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ORIGINAL RESEARCH REPORT

Advanced Aging Enhances the Positivity Effect in Memory: Due to Cognitive Control or Age-Related Decline in Emotional Processing?

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Older adults typically remember more positive than negative information compared to their younger counterparts; a phenomenon referred to as the 'positivity effect.' According to the socioemotional selectivity theory (SST), the positivity effect derives from the age-related motivational shift towards attaining emotionally meaningful goals which become more important as the perception of future time becomes more limited. Cognitive control mechanisms are critical in achieving such goals and therefore SST predicts that the positivity effect is associated with preserved cognitive control mechanisms in older adults. In contrast, the aging-brain model suggests that the positivity effect is driven by an age-related decline in the amygdala which is responsible for emotional processing and emotional learning. The aim of the current research was to address whether the age-related positivity effect is associated with cognitive control or impaired emotional processing associated with aging. We included older old adults, younger old adults and younger adults and tested their memory for emotional stimuli, cognitive control and amygdala-dependent fear conditioned responses. Consistent with prior research, older adults, relative to younger adults, demonstrate better memory for positive over negative images. We further found that within a group of older adults, the positivity effect increases as a function of age, such that older old adults demonstrated a greater positivity effect compared to younger older adults. Furthermore, the positivity effect in older old adults was associated with preserved cognitive control, supporting the prediction of SST. Contrary to the prediction of the aging-brain model, participants across all groups demonstrated similar enhanced skin conductance responses to fear conditioned stimuli – responses known to rely on the amygdala. Our results support SST and suggest that the positivity effect in older adults is achieved by the preserved cognitive control mechanisms and is not a reflection of the impaired emotional function associated with age.

Keywords: Emotion and memory; Positivity effect; Aging; Fear conditioning; Emotion regulation; Stroop

Introduction

Older adults, compared with younger adults, tend to pay attention to and remember more positive than negative information (Charles, Mather, & Carstensen, 2003; Grühn, Scheibe, & Baltes, 2007; Isaacowitz, Wadlinger, Goren, & Wilson, 2006; Reed, Chan, & Mikels, 2014; Riediger, Schmiedek, Wagner, & Lindenberger, 2009). This age-by-valence interaction is called the 'positivity effect' and has been explained by motivational shifts in aging (Scheibe & Carstensen, 2010). According to the socioemotional selectivity theory (SST), as individuals age, they perceive time left in their life as being more limited. As a result, older adults, relative to younger adults, are more likely to prioritize emotion regulation goals over other goals. This motivational shift is thought to result in the positivity effect.

In line with SST, older adults' positivity effects do not emerge when they have limited cognitive resources to regulate their emotion (Mather & Knight, 2005; Petrican, Moscovitch, & Schimmack, 2008). Older adults' positivity effects are also weakened when their motivations are manipulated to focus on goals other than emotion regulation (Löckenhoff & Carstensen, 2007) or when they are directed to think of their future as being expansive (Barber, Opitz, Martins, Sakaki, & Mather, 2016; Kellough & Knight, 2012). In addition, a positivity preference in memory can be observed in younger adults by directing them to think their time as being limited (Barber et al., 2016; Kellough & Knight, 2012).

According to SST, advancing age should be associated with one's perception of limited time left in their life. Therefore, there should be a positive correlation between the positivity effect in memory and/or attention and

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age. However, previous research has not always provided evidence consistent with this prediction (but see English & Carstensen, 2015). For example, when individuals aged older than 60 were categorized into those who are relatively young (i.e., younger old adults) and those who are relatively older (i.e., older old adults), older older adults were *less* likely to have positive biases than younger old adults in feedback-based learning (M. J. Frank & Kong, 2008; Simon, Howard, & Howard, 2010). When older adults' emotional experiences were longitudinally examined (Carstensen et al., 2011), positive experiences peaked at age 64 at which point positive emotional experiences then began to decrease with age (see also Gana, Saada, & Amieva, 2015; Jivraj, Nazroo, Vanhoutte, & Chandola, 2014).

These findings may be explained by the age-related impairment in cognitive control. As mentioned above, the cognitive control mechanisms are critical in achieving emotion regulation (Opitz, Gross, & Urry, 2012) and the positivity effect is attenuated when older adults have limited cognitive resources (Mather & Knight, 2005; Petrican et al., 2008). Of note, cognitive control is one of the most vulnerable processes of age-related decline (e.g., Milham et al., 2002) and therefore the impaired cognitive control mechanisms may obscure the positivity effects in old age. The first objective of the present study is to test whether the positivity effect becomes stronger as individuals get older within older adults and whether such effects of age within older adults are mediated by their cognitive control mechanisms. To this end, we tested memory for positive, negative and neutral stimuli in younger and older adults ensuring that a wide age range in older adults was covered. We also included the Stroop task to test their cognitive control functioning (West & Alain, 2000).

