BRIEF REPORT

Food for Happy Thought:
Glucose Protects Age-Related Positivity Effects Under Cognitive Load

Konstantinos Mantantzis

Friederike Schlaghecken

Elizabeth A. Maylor

University of Warwick, UK

Author Note

Konstantinos Mantantzis, Friederike Schlaghecken, Elizabeth A. Maylor, Department of Psychology, University of Warwick, Coventry, UK.

We thank Sandra-Ilona Sünram-Lea for useful discussions, and Anna Trendl and Naomi Muggleton for help in preparing the drinks for Experiment 2. This work was funded through a University of Warwick Postgraduate Scholarship awarded to Konstantinos Mantantzis. The study will be presented at the 4th International Aging & Cognition Conference, Zurich, April 2017.

Correspondence concerning this article should be addressed to Elizabeth A. Maylor, Department of Psychology, University of Warwick, Coventry CV4 7AL, UK. Email: e.a.maylor@warwick.ac.uk

Abstract

Older adults show a preference for positive information, which disappears under high task demands. We examined whether glucose can help older adults preserve their positivity effect (PE) under high cognitive load. One hundred and twenty-two adults (40 young and 42 older in Experiment 1; 40 older in Experiment 2) consumed a glucose (25 g) or a taste-matched placebo drink and completed an immediate recall task of emotional word-lists presented under high- and low-load conditions. Older adults showed PEs for low-load lists. Whereas PEs disappeared for older-placebo participants for high-load lists, older-glucose participants retained their positive preference. Providing the brain with extra energy resources can help older adults achieve PEs even under demanding conditions.

Keywords: aging, positivity effect, cognitive control, glucose, cognitive load

Food for Happy Thought: Glucose Protects Age-Related Positivity Effects Under Cognitive Load

Despite the physiological and neuroanatomical degradations that accompany aging (Salthouse, 2010), emotional wellbeing remains impervious to age-related decrements, with older adults appearing to be well-adjusted and emotionally resilient throughout the aging process (e.g., Carstensen, Pasupathi, Mayr, & Nesselroade, 2000). According to the Socioemotional Selectivity Theory (SST; Carstensen, 1995), as people grow older they experience a motivational shift, favoring emotional stability and positive experiences over 'expansive' goals relating to wealth or social status (Carstensen, Isaacowitz, & Charles, 1999). This preference extends to a range of cognitive domains and emerges as a cognitive bias towards the processing of positive over negative information in memory and attention, a phenomenon called the positivity effect (PE; for a meta-analysis see Reed, Chan, & Mikels, 2014).

The 'cognitive control' extension of the SST (Mather & Carstensen, 2005) posits that PEs are a result of top-down processes employed by older adults in order to downregulate negative affect. Compared to young adults, older individuals show increased functional connectivity between the amygdala and the prefrontal cortex (PFC) and a decrease in amygdala-hippocampal coupling during the encoding and retrieval of negative versus neutral information (Murty et al., 2009). It has been suggested that the age-related differences in the recruitment of frontal brain areas during exposure to negative stimuli indicate an emotion-regulation attempt (an assumption for which there is as yet only limited evidence; see Isaacowitz & Blanchard-Fields, 2012), with the PFC being employed to minimize amygdala activation and dampen responses to negative stimuli (St. Jacques, Bessette-Symons, & Cabeza, 2009). The downregulation of negative affect appears to be more successful for material requiring elaborate processing (i.e., low-arousal stimuli; Dolcos, Katsumi, & Dixon,

2014; Kensinger, 2008) than for high-arousal stimuli, which are thought to be processed in a more automatic fashion (Kensinger, 2004). Neuroimaging and behavioral studies have shown that the amygdala's activation patterns in response to high-arousal material remain relatively intact throughout aging, suggesting that the PFC cannot suppress strong activations triggered by highly aversive stimuli (Leclerc & Kensinger, 2008; Mather & Knight, 2006). Interestingly, although the amygdala does not seem to be particularly sensitive to age-related structural and functional degradations (for review, see Mather, 2016), aging is accompanied by a shift in the valence to which the amygdala is more responsive. Specifically, whereas the amygdala of young adults is more responsive to negative information, the reverse is true for older adults, who exhibit stronger amygdala activation when presented with positive compared to negative stimuli (Kehoe, Toomey, Balsters, & Bokde, 2013; Mather et al., 2004).

