

11 **Experiment 2**

12 *Methods*

13 *Participants*

14 We recruited two new groups of native speakers of Portuguese: a younger group of 24

15 undergraduate participants (15 F; Age = 24 ± 7.2) and an older group of 24 participants (16

16 F, Age = 66.6 ± 4) with no recorded history of neuropsychological deficits. All participants

17 had normal or corrected-to-normal vision. As in Experiment 1, the younger participants

18 were awarded course credits, and the older participants were paid 15 Euro for taking part

19 in the experiment.

1   *Design, stimuli and procedure*

2   The 2x2x3 design of Experiment 2 mostly followed that of Experiment 1. The only

3   difference was that instead of using scenes as Primes, we now used words as Primes (i.e.

4   the word "Restaurant" instead of the image of a restaurant), and included a neutral prime

5   (i.e., a scrambled word) along with the congruent and incongruent primes. The other

6   experimental conditions were the same as in Experiment 1 with a within-participant Object

7   variable (Consistent, Inconsistent) and a between-participant Group variable (Older,

8   Younger; see Figure 1 for the experimental design) crossed.

9   We used 62 experimental scenes and 62 filler scenes, all naturalistic images and used

10   written prime words. Additionally, we added a neutral prime condition, consisting of a

11   scrambled version of the incongruent or congruent word prime. Compared to Experiment

12   1, we added 20 experimental trials to account for the neutral prime condition, along with a

13   further 20 filler trials to preserve an equal number of target-present and target-absent trials.

14   The additional experimental and filler images belong to a database used by Coco,

15   Nuthmann, & Della Sala (2017), a study also investigating object consistency using

16   naturalistic images (refer to Appendix A for the norming of the material).

17   The procedure of Experiment 2 was identical to that of Experiment 1, except that the prime

18   was now a word. When the prime was neutral, and therefore already a scrambled word, we

19   showed a different shuffle of the same scrambled mask so that they would be visually

20   different (see Figure 2). Participants were instructed using the same protocol as for

21   Experiment 1, and we used the same eye-tracking calibration procedure and deviation

22   thresholds. On average, the younger group displayed a $0.34º \pm 0.17º$ visual angle deviation

23   error on the x-axis and $0.31º \pm 0.16º$ on the y-axis while the older group displayed a $0.48º$

1   ± 0.37º error on the x-axis and 0.36º ± 0.26º on the y-axis. Participants also undertook the

2   MoCA and the same computerised version of the Stroop and Flanker tasks.

3   *Analyses*

4   As in Experiment 1, raw gaze data were pre-processed into fixations and saccades using

5   BeGaze 3.7 and further analysed using R 3.4.4. Of the 2,976 total trials (i.e., 62 scenes and

6   48 participants), we excluded 9 items (120 trials) because participants could not correctly

7   identify the target object above the 50% chance level, and an additional 75 trials (by

8   participant and experimental condition) because the response times were 2.5 SDs above

9   the mean. Of these 2,781 trials, we retained the 2,419 trials in which the target object was

10 fixated. We considered the same dependent measures of Experiment 1: (a) response

11 accuracy to the visual search task and, on correct trials (i.e., 2,302), (b) the time to the first

12 fixation of the target object from scene onset, and (c) the total fixation time on the object.

13 We used the same modelling approach of Experiment 1 to analyse the data, and hence we

14 refer the reader to that section for the details. The only fundamental difference in the

15 analysis of Experiment 2 is that the Prime variable has now three levels instead of two, i.e.,

16 Congruent, Incongruent and Neutral. We have chosen Neutral as the reference level and

17 compared Congruent and Incongruent against it.

18

19

20   -------------------------------

21   INSERT TABLE 3 HERE

1   -------------------------------

2   ***Results***

3   *General cognitive abilities*

4   On the MoCA, the older group was significantly worse than the younger group (t [44.7] =

5   -2.23, p < 0.03; refer to Table 3 for a summary of the measures).