The present study also aimed to test a prediction made by an alternative theory for the positivity effect. Cacioppo and colleagues suggested the aging-brain model which posits that normal aging is associated with neural degeneration of the amygdala. This amygdala degeneration is considered to result in decreased amygdala activity to negative stimuli, leading to the selective impaired processing of negative stimuli in older adults (Cacioppo, Berntson, Bechara, Tranel, & Hawkley, 2011). Contrary to the prediction of the aging-brain model, previous research has shown that fear conditioning – which is known to rely on the amygdala (Delgado, Olsson, & Phelps, 2006) – is preserved in older adults (LaBar, Cook, Torpey, & Welsh-Bohmer, 2004; Lee et al., 2018). However, fear conditioning and the positivity effect in attention or memory are often studied separately and have never been studied within the same sample, making it difficult to examine whether and how strongly the age-related positivity effect in attention and/or memory is related to fear conditioning. In the current study, we included a fear conditioning task and examined whether the positivity effect is associated with weaker/impaired fear conditioned responses as predicted by the aging-brain hypothesis.

Methods

Participants

Participants included 46 older adults (26 females; age range: 57–87; M_{age} = 72.43, SD = 6.61) and 45 younger adults (41 females; age range: 18–23; M_{age} = 19.71, SD = 1.24). The sample size was determined not only to have the statistical power of .80 to detect the medium-sized differences between younger and older adults in the effects of valence on memory documented in the literature (Reed et al., 2014) but also to detect medium- to large- sized correlations within each age group. Older adults were recruited from the Ageing Research Panel at the University of Reading and the local area around Reading, Berkshire, UK, ensuring a wide age range was covered. Younger adults were undergraduate and graduate students at the University of Reading. Potential participants were excluded if they reported that they had cognitive impairments, did not have normal or corrected vision and hearing, and were not able to speak English fluently. To make sure the administration of electrical stimulation was done safely (see Procedures), participants were screened so that they did not have post-traumatic stress disorder, panic disorder, heart disease, peripheral vascular disease, diabetes, Reynaud's phenomenon, cryglobulinemia, vasculitis, lupus, or tingling or numbness in hands and/or feet, or any serious chronic illness and they did not use psychoactive drugs, beta-blocker medication or corticosteroid medication. Participants were not screened for color blindness. Three participants (2 older adults and 1 younger adult) showed almost 0% accuracy in incongruent trials (<.05%) and almost 100% accuracy in congruent trials (>.95%) in the Stroop task (see Procedures); indicating that they did not understand or follow the instructions of the Stroop task and just responded to the words ignoring the font colors. Data from the three participants were excluded from the analyses reported in this paper. Analyses were thus performed on data from 44 older adults (24 females; age range: 57–87; M_{age} = 72.38, SD = 6.75) and 44 younger adults (40 females; age range: 18–23; M_{age} = 19.73, SD = 1.25). Participants signed the consent form approved by the University Research Ethics Committee at the University of Reading. Participants received £7/hour or course credits.

Materials

Fifteen positive, 15 negative and 15 neutral images obtained from the International Affective Picture System (IAPS; Lang, Bradley, & Cuthbert, 1997) were used in the study. The IAPS has normative ratings of arousal and valence. The average valence ratings were 7.45 (SD = .34) for the positive images, 5.05 (SD = 0.32) for the neutral images and 2.71 (SD = 0.69) for the negative images. The mean arousal level was matched between the negative and the positive images (M_{neg} = 5.35, SD = .92; M_{pos} = 5.34, SD = .79), and both positive and negative images were more arousing than neutral images (M = 3.22, SD = .62).

Procedures

Participants completed two sessions that were on average one week apart (M = 6.58 days). In the first session, participants completed a questionnaire on life satisfaction (Diener, Emmons, Larsen, & Griffin, 1985), followed by the Stroop task, where they were shown words and asked to identify their font colors (i.e., red, blue, green and purple)

by pressing one of four keys that had corresponding colored stickers. The words "red," "blue," "green" and "purple" were sometimes shown in the font color consistent with the word (congruent trials; e.g., "red" in red) and sometimes shown in a different font color (incongruent trials; e.g., "red" in blue). There were 60 congruent trials and 60 incongruent trials. In each trial, participants were shown a word for 1.25 sec, followed by a 750 ms blank screen. They were asked to respond as quickly and as accurately possible.

Next, participants were shown 45 IAPS images in a random order; each image was presented for 2 sec. Half of the images from each valence condition had a red frame and the other images had a yellow frame. Participants were asked to indicate whether the image had a red or yellow frame by key press ("r" key for the red frame and "y" key for the yellow frame) as done in a previous study (Barber et al., 2016). After the picture viewing task, they completed Sudoku puzzles for 3 min, followed by a self-paced free recall task. During the free recall task, participants were asked to describe aloud as many of the images that they had seen in the earlier session that they could possibly remember without any time limit. The experimenter typed participants' responses into the computer. After the free recall task, older adults also completed the mini-mental state examination (MMSE; Folstein, Robins, & Helzer, 1983); two older adults did not complete MMSE.