If PEs do indeed depend on cognitive control (a finding challenged by some studies; see Allard & Isaacowitz, 2008; Petrican, Moscovitch, & Schimmack, 2008), then this poses constraints on the circumstances under which the phenomenon emerges. Increasing cognitive load by introducing a cognitively demanding secondary task during encoding of emotional words (Mather & Knight, 2005) or during a visual attention task with emotional material (Knight et al., 2007) attenuates or even reverses PEs (i.e., negativity bias). In situations where high task demands limit the availability of cognitive resources, the PFC can no longer suppress the encoding of negative stimuli which gain an advantage due to their affective salience (Baumeister, Bratslavsky, Finkenauer, & Vohs, 2001). It should be noted that the mere introduction of a divided attention task is not always sufficient to hinder the age-related positivity preference (e.g., Allard & Isaacowitz, 2008). The secondary task must place considerable strain on cognitive control resources to successfully diminish the PE in older adults (e.g., Knight et al., 2007; Mather & Knight, 2005). In view of the evidence for the role

of cognitive control in the emergence of PEs, an interesting question arises: If PEs are dependent on cognitive resources, could increasing the availability of these resources help older adults retain their preference for positive material when cognitive demands are high?

A number of studies have demonstrated that orally administered glucose can lead to significant improvement in cognitive processes in both young and older adults (for review, see Riby, 2004). In young adults, glucose is thought to primarily target the hippocampus, leading to a facilitation of memory processes (for review, see Hoyland, Lawton, & Dye, 2008; Messier, 2004). The beneficial effects of glucose administration have been shown to be particularly sensitive to task difficulty (Kennedy & Scholey, 2000; Scholey, Harper, & Kennedy, 2001). Specifically, the magnitude of cognitive improvement seems to be proportional to the amount of effort that the task requires, with the facilitation being more reliable under high than low cognitive load (Scholey et al., 2009; Sünram-Lea, Foster, Durlach, & Perez, 2002). Consistent with findings from young adults, glucose has been shown to enhance memory processes in older adults (Riby et al., 2006; Riby, Meikle, & Glover, 2004). In addition to memory improvement, recent studies have also found that glucose administration in older adults can improve attention and minimize the cognitive cost associated with task-switching – a cost arising from participants' difficulty in effectively splitting available cognitive resources between two tasks (Gagnon, Greenwood, & Bherer, 2010; Macpherson et al., 2015). Similarly to young adults, this facilitation effect is only observed when processing load is high (i.e., dual-task conditions). According to these studies, glucose can equip older adults with the necessary metabolic and cognitive resources to successfully coordinate different cognitive strategies and manage the processing demands of a challenging dual-task (Gagnon et al., 2010). Although it is difficult to pinpoint the cognitive domain benefitting the most from moderate increases in blood glucose levels, it is possible that, under high cognitive load, glucose administration has the potential to enhance both

hippocampal- (memory) and PFC-mediated (attentional) processes in older adults (Donohoe & Benton, 1999). Irrespective of whether glucose effects are domain-specific or context-dependent, task difficulty appears to be an important determinant of the glucose facilitation effect, with the cognitive enhancement being more robust when cognitive demands are high and attentional resources are split across a number of tasks (for review, see Messier, 2004; Smith et al., 2011).

With the recent controversy surrounding the glucose model of ego depletion (for a review, see Vadillo, Gold, & Osman, 2016), it is important to distinguish between the self-control tasks used in the ego depletion line of research and dual-task paradigms. Whereas studies investigating self-control have adopted a sequential task presentation (i.e., two single tasks presented in succession; see Gailliot et al., 2007), dual-task experiments require participants to perform two cognitively demanding tasks concurrently. Thus, successful performance in dual-task paradigms is more cognitively demanding (e.g., requiring more complex attentional or strategic processes; Pashler, 1994) than self-control tasks, which allow participants to direct all available resources toward a single task. If glucose effects are mostly evident for tasks that tap into multiple cognitive functions simultaneously (Scholey et al., 2013), ego depletion should be unaffected by glucose administration (e.g., Carter, Kofler, Forster, & McCullough, 2015), whereas dual task performance should show a systematic modulation.

Considering the role of cognitive control in PEs, the idea of attentional resources being sensitive to manipulations in glucose availability can be of particular interest when examining failures in retaining the positivity preference under high cognitive demands. To date, the effects of glucose on emotional memory have been examined only in young adults, where no selective glucose facilitation of either positive or negative material under single- (Brandt, Sünram-Lea, & Qualtrough, 2006) or dual-task conditions (Brandt, Sünram-Lea,

Jenkinson, & Jones, 2010) has been observed. Surprisingly, no studies have addressed the same question from an aging perspective. In view of findings suggesting that the age-related PEs disappear under high cognitive load and that glucose can improve attentional resources in the presence of a demanding secondary task, our goal was to investigate whether glucose administration prior to a difficult task would allow older adults to preserve their preference for positive material.