6   For the Stroop task, on a total of 3,520 trials, we excluded 34 trials for the younger group

7   and 67 trials for the older group as they were either below 1% or above 99% of the RT

8   distribution of their age group. A mixed ANOVA analysis of the accuracy revealed only a

9   significant main effect of Congruency, with less accurate performance in incongruent than

10   congruent trials [F(1,46)= 7.4; p = 0.01]. On the response time, we found significant main

11   effects of Group, with older adults being slower than younger adults [F(1,46)= 38.76; p <

12   0.0001], and Congruency, with longer response times for incongruent than congruent trials

13   [F(1,46)= 132.7; p < 0.0001]. We also found a significant two-way interaction between

14   Group and Congruency with older adults being slower than younger adults in incongruent

15   trials [F(1,46)= 4.12; p < 0.05].

16   For the Flanker task, on a total of 3,520 trials, we excluded 33 trials for the younger group

17   and 36 trials for the older group as they were either below 1% or above the 99% of the RT

18   distribution. Regarding accuracy, we only found a significant main effect of Congruency,

19   with less accurate performance in incongruent than congruent trials [F(1,46)= 1628.05; p

20   < 0.0001]. On the response time, we found significant main effects of Group, with older

21   adults being slower than younger adults [F(1,46)= 26.6; p < 0.0001], and Congruency, with

22   incongruent trials responded to slower than congruent trials [F(1,46) = 14.74; p < 0.0001].

1   We did not find a significant interaction between Congruency and Group. These results are

2   in line with Experiment 1.

3   -------------------------------

4   INSERT FIGURE 4 AND TABLE 4 HERE

5   -------------------------------

6   *Visual search analysis*

7   On response accuracy (Figure 4, upper panel), we found significant main effects of Group,

8   with younger participants being more accurate than older participants, and of Prime,

9   whereby incongruently primed trials were performed more accurately than neutral trials.

10   We also observed a significant three-way interaction between Prime, Object and Group,

11   whereby older adults were less accurate on detecting inconsistent objects when primed with

12   neutral information, as opposed to incongruently primed (refer to Table 4 for the model

13   output).

14   On time to the first fixation to the target object (Figure 4, middle panel), we found a main

15   effect of Object, whereby inconsistent objects were looked at faster than consistent objects,

16   especially when primed with incongruent, as opposed to neutral, information (a Prime and

17   Object interaction). When looking at the total fixation time on the object (Figure 4, lower

18   panel), we only observed a significant two-way interaction between Prime and Object,

19   whereby inconsistent objects were looked at for longer than consistent objects when

20   participants were primed with a neutral prime as compared to a congruent prime.

1   ***Discussion***

2   In this follow-up experiment, we tested the impact of conceptual cueing of contextual

3   information on the visual search. The experimental design also included primes carrying

4   no semantic information (i.e., a scrambled word mask), defined as 'neutral' primes.

5   The most prominent result of this follow-up experiment is the disrupting effect of the

6   neutral prime, which has led to a worse target detection performance compared to the

7   incongruent priming condition, especially in older adults searching for an inconsistent

8   target object. We speculate that a neutral cue increases the attentional load of the

9   participants to retain the identity of the target object in memory and hence acts as a

10   perceptual distractor (e.g., Lustig, Hasher, & Tonev, 2006). This increased load needs to

11   be dealt with for a target to be remembered and correctly identified; and this distractor

12   effect may be especially strong when the target is inconsistent with the scene context, and

13   is already less readily associated with it.

14   This result may also be read in parallel with those of Experiment 1 with the congruent

15   visual priming condition. A congruent scene prime created a high-level conceptual overlap

16   with the search scene, but it also triggered a low-level perceptual (visual) interference due

17   to differences in the spatial layout of the scenes. A neutral prime created a low-level

18   perceptual interference as well, but in this case on the identity of the target cued. Thus, this

19   result seems to indicate that the increased difficulty of older adults may not only relate to

20   the inhibition of irrelevant (conceptually conveyed) contextual information, but also the

21   inhibition of irrelevant (perceptual) non-contextual information. Regarding eye-

22   movements, we replicated Experiment 1 by showing that inconsistent objects are looked at

23   earlier than consistent objects, especially when the priming was incongruent (relative to

1 neutral), and for longer when the priming is neutral (relative to congruent). Both findings

2 seem to converge upon the idea that a neutral prime acts as a perceptual distractor and

3 hence it disrupts eye-movement responses of target identification (time to first fixation)

4 and processing (total fixation time).