In the second session, participants completed the Positive Affect and Negative Affect Scale (PANAS; Watson, Clark, & Tellegen, 1988) and the Center for Epidemiologic Studies Depression Scale (CES-D; Radloff, 1977), followed by a fear conditioning procedure. Conditioned stimuli (CS) were two neutral tones that were different in their pitches; which tone was used as CS+ was counterbalanced across participants. The US was electric stimulation. The fear conditioning task included 36 trials in a randomized order (12 trials for CS+ with shock, 12 trials for CS+ without shock and 12 trials for CS–). On each trial, participants were presented with CS+ or CS– for 500 ms and pressed a key to indicate whether the tone was high- or low- pitched. After a 400-ms blank screen, participants received a shock for 0.4 sec in the CS+ with shock trials. Each trial ended with a jittered fixation cross (6, 8, or 10 sec). Prior to the task, participants were informed which tone was predictive of shock but were not informed of the probability of shock. After the fear conditioning task, participants also completed the Wechsler Test of Adult Reading (WTAR; Wechsler, 2001) which allowed us to estimate their IQ. Participants were fully debriefed after the experiment.

Electric shock and skin conductance

Electric stimulation was delivered to the fourth finger of the left hand as US via a shock stimulator (Powerlab 26T, AD Instrument Ltd, Oxford, UK). Prior to the experiment, we determined the intensity of "highly unpleasant but not painful" electric stimulation for each participant (older adults: M = 6.33 mA; SD = 3.31; younger adults: M = 4.07 mA; SD = 1.67). The level determined was used throughout the experiment as the US. SCR data were recorded at 1 k Hz sampling rates through the Powerlab 26T system.

SCR data epochs were extracted from a time window between 0 and 10 sec after CS tone onset, and baseline-corrected between 0 and 1 sec. The peak SCR amplitude was taken between 2 and 8 sec from the trial-by-trial average SCR epoch as a function of CS tone. To examine the effects of conditioning, rather than shock itself, our SCR analysis focused on SCR between the CS+ without shock condition and the CS– condition. Due to technical problems, SCR data from two participants were not recorded; thus, data from these participants were not included in the SCR analysis.

Free recall coding

Participants' responses in the free-recall test were matched to the corresponding images by two independent coders. Participants' responses were randomly divided into two sets and each coder coded responses from one of the two sets. 35% of responses were randomly selected within each age group and were coded by both of the two coders. They agreed on 91.86% of these responses. The coders met and reached consensus over the discrepancies. Corresponding images were not identified for 11% of responses when responses were too vague (e.g., "a photograph of some children"; "a man and a woman") or referred to something which was not shown during the picture presentation session.

Results

All analyses were performed with SAS ver 9.4 (SAS Institute, Cary, NC, USA).

Picture recall

Younger adults generated more responses than did older adults during the free recall task (M_{old} = 6.89, SD = 4.05 vs. M_{young} = 8.66, SD = 3.14), $F(1, 86) = 5.27$, $p = .02$, $\eta^2 = .06$. While the difference was not significant, the ratio for responses that could not be matched was higher for older than for younger adults (M_{old} = .15, SD = .21 vs. M_{young} = .09, SD = .13; $p = .15$). To account for these general age-related differences in memory performance, we obtained a proportion of images participants remembered for each valence category based on the total number of images that the participant recalled (e.g., Barber et al., 2016).

A 2 (age group: young, old) × 3 (valence: negative, positive vs. neutral) ANOVA was performed on the proportion of images recalled (**Figure 1A**). This ANOVA revealed a main effect of valence, $F(2, 172) = 27.34$, $p < .001$, $\eta_p^2 = .32$, and an age-by-valence interaction, $F(2, 172) = 4.58$, $p = .01$, $\eta_p^2 = .05$. Subsequent analyses revealed that older adults recalled a smaller proportion of negative images compared with younger adults (M_{old} = .29, SD = .22 vs. M_{young} = .42, SD = .17), $F(1, 86) = 9.32$, $p = .003$, $\eta^2 = .10$. The groups did not significantly differ for positive ($p = .40$; M_{old} = .41, SD = .25 vs. M_{young} = .38, SD = .16) and neutral images ($p = .09$; M_{old} = .19, SD = .21 vs. M_{young} = .12, SD = .12). Thus, we replicated the reduced memory performance for negative stimuli in older adults relative to younger adults as observed in previous studies (e.g., Charles et al., 2003; Grühn et al., 2007).