In the present study, we asked young and older adults to memorize emotionally valenced words (both high- and low-arousal) under high versus low cognitive load conditions (Experiment 1). Half of the participants in each age group were given a glucose drink, and half a placebo drink. Young adults were expected to show a preference for negative material regardless of drink or cognitive load. Older adults were expected to show PEs (irrespective of drink), under low-load conditions. Our central prediction was that under high-load conditions, older adults in the placebo group would exhibit a negativity bias, whereas older adults in the glucose group would retain their PEs. Furthermore, as previous research has indicated that PEs are more evident for material that is low in arousal (e.g., Kensinger, 2008), we expected PEs to emerge for low- rather than high-arousal stimuli. In Experiment 2, we conducted a replication with a new sample of older adults only, to establish the reproducibility of the new findings and to rule out two potential confounding factors.

Experiment 1

Method

Design and Drinks. A between-subjects 2 (Age: young, older) × 2 (Drink: glucose, placebo) randomized, placebo controlled design was employed. Participants were randomly assigned to ingest a drink containing either 25 g of glucose or an artificial sweetener (five aspartame tablets), dissolved in 300 ml of water. To improve palatability, 25 ml of sugar-free

orange cordial was added to both drinks. Past research has identified a 25-g glucose dose to be effective for cognitive facilitation in young and older populations (Parsons & Gold, 1992; Sünram-Lea, Owen, Finnegan, & Hu, 2011).

Participants. A total of 41 young adults (age range 18-30) and 44 community-dwelling older adults (age range 65-82) with no recent history of neurological, psychiatric, or endocrine disorders participated in the study. Sample size was based on past research showing that for glucose intervention studies in aging, a total of 20-25 participants per experimental group is sufficient to identify potential glucose effects on cognition (e.g., Gagnon et al., 2010; Macpherson et al., 2015). Young adults received course credits as part of their course requirements. Older adults received £10 for their participation. One young adult was excluded from the sample for not being familiar with the words presented, and two older adults were excluded for failing to perform the secondary task, resulting in a final sample of 40 young and 42 older adults (see Table 1 for characteristics). Participants completed the Digit Symbol Substitution task (DSST; Wechsler, 1981) and the Mill Hill vocabulary test (MHVT; Raven, Raven, & Court, 1988) to assess processing speed and crystallized intelligence, respectively. Young adults had higher processing speed scores, $t(80) = 4.70$, $p < .001$, but lower performance on the vocabulary test, $t(80) = -10.66$, $p < .001$, and fewer years of full-time education, $t(80) = -5.86$, $p < .001$, compared to older adults. No differences in age or in DSST and MHVT scores were identified between participants assigned to glucose and placebo within each age group (all *p*s > .24). The only significant intergroup difference was that young glucose adults had a few months more formal education than their placebo counterparts, $t(38) = 3.38$, $p = .002$. The study was approved by the Psychology Department's Research Ethics Committee at the University of Warwick. Written consent was obtained from all participants prior to beginning the study.

Cognitive tasks. Participants were presented with four 25-word lists, each with 10 positive (valence ratings: 6-9), 10 negative (1-3.99) and five neutral (4-5.99) words. In each list, five positive and five negative words were low arousal (arousal ratings: 1-4.99), and the remaining five from each valence category were high arousal (5-9). All neutral words were low arousal. Valence and arousal ratings were obtained from Warriner, Kuperman, and Brysbaert (2013). Two buffer words were added at the beginning and two at the end of each list. Words were presented on a 15.6-inch laptop screen for 3 s, with a 1-s interstimulus interval. They appeared in black lowercase letters on a white background, with a letter height of approximately 3.4^{o} at a 60-cm viewing distance. Word-lists were matched for frequency (Coltheart, 1981), imagery (Cortese & Fugett, 2004; Schock, Cortese, & Khanna, 2012) and concreteness (Brysbaert, Warriner, & Kuperman, 2014). The lists contained one- and two-syllable words with no more than two words from the same valence category being presented consecutively. Two of the lists were presented under low cognitive load and two under high cognitive load conditions. The allocation of the lists to the conditions was randomized and the condition order was counterbalanced. Memory performance was measured with an immediate free recall task at the end of each list.

During the encoding of the high-load word-lists, participants were asked to simultaneously perform an auditory 1-back task. A sequence of single-digit numbers was presented through headphones, with each number played for 1 s followed by an interstimulus interval of 1 s. Participants had to press a key each time the number they heard matched the one that immediately preceded it. Before the presentation of the lists, participants were reminded that they should pay equal attention to the two tasks and not prioritize one over the other. Numbers were presented in a pseudorandom order to ensure that the possibility of a 1-back match occurring during the presentation of positive or negative words was equal. Participants' reaction times and accuracy were measured.