5 **Individual differences in cognitive control and their impact on visual search**

6 The results reported so far show that cognitive ageing mediates the access and use of

7 contextual information. As amply reviewed, most literature on ageing supports the idea

8 that cognitive control is directly involved in top-down mechanisms (e.g., Gazzaley &

9 D'Esposito, 2007), and that contextual information plays a prominent role on such

10 mechanisms (Gilbert & Li, 2013). Often in this literature, cognitive control is discussed by

11 looking only at group responses from a single task. Here, we want to go one step further,

12 and explore how and to what extent participants' performance on two tasks known to tap

13 into cognitive control (i.e., the Stroop and the Flanker) correlate with their search

14 performance.

15 In order to do so, as a first step, we pool together the data from Experiment 1 and

16 Experiment 2[1] to have greater statistical power, as well as to compare directly the influence

17 of prime type (scene vs word) on search performance. We compute, for each participant,

18 aggregate (mean) measures of the three DVs of the search task (i.e., response accuracy, and

19 z-scored time to first fixation and total time of fixation) independently for each of the four

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[1] We exclude the neutral priming condition from this analysis as the two datasets can only be compared on the same levels of
congruency, i.e., Congruent and Incongruent prime. Additionally, in order to obtain more solid insights about the influence
of prime type (scene vs word) on visual search performance, we must directly compare the two.

1   experimental conditions (i.e., crossing Object: Consistent vs Inconsistent; and Prime:

2   Congruent vs Incongruent). Then, we aggregate the performance measures of response

3   accuracy and response time (on correct trials only) of the same participants on the Stroop

4   and Flanker executive control tasks for Congruent and Incongruent trials separately

5   yielding a total of 8 measures for each participant. From these 8 measures, we want to

6   obtain a single summary measure of cognitive control per each participant to correlate with

7   his/her search performance. However, as Friedman & Miyake (2004) highlight, inhibition-

8   related processes may be more than a single unitary construct, and different executive

9   cognitive control tasks may tap into different aspects of response inhibition. Moreover,

10 responses collected in any such tasks never reflect pure inhibition as they likely involve

11 other cognitive processes (i.e., task impurity). Therefore, we use Exploratory Factor

12 Analysis (EFA) to examine the loading of these 8 different measures into factors. Indeed,

13 we find that these 8 measures loaded into different factors. For example, the response times

14 to Congruent and Incongruent trials in the Stroop task load into a different factor than

15 response times to Congruent and Incongruent trials in the Flanker task. Nevertheless, when

16 we correlate the loading of these separate factors with the different search measures, we

17 obtain similar results (refer to Supplementary Material A and Table S1 for the results). In

18 a way, this result aligns well with Friedman and Miyake (2004), which indeed finds that

19 the Stroop and Flanker load into different factors, but they are nevertheless very strongly

20 related[2]. In the current study, we are not interested in discriminating among the different

21 types of inhibition, and have observed very similar results when factor loadings for the

22 Stroop and Flanker tasks are independently used as predictors of search performance. For

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[2] See Figure 2 (page 112 of Friedman and Miyake, 2004), which shows a .68 relation between response
inhibition and distractor inhibition.

1   this reason, we use Principal Component Analysis to compress the 8 measures of Stroop

2   and Flanker data obtained for each participant into a single measure of cognitive control[3].