Next, we examined whether the positivity effect increases with age within older adults. To address this issue, we obtained a memory positivity score by subtracting the proportion of negative images remembered from

the proportion of positive images recalled. This memory positivity score was significantly correlated with age within older adults (**Figure 2**), $r(42) = .32$, $p = .03$, suggesting that the positivity effect becomes stronger as individuals get older. To further confirm this, we split older adults based on the median age (72.5; see **Table 1**). A 3 (age group: young, young-old, vs. old-old) × 3 (valence) ANOVA on the proportion of images recalled (**Figure 1B**) revealed a significant effect of valence, $F(2, 170) = 22.97$, $p < .001$, $\eta_p^2 = .27$, and a significant interaction between age and

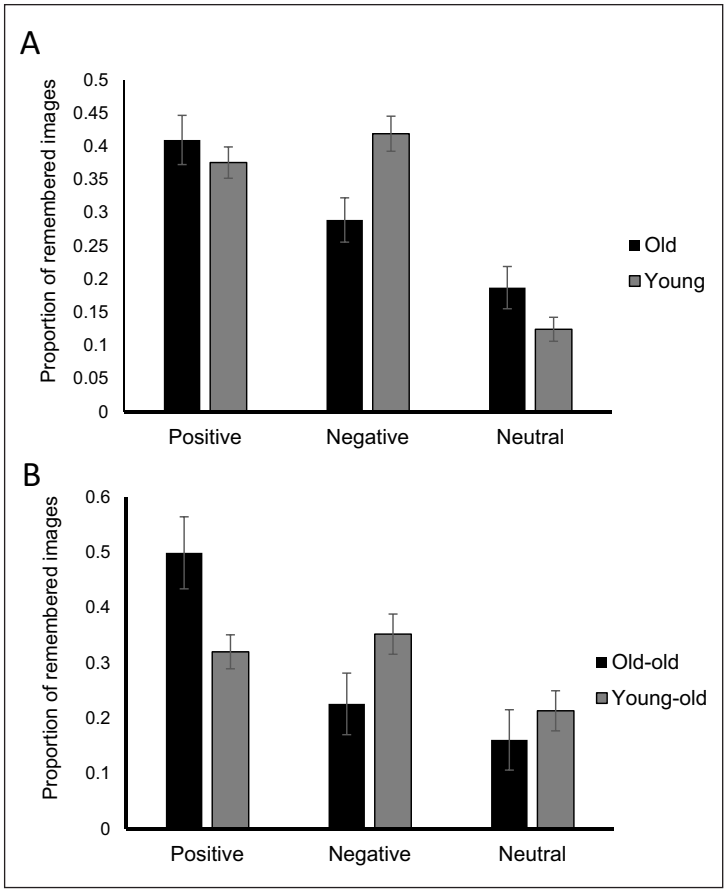

Figure 1: (A) Performance in the free recall test for younger and older adults. **(B)** The results from the free recall test when older adults were further categorized into older old adults (older than 72) and younger old adults (aged 72 or younger).

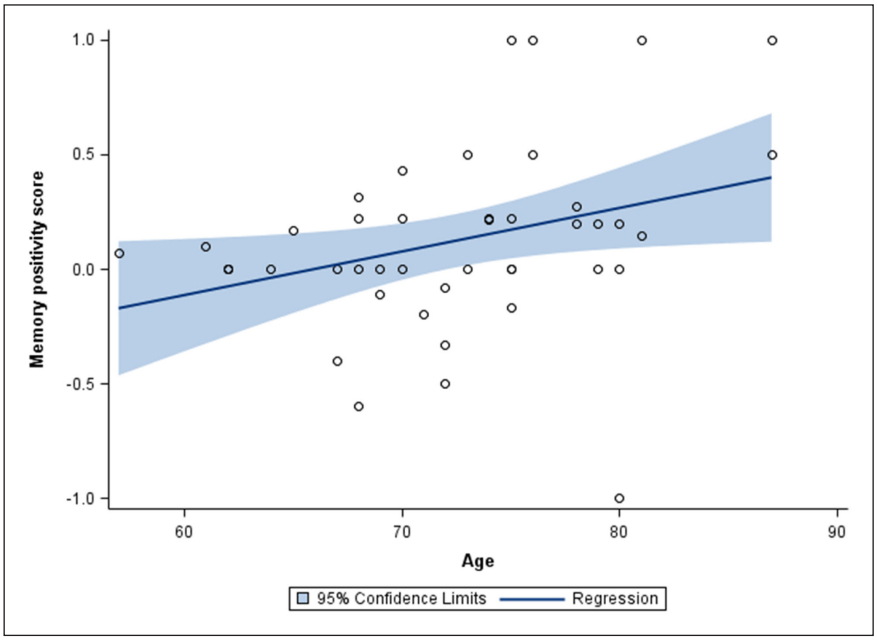

Figure 2: Relationship between memory positivity and age. Within the group of older adults, there was a positive correlation between age and memory positivity.

Table 1: Demographic measures and results in cognitive and self-reported questionnaires.