Procedure. Participants were asked to refrain from any food and drink for two hours before the testing session. Those who did not abide by that condition (n = 1) were asked to reschedule their visit. Participants consumed a glucose or placebo drink and completed a short practice block consisting of one low- and one high-load list (eight words each) to familiarize themselves with the tasks. After a 10-minute waiting period, participants were presented with two low-load followed by two high-load lists, or vice-versa. At the end of each list, they were asked to verbally recall the words. Next, participants provided demographic information and completed the DSST. Then ten minutes from the end of the last recall task, participants completed a delayed recall task of all the words; performance was very poor, hence results from delayed recall are not reported here. Finally, participants completed the MHVT, after which they were debriefed and compensated for their participation.

Results

Word recall. A five-way mixed analysis of variance (ANOVA) was performed on words correctly recalled, with age (young, older) and drink (glucose, placebo) as between-subjects factors, and valence (negative, positive), load (low, high) and arousal (low, high) as within-subjects factors. As there was no main effect or interaction involving arousal (all Fs < 2.31, all ps > .1), Figure 1A displays the number of correctly recalled words collapsed across this factor. Young adults recalled more words than did older adults, $F(1, 78) = 60.50$, $p < .001$, $\eta_p^2 = .437$. Recall was greater with glucose than with placebo, $F(1, 78) = 6.92$, $p = .010$, $\eta_p^2 = .081$, and greater under low-load than high-load conditions, $F(1, 78) = 83.66$, $p < .001$, $\eta_p^2 = .518$. There were two significant two-way interactions: Drink × Valence, $F(1, 78) = 4.72$, $p = .033$, $\eta_p^2 = .057$, and Valence × Load, $F(1, 78) = 4.31$, $p = .041$, $\eta_p^2 = .052$, and a marginal Age × Valence interaction, $F(1, 78) = 3.90$, $p = .052$, $\eta_p^2 = .048$. There were two

three-way interactions: Age × Drink × Valence, $F(1, 78) = 5.73$ $p = .019$, $\eta_p^2 = .068$, and Age × Drink × Load, $F(1, 78) = 4.79$, $p = .032$, $\eta_p^2 = .058$.

These interactions were qualified by a four-way interaction between age, drink, valence and load, $F(1, 78) = 4.87$, $p = .030$, $\eta_p^2 = .059$ (see Figure 1A). To determine the source of the interaction we conducted two additional three-way mixed ANOVAs with drink, valence and load as factors, one for each age group. Follow-up *t*-tests were used to further examine significant effects. Unsurprisingly, both age groups performed better in the low-load than in the high-load condition (both *F*s > 29.28, both *p*s < .001). Young adults performed better with glucose than with placebo, $F(1, 38) = 7.05$, $p = .012$, $\eta_p^2 = .156$, and this benefit was larger for the high-load than for the low-load lists, $F(1, 38) = 6.55$, $p = .015$, $\eta_p^2 = .147$. Furthermore, young adults showed a preference for negative over positive words, $F(1, 38) = 4.31$, $p = .045$, $\eta_p^2 = .102$, which was not modulated by drink or load (both *F*s < 1). In contrast, older adults showed no main effects of either drink or valence (both *F*s < 1). However, two two-way interactions were identified: Drink × Valence, $F(1, 40) = 13.95$, $p = .001$, $\eta_p^2 = .259$, and Valence × Load, $F(1, 40) = 7.73$, $p = .008$, $\eta_p^2 = .162$, which were qualified by a three-way interaction between drink, valence and load, $F(1, 40) = 6.29$, $p = .016$, $\eta_p^2 = .136$. Under low-load conditions, older adults showed an overall preference for positive over negative material, $t(41) = 2.33$, $p = .025$. Whereas under high-load conditions, older adults in the placebo group produced a substantial negativity bias, $t(20) = 4.66$, $p < .001$, older adults in the glucose group produced a PE that despite being only marginally significant, $t(20) = 1.94$, $p = .067$, was indistinguishable from the PE produced under low-load conditions, $t < 1$. No other effects in the two ANOVAs were significant (all other *F*s < 1).

Secondary task performance. Two two-way ANOVAs with age and drink as between-subjects factors were conducted on mean correct reaction times and accuracy (see

Table 1 for means). For reaction times, there were no significant effects (all *F*s < 1.35, all *p*s > .25). Older adults were significantly more accurate on the secondary task than were young adults, $F(1, 78) = 6.36$, $p = .014$, $\eta_p^2 = .075$, but there was no effect of drink on accuracy or any interaction between age and drink (both *F*s < 1).