3   By doing so, we also partly address potential issues of task impurity, as our aggregated

4   measure of cognitive control is estimated out of the participant performance in two

5   different tasks (see Appendix B for more details on the PCA decomposition). We run the

6   PCA independently for each age group. This approach assures that the first component of

7   the PCA should not just reflect simple baseline differences between younger and older

8   adults (e.g., overall slower responses in the older adults), as the groups were kept separate,

9   and hence should genuinely index the cognitive control of each participant within his/her

10 age group.

11 Statistical inference is then obtained using linear mixed-effects modelling with the same

12 approach described above. The only difference now is the addition of prime Type (Word =

13 -.5, Scene = .5) and the first component of the PCA[4], referred to as Cognitive Control (CC)

14 as fixed effect predictors in the model, and that we only had Participants (101 levels) as the

15 random effect, nested into their respective age Group.

16   -------------------------------

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[3]. Note, the results observed with Stroop and Flanker as separate EFA factors are equivalent to those

obtained by using the first component of the PCA (compare Table 5 and S1).

[4] An increase on the first component of the PCA implies more difficult processing. Therefore, for

interpretability, we reversed the sign of this predictor before entering it into the LME analysis, such

that increase on Cognitive Control would imply easier, rather than more difficult, performance on the

Stroop and Flanker tasks.

1   INSERT FIGURE 5 AND TABLE 5 HERE

2   -------------------------------

3   *Results and discussion*

4   On response accuracy, we found significant main effects of Group, with younger

5   participants being more accurate than older participants, and of Cognitive Control, whereby

6   participants with better performances in the Stroop and Flanker tasks were also better at

7   detecting the target object in the search task (refer to Table 5 for the model output). Older

8   participants found it harder than younger participants to find an inconsistent target object

9   when primed with congruent information (three-way interaction between Prime, Object

10   and Group), mainly confirming the results presented in the *Visual search analysis* of

11   Experiment 1 and Experiment 2. Additionally, we now find that older participants with

12   better cognitive control were also better at detecting inconsistent targets when primed with

13   a scene as opposed to with a word cue (four-way interaction, see Figure 5 for a visualisation

14   of these results).

15   On time to the first fixation, we confirm the main effect of Object, whereby inconsistent

16   objects were looked at faster than consistent objects. This effect was particularly strong

17   when the participants received an incongruent prime, and it was a scene rather than a word

18   (refer to Table 5 for the model output). As for the total fixation time on the object, we found

19   that an inconsistent object was looked at for longer by older participants, and especially

20   when the information primed was congruent and a visual scene (two, three and four-way

21   interactions). We have not found any significant effect of cognitive control on eye-

22   movement responses (the reader is referred to the Supplementary Material - Figure S4 for

23   a visualisation of these results).

1   In this pooled analysis, we replicate most of the results observed when Experiment 1 and

2   2 were analysed separately, but also obtained some novel insights. We confirm that

3   younger participants display a better performance than older participants on the search task,

4   but also find that, regardless of the age group, better a cognitive control helps participants

5   to be more accurate in the search. We also replicate that older adults had greater difficulty

6   in suppressing congruent information when the search target was inconsistent with the

7   context. In addition we find that older adults with better cognitive control are more accurate

8   at detecting inconsistent objects when cued with scenes as opposed to words. This result

9   indicates that older adults have greater difficulty in suppressing irrelevant information than

10   younger adults but that cognitive control may be implicated in filtering it out to optimize

11   search performance.

12   On the eye-movement measures, we confirm that older adults have greater difficulty in

13   locating an inconsistent object when primed with congruent information, mainly if the

14   primeis a scene. Once the inconsistent object is found, they also spend significantly more

15   time than younger adults attending at it. However, we could not explain these findings on

16   the eye-movement responses in terms of cognitive control, as measured using the Stroop

17   and Flanker tasks. Thus, this result indicates that classic tasks indexing cognitive control

18   may not reflect all types of inhibitory mechanisms and that additional top-down cognitive

19   mechanisms are at work when overt attention is allocated during naturalistic scene

20   understanding.