	Young	Younger old	Older old
Age	19.73 (1.25)	67.00 (4.11)	77.77 (3.95)
Sex (females/males)	40/4	11/11	13/9
MMSE	–	28.10 (1.09)	27.81 (1.60)
WTAR	40.00 (5.63)	48.95 (1.25)	48.36 (1.92)
Positive affect	2.76 (0.66)	3.09 (0.68)	3.44 (0.73)
Negative affect	1.40 (0.49)	1.22 (0.27)	1.17 (0.24)
CES-D	0.84 (0.37)	0.73 (0.50)	0.76 (0.33)
Life satisfaction	4.88 (0.85)	4.95 (1.04)	5.10 (0.98)

Note: Standard deviations (SD) are in parentheses. MMSE stands for the mini-mental state examination; WTAR stands for the Wechsler Test of Adult Reading and CES-D stands for the Center for Epidemiologic Studies Depression Scale.

valence, $F(4, 170) = 5.24$, $p < .001$, $\eta_p^2 = .12$. Subsequent analyses conducted separately for each valence condition revealed significant effects of age groups for positive, $F(2, 85) = 4.88$, $p = .01$, $\eta^2 = .10$, and negative images, $F(2, 85) = 7.14$, $p = .001$, $\eta^2 = .14$, but not for neutral images ($p = .14$). Older old adults remembered a greater proportion of positive images ($M = .50$, SD = .29) compared to the proportions remembered by younger old adults and younger adults ($M_{younger\text{-}old} = .32$, SD = .15; $M_{young} = .38$, SD = .16), $t(85) = 3.02$, $p = .01$, $t(85) = 2.41$, $p = .048$ (Tukey), and remembered a smaller proportion of negative images ($M_{old\text{-}old} = .23$, SD = .25) compared to younger adults ($M_{young} = .42$, SD = .17), $t(85) = 3.78$, $p < .001$ (Tukey). Older old adults also remembered a smaller proportion of negative images than younger old adults ($M_{young\text{-}old} = .35$, SD = .17) but the difference did not reach significance after applying the Tukey multiple comparison test, $t(85) = 2.13$, $p = .09$ (Tukey). Younger old adults did not significantly differ from younger adults across all valence categories ($ps > .10$).

These results suggest that the positivity effect in memory increases over the course of aging. In addition, while the age effects were stronger for negative images than positive images when we compared younger vs. older adults as described in the previous paragraph, this additional analysis revealed that older old adults remembered more positive images than younger old adults and younger adults. Thus, results from this additional analysis suggests that old age is associated with a larger proportion of positive stimuli recalled as well as a smaller proportion of negative stimuli recalled. In summary, the positivity effect in memory appears to steadily increase with age. The interaction between age and valence remained significant even after controlling for the effects of positive affect from PANAS, negative affect from PANAS, WTAR scores, and their interactions with the three age groups, $F(4, 164) = 4.46$, $p = .002$, $\eta_p^2 = .11$.

Effects of Stroop performance on memory positivity

For each condition for each participant, trials with outlier reaction times were defined based on 2 SDs above the mean in the Stroop task. After removing these outlier trials, we obtained the mean accuracy for the congruent and incongruent trials during the Stroop task. An interference score was then obtained by subtracting accuracy in the incongruent trials from accuracy in the congruent trials. The interference score was significantly different across the three age groups, $F(2, 85) = 5.41$, $p = .007$, $\eta^2 = .11$, such that older old adults (M = .09, SD = .09) and younger old adults (M = .08, SD = .07) had a higher interference score than did younger adults (M = .04, SD = .05), $t(85) = 2.96$, $p < .01$, $t(85) = 2.35$, $p = 05$ (Tukey). The two older adult groups were not significantly different ($p = .86$).

To examine whether preserved cognitive control is critical for older adults' positivity effect in memory, we next ran a general linear modelling (GLM) analysis on the memory positivity score. Independent variables included the three age groups, the Stroop interference score (as a continuous variable), and the interaction between them. This analysis confirmed the significant effect of age, $F(2, 82) = 10.24$, $p < .001$, $\eta^2 = .20$, consistent with the results from previous ANOVAs. The main effect of Stroop interference score was not significant ($p = .76$). More interestingly, there was a significant interaction between age group and the interference score, $F(2, 82) = 3.33$, $p = .04$, $\eta^2 = .06$. Since there were some possible outliers (see **Figure 3**), we used Spearman correlation coefficients to test the correlation between the interference score and memory positivity score for each group to reduce the effects of these outliers. The results indicated that in older old adults, the lower interference scores were associated with stronger positive memory, $\rho(21) = -.42$, $p = .05$. In contrast, the correlation was not significant either in younger adults or in younger old adults ($ps > .20$). These results suggest that the preserved cognitive control mechanisms are important especially for older old adults to show the positivity effect.

Fear conditioning

Participants' SCRs were submitted to a 2 (cue: CS+ vs. CS–) × 3 (age groups: older old, young old, young) ANOVA. There was a significant effect of cue, $F(1, 83) = 7.56$, $p = .007$, $\eta_p^2 = .09$, reflecting stronger SCRs to CS+ than CS–. Neither the main effect of age ($p = .70$) nor the interaction ($p = .32$) was significant. In fact, both older old adults, $t(20) = 2.35$, $p = .03$, and younger adults, $t(42) = 2.63$, $p = .01$, showed the enhanced SCRs to CS+ than CS– (**Figure 4**). While the difference did not reach significance, younger old adults also showed the same pattern, $t(21) = 1.73$, $p = .099$. Within older adults, the difference in SCR between CS+ and CS– was not significantly associated with age, nor with the memory positivity score ($ps > .50$).