Experiment 2

Although the results of Experiment 1 were in line with our central prediction (i.e., under high-load conditions, the older placebo group showed a negativity bias, whereas the older glucose group retained their PE), they might have been affected by two factors unrelated to our hypothesis: 1) the experimenter was aware of the experimental conditions (glucose/placebo), and thus might have subconsciously influenced participants during recall, and 2) the palatability of the two drinks, which potentially might bias recall of positive versus negative words, was not assessed.

In order to address these issues, we conducted a second experiment with 40 older adults aged 65-79 who had not taken part in Experiment 1 (see Table 1 for characteristics; one additional participant was excluded from the sample for failing to perform the secondary task). As before, the glucose and placebo groups were well-matched in terms of background characteristics. The stimulus material was identical to Experiment 1. The procedure was also identical except that a) the drinks were prepared by assistants, keeping the experimenter blind to the experimental conditions, b) at the end of the experiment, participants were asked to rate how much they enjoyed the drink on a scale ranging from 1 (‘not at all’) to 10 (‘very much’), and c) the delayed recall task was omitted as recall was so low. The number of correctly recalled words was analyzed using a three-way mixed ANOVA with drink (glucose, placebo) as the between-subjects factor, and valence (negative, positive) and load (low, high) as within-subjects factors, and follow-up analyses were conducted using *t*-tests.

Results

The pattern of results closely resembles that obtained in Experiment 1 (see Figure 1B). Recall was greater under low load than under high load, $F(1, 38) = 66.91$, $p < .001$, $\eta_p^2 = .638$, and greater for positive than for negative words, $F(1, 38) = 10.01$, $p = .003$, $\eta_p^2 = .209$. These two factors interacted, $F(1, 38) = 25.04$, $p < .001$, $\eta_p^2 = .397$, as the overall positivity bias under the low-load condition disappeared under the high-load condition, $t(39) = 6.07$, $p < .001$, and $t(39) = -1.48$, $p = .147$, respectively. There was no main effect of drink, $F < 1$, but there was a significant Drink × Valence interaction, $F(1, 38) = 22.19$, $p < .001$, $\eta_p^2 = .369$, further qualified by a marginal interaction between drink, valence and load, $F(1, 38) = 4.05$, $p = .051$, $\eta_p^2 = .096$. Whereas in the placebo group, older adults' PE turned into a significant negativity bias under high cognitive load, $t(19) = -3.99$, $p < .001$, participants in the glucose group managed to retain a preference for positive words, $t(19) = 1.99$, $p = .030$ (one-tailed), even though this preference was smaller than in the low-load condition, $t(19) = 2.17$, $p = .043$.

Type of drink did not affect reaction times or accuracy in the secondary task (all *F*s < 1, all *p*s > .643). Finally, taste ratings for glucose ($M = 4.85$, $SD = 1.04$) and placebo ($M = 4.70$, $SD = 1.42$) drinks did not differ, $t < 1$, $p = .705$. Taken together, the results suggest that the modulation of older adults' memory performance observed in Experiment 1 is a genuine effect of glucose, rather than an artifact of unconscious experimenter bias or differences in palatability between glucose and placebo drinks.

It has to be noted, though, that although glucose significantly altered older adults' recall preference under high cognitive load (Drink x Valence for older adults under high load: $F(1, 40) = 22.24$, $p < .001$, $\eta_p^2 = .357$, in Experiment 1; $F(1, 38) = 18.87$, $p < .001$, $\eta_p^2 = .332$, in Experiment 2), the positivity preference it produced was only marginally significant ($p =$

.067 in Experiment 1; p = .061, in Experiment 2). However, when the older adult data from the two experiments were pooled to increase statistical power, the glucose group's (N = 41) PE under high cognitive load became highly significant, $t(40) = 2.80$, p = .008, and was statistically indistinguishable from the PE found under low cognitive load, $t(40) = 1.49$, p = .145.

Discussion

The aim of this study was to examine whether glucose administration can preserve older adults' PEs when cognitive demands are high. In Experiment 1, we gave young and older participants 25 g of glucose or a placebo drink and compared their performance on an immediate recall task of emotional word-lists presented under low- and high-load conditions. As predicted, young adults showed a preference for negative over positive words throughout the experiment, irrespective of drink or load condition. Glucose facilitation manifested in this group as generally improved memory for high-load lists, replicating previous studies showing that glucose facilitation is more reliable when task demands are high (e.g., Scholey et al., 2009; Sünram-Lea et al., 2002). Similarly consistent with previous research (e.g., Brandt et al., 2010, 2006) was the finding that in young adults, glucose facilitated recall irrespective of word valence.