21   **General Discussion**

22   Research on healthy ageing has shown that, beyond a slowing of cognitive processing (e.g.,

23   Salthouse, 2012), older adults become over-reliant on contextual information (e.g.,

1 Gazzaley & D'Esposito, 2007; Lindenberger & Mayr, 2014) and experience difficulties in

2 suppressing it when irrelevant to the task at hand (e.g., Lustig & Jantz, 2015; Zanto &

3 Gazzaley, 2014). Visual search tasks require an active inhibition of distractor objects to

4 locate the target efficiently. The inhibition of irrelevant information is a costly cognitive

5 operation, which for older adults may be more challenging due to their reduced cognitive

6 control (e.g., Lustig et al., 2006, Schwarzkopp et al., 2016).

7 Most ageing research on visual search has focused on object arrays (e.g., Potter et al., 2012)

8 rather than more naturalistic scenes (but see Neider & Kramer, 2011). Moreover, little

9 attention was paid to the relationship between top-down contextual information, which is

10 key to scene understanding (e.g., Torralba, Oliva, Castelhano, & Henderson, 2006) and

11 cognitive control, which is fundamental to selective attention (e.g., Lavie, Hirst, De

12 Fockert, & Viding, 2004), especially in the context of cognitive ageing.

13 In order to better examine this relationship, we elicited the pre-activation of top-down

14 contextual information before a search task to bias the participants towards expectations

15 (conceptual and visual-perceptual) that may support (or hinder) the search for the target.

16 When these expectations can hinder visual search, they have to be suppressed to maximise

17 search efficiency. As said, the inhibition of irrelevant information is a cognitive control

18 operation that is assumed to be impaired in older adults, and hence we predicted they would

19 experience more difficulties in detecting a target violating contextual expectations that are

20 irrelevant, or misleading, to the search. Moreover, we explicitly measured cognitive control

21 using classic tasks, such as Stroop and Flanker, to assess its genuine role in the visual

22 search.

1   We tested these hypotheses on two different groups of younger and older adults who

2   performed a visual search task after being primed with contextual information (a scene or

3   a word) congruent, incongruent or neutral (only in Experiment 2) with the context of the

4   search scene. The semantic relationship between the target object and the search scene was

5   also manipulated so that the former was either consistent or inconsistent with the latter.

6   Additionally, we correlated the search performance of our participants with their

7   performance on the Stroop and Flanker tasks, together represented using PCA, while

8   comparing the effect of prime types (i.e., scenes vs words).

9   When the prime was a scene (Experiment 1), older adults were slower and less accurate

10   than younger adults at identifying objects that were inconsistent with the search scene (e.g.,

11   a clothes iron in a restaurant). Critically, this detrimental effect on target detection was

12   more prominent when the context of the scene was pre-activated (via, for example,

13   exposure to a prime restaurant scene before searching in a different restaurant scene). This

14   pre-activated congruent context reinforced expectations for the presence of consistent,

15   rather than inconsistent, objects (conceptual overlap), and boosted expectations for a

16   specific spatial layout of the objects building the scene. In other words, by visually priming

17   a congruent context, we increased the expectation for consistent objects, thereby making

18   an inconsistent object more likely to be considered a distractor and hence ignored, while

19   the spatial layout of the objects between the prime and the search scene had also to be re-

20   assessed. Arguably, this process of attentional re-orienting due to conflicting information

21   is detrimental to perceptual identification (e.g., Vallesi et al., 2009). Younger adults were

22   better able to suppress the violation of such expectations and maintain an efficient search

23   in this condition. Older adults instead were lesser able to do so, due to their reduced

24   cognitive control ability.

1 When participants were primed with simple conceptual information via words rather than

2 picture cues, the older group still performed worse when searching for inconsistent objects,

3 now after being neutrally, relative to incongruently primed. It is possible that both the

4 congruent condition for the visual primes and the neutral condition for word primes tax

5 participants' cognitive control mechanisms in similar ways: they both involve the

6 suppression of distracting perceptual information. In Experiment 1, the distracting

7 information was the different spatial layout for contextually congruent scenes (i.e., they

8 mostly share the same objects but these are placed differently). In Experiment 2, the

9 distracting information was instead the scrambled word prime that increased the attentional

10 load to retain information about the target identity and hence acted as a perceptual

11 distractor. More research on the effect of perceptual distractors during scene viewing in

12 contextual cueing paradigms is needed, however. In particular, the spatial dependency of

13 objects in the scene is a crucial factor when attention is allocated during scene

14 understanding (e.g., Brockmole & Henderson, 2006; Wu, Wang, & Pomplun, 2014).