To further confirm that the Stroop interference score is more critical than the fear responses acquired during conditioning for the age-related positivity effect, we ran a similar GLM analysis to the one used for the Stroop and memory positivity, while including the acquired fear responses in conditioning (i.e., the difference in SCR between CS+ and CS–) as a covariate. This analysis confirmed a significant interaction between age and the Stroop interference score, $F(2, 79) = 3.22$, $p = .045$, $\eta^2 = .08$. Taken together, these results suggest that the preserved

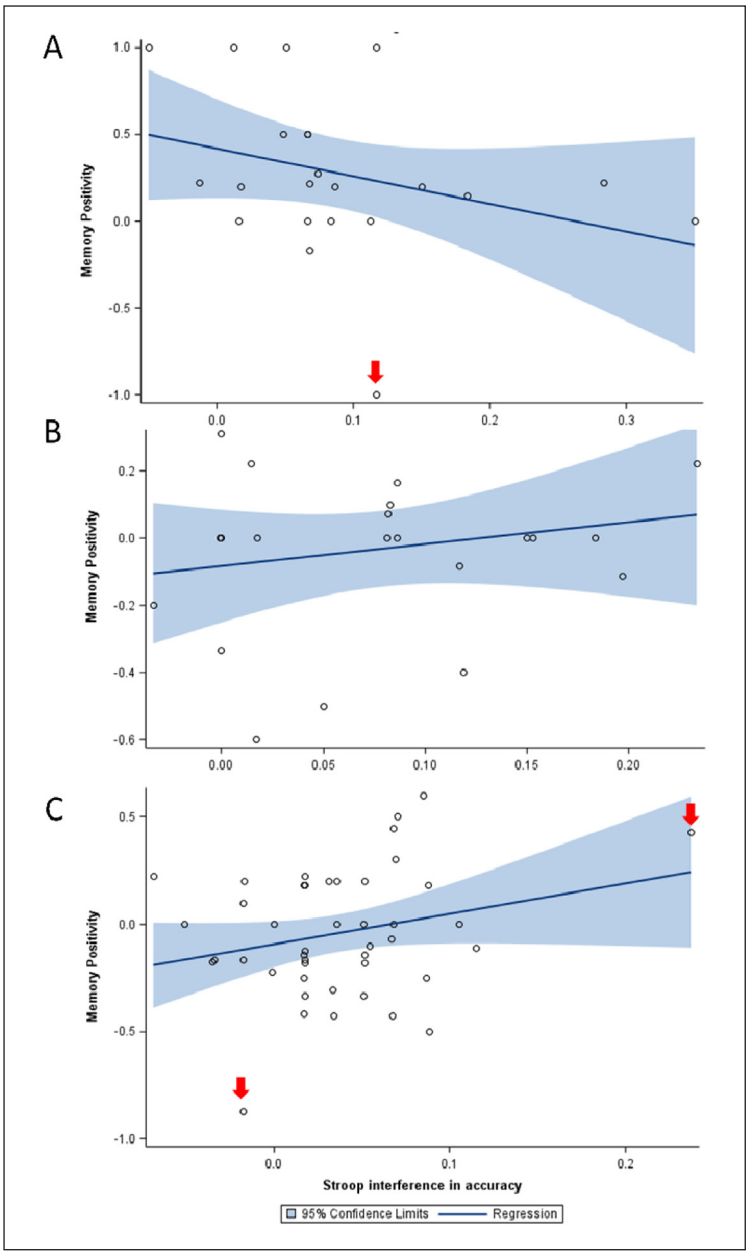

Figure 3: Relationship between memory positivity and the interference score from the Stroop task in **(A)** older old adults, **(B)** younger old adults and **(C)** younger adults. Possible outliers are pointed by a red arrow.