In line with studies describing an age-related advantage for positive material (see Reed et al., 2014), our data showed PEs in the low-load condition, with older adults remembering more positive words when attention was focused solely on the encoding of word-lists. Although some studies have identified PEs mainly for low-arousal stimuli (e.g., Kensinger, 2008), the positivity bias in our experiments did not arise specifically for material low in arousal as initially predicted. Consistent with previous findings indicating that PEs can be observed across high- and low-arousal material (e.g., Mather & Knight, 2005), our results

support the possibility that the strength of the positivity phenomenon is not always modulated by arousal conditions. It should be noted that, with the exception of a few studies (e.g., Dolcos et al., 2014; Kensinger, 2008), the role of arousal in PEs has not been systematically examined to date. The importance of arousal intensity has been highlighted by studies showing that memorability for emotional information (and by extension the PE) might be an arousal-driven phenomenon (e.g., Grühn and Scheibe, 2008). Further investigations into the role of arousal might offer interesting insights regarding the parameters influencing the emergence of the positivity preference in aging.

In both experiments, as hypothesized, PEs turned into a negativity bias for dual-task lists in older adults administered a placebo. When cognitive load was increased, the preference for positive material was eliminated and negative words were prioritized, possibly due to the inability of the PFC to suppress activity triggered by negative information while managing multiple task demands. The novel finding of our study is that when given a glucose drink, older adults managed to retain their preference for positive material despite the presence of a demanding secondary task. In Experiment 1, although glucose had to counteract a strong negativity bias – as observed in the older-placebo group – participants in the older-glucose group produced PEs that not only approached statistical significance, but were indistinguishable from those produced under low-load conditions. Experiment 2 succeeded in replicating the negativity reversal in the older-glucose group but, on this occasion, glucose was not able to completely reinstate the positivity preference found under low-load conditions. Interestingly, when we pooled the data from the two experiments, the PE for the older-glucose group became significant even under high task demands. Furthermore, the results mirrored those of Experiment 1, with the older-glucose group producing a PE of similar magnitude under both low and high cognitive load.

We speculate that even though there was no behavioral enhancement in the traditional view of improved memory (e.g., Riby et al., 2006) or shorter reaction times (e.g., Gagnon et al., 2010), the ability of the older-glucose group to preserve the positivity preference under high cognitive load could reflect a glucose-related improvement of PFC-mediated processes and, specifically, an increase of available cognitive resources (e.g., Gagnon et al., 2010; Macpherson et al., 2015). This would, theoretically, allow the PFC to effectively control both task demands, while simultaneously minimizing the potential affective impact of negative information. It is important to note that the older group used this attentional advantage not to outperform the placebo group but to retain their positive preference. In contrast to the widespread memory facilitation of glucose that was observed in young adults under cognitive load, older adults exhibited a more valence-specific glucose enhancement by remembering more positive words compared to the placebo group. Consistent with the idea that this preference for positive information can be a strong moderator of memory and attention processes in older adults' cognition (see Reed et al., 2014), it seems plausible that the positivity-related glucose facilitation effects were driven by older adults' priority to selectively remember more positive than negative information. Our findings seem to be in line with the cognitive control model of PEs showing the relevance of the availability of cognitive resources in the emergence of the phenomenon (Mather & Carstensen, 2005).

In summary, our results provide evidence to support the role of cognitive control as a potential moderator of PEs. If the necessary resources are available, older adults are more likely to recruit them to achieve goals that are consistent with their intrinsic motivation to prioritize positive material, rather than enhancing their overall cognitive performance. Furthermore, our findings can offer interesting insights into how older adults approach/avoid difficult situations. Lifestyle changes are imperative for maintaining good health. However, older adults' resistance to novelty (e.g., Fung, Carstensen, & Lutz, 1999) means that initiating

such changes requires effortful behavioral strategies. Considering that exerting effort can be inherently aversive (see Kurzban, 2016), failing to implement changes could be attributed to older adults' motivation to avoid unpleasant emotions. Glucose prior to a difficult task could potentially enable aging individuals to focus on the positive aspect of behavioral change (gains over costs), facilitating the transition to healthier lifestyles. If there is indeed a connection between emotionality and glucoregulation in aging, it would be interesting to explore whether motivation is driving the allocation of energy resources toward tasks that are more closely aligned with older adults' positivity preference.

References

Allard, E. S., & Isaacowitz, D. M. (2008). Are preferences in emotional processing affected by distraction? Examining the age-related positivity effect in visual fixation within a dual-task paradigm. *Aging, Neuropsychology, and Cognition*, *15*, 725–743.

Baumeister, R. F., Bratslavsky, E., Finkenauer, C., & Vohs, K. D. (2001). Bad is stronger than good. *Review of General Psychology*, *5*, 323–370.