15 Therefore, it would be relevant for future work to establish how a more systematic

16 manipulation of the spatial configuration of objects between the prime and the search scene

17 (and not just their semantic association) would modulate object recognition and

18 identification.

19 In both experiments, we observed that greater cognitive control was linked to higher

20 accuracies in trials with inconsistent objects, both for visual and word primes, and when

21 the primes were congruent or neutral, respectively. Proactive control has been proposed as

22 a mechanism that acts upon prior expectations. We posit that the difficulty experienced by

23 the older participants in inhibiting the irrelevant pre-activated contextual information may

24 be due to compromised proactive control. In future studies, it would be essential to examine

1 whether changes in the proportion of congruent and incongruent contextual priming (e.g.,

2 75% vs 25%, and vice-versa) may provide a different impact on target detection. We could

3 expect that greater congruent priming may lead to a further decrease in the detection of

4 inconsistent targets.

5 When looking at eye-movement responses, we found that inconsistent objects were fixated

6 earlier, especially when using a word prime that was incongruent, rather than neutral. Older

7 participants looked at the target objects for longer when congruently primed with a scene,

8 and when the target of the search was inconsistent with it. The violation of object-scene

9 information is known to be associated with more complex behavioural and neural

10 processing (e.g., Coco, Araujo, & Petersson, 2017; Coco, Malcolm, & Keller, 2014;

11 Mudrik, Lamy, & Deouell, 2010). We add to this literature that beside having a more

12 effortful attentional processing to detect a target (e.g., Williams et al., 2009), older

13 participants display additional efforts with target objects that violate the context of the

14 scene. Future research should better examine the mechanisms of object-scene integration

15 in cognitive ageing, perhaps by applying contextual cueing to other tasks where short-term

16 memory is involved (e.g., change-detection). In such a task, we may expect that the

17 recognition of a changed inconsistent object may be more difficult for older participants if

18 the prime and search scene share the same context.

19 Although our data suggest that, at least for accuracy in the search task, a higher cognitive

20 control improves visual search performance, we cannot explain the whole pattern of results

21 only through this factor. Firstly, cognitive control capacity modulated the detection of the

22 target also for the younger group, suggesting that this capacity plays a role regardless of

23 age differences. Secondly, although we found group differences in the attentional patterns

24 between older and younger adults, we did not find any effect of cognitive control on any

of the eye-movement measures analysed. One possibility is that Stroop and Flanker tasks better index response inhibition rather than distractor inhibition. The need to inhibit a detection response holds throughout the visual search process, and perhaps, that's the reason why we observed effects of cognitive control only on response accuracy, rather than on the eye-movement measures, which are more sensitive to distractor inhibition. The other possibility is that the inhibitory mechanisms underlying these two tasks do not directly relate to visual search, or perhaps, they are not fine-grained enough to capture age-related differences on the allocation of overt attention. Our study, therefore, highlights the importance of collecting other measures of cognitive control to examine better its multi-faceted role in tasks involving top-down processing, such as visual search.