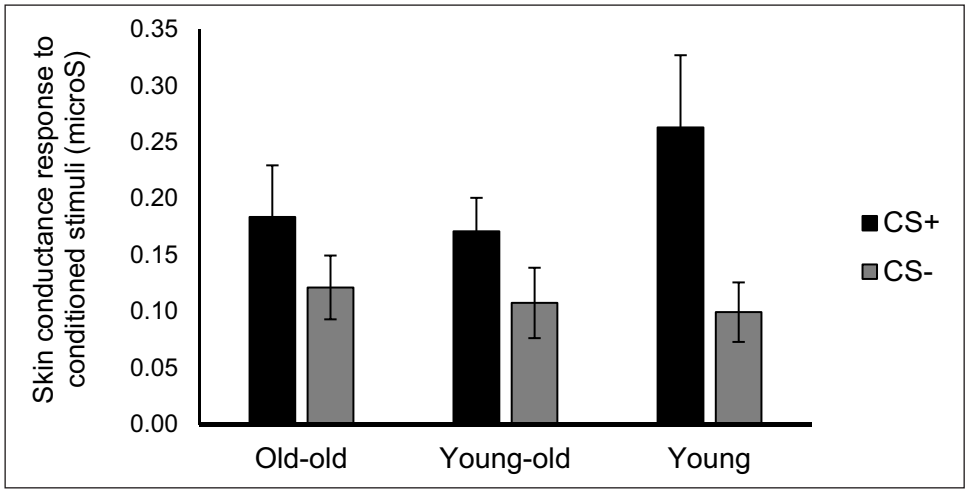

Figure 4: Skin conductance response to a fear conditioned tone (CS+) or a neutral tone (CS–) across the age groups.

cognitive control mechanisms are more important than the preserved fear learning mechanisms for older adults to demonstrate the positivity effect.

Other questionnaires and cognitive tasks

Participants' performance in other cognitive tests and self-reported questionnaires is shown in **Table 1**. The three age groups significantly differed in WTAR, $F(2, 85) = 47.74$, $p < .001$, $\eta^2 = .53$, reflecting poorer performance for younger adults compared to the two older adult groups, $ts(85) = 7.70, 8.24$, $ps < .001$ (Tukey). In addition, the three groups differed in PANAS positive affect, $F(2, 85) = 7.43$, $p = .001$, $\eta^2 = .15$, and in PANAS negative affect, $F(2, 85) = 3.08$, $p = .05$, $\eta^2 = .07$. Older old adults reported a stronger positive affect than younger adults did, $t(85) = 3.81$, $p < .001$ (Tukey), and although it was not significant, there was a trend for reduced negative affect in older old adults than younger adults, $t(84) = 2.24$, $p = .07$ (Tukey). The groups did not significantly differ in depression ($p = .55$) or life satisfaction ($p = .67$). The WTAR and MMSE scores were not significantly correlated with the Stroop interference scores in any of the three groups ($ps > .35$).

While the two older adult groups did not differ in the average MMSE score ($p = .50$), one participant in the older old group showed a MMSE score of 25 which is below the cut-off (26) for possible cognitive impairments (Perneczky, Wagenpfeil, Komossa, Grimmer, & et al., 2006). To confirm that the results reported in the paper were not due to this particular participant, we ran our main analyses after removing this participant. A 2 (age group: young, old) × 3 (valence) ANOVA on the proportion of images recalled replicated the age-by-valence interaction, $F(2, 170) = 4.30$, $p = .02$, $\eta_p^2 = .05$. Within older adults, age was also positively correlated with the memory positivity score, $r(41) = .32$, $p = .04$, even without this possible dementia case. A GLM analysis on the memory positivity score also replicated a significant interaction between age group and the Stroop interference score, $F(2, 81) = 3.08$, $p = .05$, $\eta^2 = .06$.

Discussion

Previous research indicates that older adults tend to remember more positive and less negative information compared to younger adults (Charles et al., 2003; for a review see Reed et al., 2014). According to SST (Scheibe & Carstensen, 2010), this age-related positivity effect is driven by emotion regulation goals activated by the limited future perspective older adults hold. Given that advancing age is likely to lead to more limited future perspectives, the positivity effect should be stronger in older old adults than in younger old adults. While previous studies did not always provide evidence consistent with this prediction, the lack of age effects within older adults may be due to the age-related impairment in cognitive control. In the present study, we tested this prediction by examining memory for positive, negative and neutral images in older old adults, younger old adults and younger adults. Consistent with SST, we found that the positivity effect in memory was stronger for older old adults than for younger old adults. In addition, within a group of older old adults, a stronger positivity effect in memory was associated with smaller interference scores in a Stroop task. These results suggest that the positivity effect in old age is determined not only by one's limited time perspective due to advancing age but also by preserved cognitive control mechanisms underlying emotion regulation.

The second goal of the present study was to test a prediction of another theory on the positivity effect. According to the aging-brain model (Cacioppo et al., 2011), normal aging leads to impaired amygdala function, which leads to impaired processing of emotionally negative stimuli and the apparent positivity effect in older adults. If this is true, older adults who show the positivity effect in attention or memory should show impaired emotional processing in other tasks that rely on the amygdala. In the present study, we used fear conditioning paradigms because acquisition of conditioned fear has been revealed to rely on the amygdala (e.g., Delgado et al., 2006). We found that across age groups, all participants acquired fear responses to a cue predictive of shock. In addition, the magnitude of fear responses acquired was not correlated with the positivity effect in memory. Thus, our results suggest that older adults who have a preserved amygdala function to learn fear are able to show the positivity effect in memory at the same time, arguing against the aging-brain model.