Brandt, K. R., Sünram-Lea, S. I., Jenkinson, P. M., & Jones, E. (2010). The effects of glucose dose and dual-task performance on memory for emotional material. *Behavioural Brain Research*, *211*, 83–88.

Brandt, K. R., Sünram-Lea, S. I., & Qualtrough, K. (2006). The effect of glucose administration on the emotional enhancement effect in recognition memory. *Biological Psychology*, *73*, 199–208.

Brysbaert, M., Warriner, A. B., & Kuperman, V. (2014). Concreteness ratings for 40 thousand generally known English word lemmas. *Behavior Research Methods*, *46*, 904–911.

Carstensen, L. L. (1995). Evidence for a life-span theory of socioemotional selectivity. *Current Directions in Psychological Science*, *4*, 151–156.

Carstensen, L. L., Isaacowitz, D. M., & Charles, S. T. (1999). Taking time seriously: A theory of socioemotional selectivity. *American Psychologist*, *54*, 165–181.

Carstensen, L. L., Pasupathi, M., Mayr, U., & Nesselroade, J. R. (2000). Emotional experience in everyday life across the adult life span. *Journal of Personality and Social Psychology*, *79*, 644–655.

Carter, E. C., Kofler, L. M., Forster, D. E., & McCullough, M. E. (2015). A series of meta-

analytic tests of the depletion effect: Self-control does not seem to rely on a limited resource. *Journal of Experimental Psychology: General*, *144*, 796–815.

Charles, S. T., Mather, M., & Carstensen, L. L. (2003). Aging and emotional memory: The forgettable nature of negative images for older adults. *Journal of Experimental Psychology: General*, *132*, 310–324.

Coltheart, M. (1981). The MRC psycholinguistic database. *The Quarterly Journal of Experimental Psychology Section A*, *33*, 497–505.

Cortese, M. J., & Fugett, A. (2004). Imageability ratings for 3,000 monosyllabic words. *Behavior Research Methods*, *36*, 384–387.

Dolcos, S., Katsumi, Y., & Dixon, R. A. (2014). The role of arousal in the spontaneous regulation of emotions in healthy aging : A fMRI investigation. *Frontiers in Psychology*, *5*, 1–12.

Donohoe, R. T., & Benton, D. (1999). Cognitive functioning is susceptible to the level of blood glucose. *Psychopharmacology*, *145*, 378–385.

Fung, H. H., Carstensen, L. L., & Lutz, A. M. (1999). Influence of time on social preferences: Implications for life-span development. *Psychology and Aging*, *14*, 595–604.

Gagnon, C., Greenwood, C. E., & Bherer, L. (2010). The acute effects of glucose ingestion on attentional control in fasting healthy older adults. *Psychopharmacology*, *211*, 337–346.

Gailliot, M. T., Baumeister, R. F., DeWall, C. N., Maner, J. K., Plant, E. A., Tice, D. M., … Schmeichel, B. J. (2007). Self-control relies on glucose as a limited energy source: Willpower is more than a metaphor. *Journal of Personality and Social Psychology*, *92*, 325–336.

Grühn, D., & Scheibe, S. (2008). Age-related differences in valence and arousal ratings of pictures from the International Affective Picture System (IAPS): Do ratings become more extreme with age? *Behavior Research Methods*, *40*, 512–521.

Hoyland, A., Lawton, C. L., & Dye, L. (2008). Acute effects of macronutrient manipulations on cognitive test performance in healthy young adults: A systematic research review. *Neuroscience & Biobehavioral Reviews*, *32*, 72–85.

Isaacowitz, D. M., & Blanchard-Fields, F. (2012). Linking process and outcome in the study of emotion and aging. *Perspectives on Psychological Science*, *7*, 3–17.

Kehoe, E. G., Toomey, J. M., Balsters, J. H., & Bokde, A. L. W. (2013). Healthy aging is associated with increased neural processing of positive valence but attenuated processing of emotional arousal: An fMRI study. *Neurobiology of Aging*, *34*, 809–821.

Kennedy, D. O., & Scholey, A. B. (2000). Glucose administration, heart rate and cognitive performance: Effects of increasing mental effort. *Psychopharmacology*, *149*, 63–71.

Kensinger, E. A. (2004). Remembering emotional experiences: The contribution of valence and arousal. *Reviews in the Neurosciences*, *15*, 241–251.

Kensinger, E. A. (2008). Age differences in memory for arousing and nonarousing emotional words. *The Journals of Gerontology. Series B, Psychological Sciences and Social Sciences*, *63B*, 13–18.

Knight, M., Seymour, T. L., Gaunt, J. T., Baker, C., Nesmith, K., & Mather, M. (2007). Aging and goal-directed emotional attention: Distraction reverses emotional biases. *Emotion*, *7*, 705–714.