In sum, we have shown that the pre-activation of 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 cueing administered. We have also shown preliminary 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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18 *Appendix A: Norming the experimental material.*

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20 **Experiment 1:** The experimental material was normed in three phases. First, 10 undergraduate

21 students (6 female, age = 21.5±1.43) were asked to name 8 objects they would expect in each of

22 the 7 indoor contexts chosen (i.e., Bathroom, Church, Kitchen, Bedroom, Office, Restaurant,

23 Waiting Room). 198 unique objects were produced overall and the 8 most mentioned ones, for

24 each context, were selected as consistent targets. The 8 inconsistent objects, instead, were chosen

25 from a pool of objects never mentioned by any of the interviewees. Second, a new group of 20

1   students (12 female, age = 21.2±1.23) was asked to rate the consistency of the objects within

2   their respective contexts on a 6-point Likert scale (from *very unlikely* to *very likely*). We retained

3   the 6 objects with the highest (consistent) and lowest (inconsistent) scores (e.g., Soap –

4   Bathroom: mean = 5.9±0.31; Flashlight – Bathroom: mean = 1.3±0.67). Finally, a new group of

5   12 students (6 female, age = 22.5±1.87) was asked to rate on a 6-point Likert scale: (a) the

6   contextual congruency between the prime scene and the search scene, (b) the likelihood that each

7   scene would be a representative example of its corresponding context, (c) the consistency of the

8   target object with respect to the search scene and (d) the association between each target object

9   and its referring word cue. We show that: (a) the difference between congruous and incongruous

10   prime scenes is statistically significant (M = 5.4 vs. 1.5, $t(489) = 44$, $p < 0.001$); (b) both prime

11   scenes and the search scenes are considered as typical examples of their context (M = 5 for both,

12   $t(503) = 0.167$, $p = 0.87$); (c) consistent objects are rated as more likely to be in the search scene

13   than inconsistent objects (M = 5.1 vs. 1.7, $t(470) = 28$, $p < 0.001$); and (d) the target objects are

14   rated as highly identifiable by the word cue (mean = 5.3±1.7).

15

16   **Experiment 2:** The additional 20 experimental scenes added in Experiment 2 to accommodate

17   the effect size of the design for the additional Neutral priming condition have been taken from a

18   larger dataset of a recent study by Coco, Nuthmann and Della Sala, 2017. These photographs

19   were created following the same logic. Each scene contained a critical object that was either

20   consistent or inconsistent with the context of the scene and the position of the object was

21   counterbalanced left and right within the scene. Eight participants were asked to assess the

22   consistency of the object and its linguistic denotation. Each participant saw the experimental

23   scene and a box with a crop of the critical object along its side. He/she was asked to (a) write

24   down the name for the critical object shown, and (b) to respond to the question "How likely is it

25   that this object would be found in this room?" using a six-point Likert scale (1-6). On the subset

1   of 20 scenes used in this experiment, we obtained a mean naming agreement of 96.8%.

2   Furthermore, consistent objects were judged as significantly more likely (5.78 ± 0.57) to appear

3   in the scene than inconsistent objects (1.88 ± 1.11), as confirmed with an independent-samples

4   Kruskal-Wallis H test ($\chi2(1) = 129.2$, $p < .001$).

5

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

2   Conceptually, Principal Component Analysis (PCA) is used to reduce the dimensionality of

3   variables that are likely correlated, and hence can be "compressed" into a smaller dimensionality,

4   i.e., fewer variables. In particular, PCA finds the directions where most of the variance of the

5   data spread, with each component being one of these new dimensions (i.e., the axes). Figure 1B

6   shows the correlation of the responses for the Flanker and the Stroop tasks, for the older and

7   younger group separately (left side), as well as, the two components of the PCA computed on

8   those (right side), for the two different experiments. We find that the first component already

9   takes both in Experiment 1 and in Experiment 2 a substantial amount of the variance. In

10 particular, the first component of the PCA explains 89% of the variance in the younger group

11 and 70% in the older group for the participants of Experiment 1, and 86% of the variance for the

12 younger group and 87% for the older group in Experiment 2. These results suggest that the first

13 component of the PCA can be confidently used as a predictor for the cognitive control of each

14 participant. Moreover, by running the PCA separately for the younger and the older group, we

15 make sure that its first component is not just accounting for the baseline difference in reaction

16 time and performance of the two groups, but genuinely capture individual differences in the

17 cognitive control within his/her reference age group.

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20   INSERT FIGURE 1B HERE

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