While we found a positive correlation between memory positivity and age in the group of older adults, previous studies have not always found a similar positive correlation (M. J. Frank & Kong, 2008; Gana et al., 2015; Jivraj et al., 2014; Simon et al., 2010). This inconsistency may be due to the age-related decline in cognitive control abilities; in other words, older old adults should generally have lower cognitive control abilities than younger old adults. In the current study, older old adults were not significantly worse than younger old adults in their Stroop performance, and older adults in both groups were equally worse than younger adults. Thus, our participants in the older old group may have been relatively cognitively preserved, which may have enabled us to see the positive correlation between memory positivity and age. These results suggest that it is important to take into account cognitive control abilities in research on the positivity effect.

While our results are consistent with SST, it is important to note limitations of the present study and questions for future research. Firstly, the amygdala function is not limited to fear conditioning. In addition, we did not incorporate any neuroimaging measures that allow us to examine the structural and functional preservation of the amygdala. Future studies need to include more systematic assessments on the amygdala function/structural preservation to address the relevance of the amygdala to the positivity effect in memory and attention. The second issue concerns our measure of cognitive control. Cognitive control is defined as one's ability to coordinate thoughts and behaviors based on current goals (Miller & Cohen, 2001) which covers inhibitory control, performance monitoring, working memory, and goal-directed attention. In contrast, in the current study, we included only the Stroop task which concerns inhibitory

control. Therefore, it is unclear whether the positivity effect in older old adults is related to performance in other domains of cognitive control. On the one hand, previous research suggests that inhibitory control is key for emotion regulation (Joormann & Gotlib, 2010). Brain regions that are important for inhibitory control (e.g., the inferior frontal gyrus; Aron, Robbins, & Poldrack, 2014; Swick, Ashley, & Turken, 2008) have also been implicated in emotion regulation across younger and older adults (D. W. Frank et al., 2014; Morawetz, Bode, Derntl, & Heekeren, 2016; Winecoff, LaBar, Madden, Cabeza, & Huettel, 2011). These results suggest that the positivity effect in older adults may rely on inhibitory control more than other domains of cognitive control. But emotion regulation is also accompanied with activation in other brain regions beyond those relevant to inhibitory control (D. W. Frank et al., 2014; Morawetz et al., 2016; Winecoff et al., 2011). Prevous studies also demonstrate that the positivity effect in memory in older adults is correlated with an executive composite score, based on other cognitive control measures and inhibitory control (Mather & Knight, 2005; see also Petrican et al., 2008). Future studies need to include more systematic assessments on cognitive control to test the role of inhibitory control in the positivity effect in older old adults.

Thirdly, our analyses based on the three age groups are ad-hoc analyses and we are unlikely to have sufficient statistical power to detect the difference between older old adults and younger old adults in various analyses reported in the paper. In fact, in the current study, despite younger old adults and older old adults showing similar performance in the Stroop task, the association between Stroop performance and memory positivity was observed only in older old adults and the correlation was not significant in younger old adults. This lack of a correlation may be due to the lack of the positivity effect in younger old adults in our sample: younger old adults did not significantly differ from younger adults in the proportions of positive and negative images recalled. While we do not have an objective measure on future time perspective, it is likely that younger old adults have a more limited future time perspective than younger adults do. Therefore, if the future time perspective is critical in the age-related positivity effect as SST predicts, younger old adults should show a preference towards positive over negative stimuli compared with younger adults. In fact, past studies on emotional experiences indicate better emotional experiences in early old adulthood relative to younger adulthood (Carstensen et al., 2011; Steptoe, Deaton, & Stone, 2015). In the current study, we also found that younger old adults reported a higher positive affect score than younger adults did, although the effect did not survive when we applied multiple comparisons (**Table 1**). It is unclear why we did not see a significant difference between younger adults and younger old adults in our memory measure. One possibility is that our sample size was too small to detect a difference after splitting older adults into two sub-groups. Future studies need to employ a larger sample size to address this issue.

Lastly, the present study is based on a cross-sectional comparison of age. Therefore, there may be some differences other than age across the age groups. In fact, the three groups were significantly different in WTAR scores, suggesting that their educational backgrounds or intelligence levels may be different. While the age-related positivity effect remained significant even after controlling for WTAR scores, we also had a number of exclusion criteria, including heart disease, peripheral vascular disease, and diabetes. Because age is a risk factor for these physical diseases, it may be more challenging for older old adults to meet all eligibility criteria than younger old adults. Thus, older old adults we had in this study may be exceptionally healthier than younger adults or younger old adults and therefore the three groups may not be comparable with one another. Future research should therefore examine the effects of age in older adults using longitudinal paradigms.

Data Accessibility Statement

Summarized data, a list of IAPS image used in the study and experiment codes are accessible though the following link: https://osf.io/59sx8/.

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Competing Interests

The authors have no competing interests to declare.

Author Contributions

- Contributed to conception and design: MS, JR, JF, MT
- Contributed to acquisition of data: JR, JF, MT
- Contributed to analysis and inderpretation of data: MS
- Drafted and revised the article: MS, JR
- Approved the submitted version for publication: MS, JR, JF, MT

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