Kurzban, R. (2016). The sense of effort. *Current Opinion in Psychology*, *7*, 67–70.

Leclerc, C. M., & Kensinger, E. A. (2008). Effects of age on detection of emotional

information. *Psychology and Aging*, *23*, 209–215.

Macpherson, H., Roberstson, B., Sünram-Lea, S., Stough, C., Kennedy, D., & Scholey, A. (2015). Glucose administration and cognitive function: Differential effects of age and effort during a dual task paradigm in younger and older adults. *Psychopharmacology*, *232*, 1135–1142.

Mather, M. (2016). The affective neuroscience of aging. *Annual Review of Psychology*, *67*, 213–238.

Mather, M., Canli, T., English, T., Whitfield, S., Wais, P., Ochsner, K., … Carstensen, L. L. (2004). Amygdala responses to emotionally valenced stimuli in older and younger adults. *Psychological Science*, *15*, 259–263.

Mather, M., & Carstensen, L. L. (2005). Aging and motivated cognition: The positivity effect in attention and memory. *Trends in Cognitive Sciences*, *9*, 496–502.

Mather, M., & Knight, M. (2005). Goal-directed memory: The role of cognitive control in older adults' emotional memory. *Psychology and Aging*, *20*, 554–570.

Mather, M., & Knight, M. R. (2006). Angry faces get noticed quickly: Threat detection is not impaired among older adults. *The Journals of Gerontology. Series B, Psychological Sciences and Social Sciences*, *61*, 54–57.

Messier, C. (2004). Glucose improvement of memory: A review. *European Journal of Pharmacology*, *490*, 33–57.

Murty, V. P., Sambataro, F., Das, S., Tan, H. Y., Callicott, J. H., Goldberg, T. E., … Mattay, V. S. (2009). Age-related alterations in simple declarative memory and the effect of negative stimulus valence. *Journal of Cognitive Neuroscience*, *21*, 1920–1933.

Parsons, M. W., & Gold, P. E. (1992). Glucose enhancement of memory in elderly humans:

An inverted-U dose-response curve. *Neurobiology of Aging*, *13*, 401–404.

Pashler, H. (1994). Dual-task interference in simple tasks: Data and theory. *Psychological Bulletin*, *116*, 220–244.

Petrican, R., Moscovitch, M., & Schimmack, U. (2008). Cognitive resources, valence, and memory retrieval of emotional events in older adults. *Psychology and Aging*, *23*, 585–594.

Raven, J. C., Raven, J., & Court, J. H. (1988). *The Mill Hill vocabulary scale. Manual for Raven's progressive matrices and vocabulary scales*. London: H. K. Lewis.

Reed, A. E., Chan, L., & Mikels, J. A. (2014). Meta-analysis of the age-related positivity effect: Age differences in preferences for positive over negative information. *Psychology and Aging*, *29*, 1–15.

Riby, L. M. (2004). The impact of age and task domain on cognitive performance: A meta-analytic review of the glucose facilitation effect. *Brain Impairment*, *5*, 145–165.

Riby, L. M., McMurtrie, H., Smallwood, J., Ballantyne, C., Meikle, A., & Smith, E. (2006). The facilitative effects of glucose ingestion on memory retrieval in younger and older adults: Is task difficulty or task domain critical? *The British Journal of Nutrition*, *95*, 414–420.

Riby, L. M., Meikle, A., & Glover, C. (2004). The effects of age, glucose ingestion and gluco-regulatory control on episodic memory. *Age and Ageing*, *33*, 483–487.

Salthouse, T. A. (2010). Selective review of cognitive aging. *Journal of the International Neuropsychological Society*, *16*, 754–760.

Schock, J., Cortese, M. J., & Khanna, M. M. (2012). Imageability estimates for 3,000 disyllabic words. *Behavior Research Methods*, *44*, 374–379.

Scholey, A. B., Harper, S., & Kennedy, D. O. (2001). Cognitive demand and blood glucose. *Physiology & Behavior*, *73*, 585–592.

Scholey, A. B., Sünram-Lea, S. I., Greer, J., Elliott, J., & Kennedy, D. O. (2009). Glucose administration prior to a divided attention task improves tracking performance but not word recognition: Evidence against differential memory enhancement? *Psychopharmacology*, *202*, 549–558.

Scholey, A., MacPherson, H., Sünram-Lea, S., Elliott, J., Stough, C., & Kennedy, D. (2013). Glucose enhancement of recognition memory: Differential effects on effortful processing but not aspects of "remember-know" responses. *Neuropharmacology*, *64*, 544–549.

Smith, M. A., Riby, L. M., Eekelen, J. A. M. Van, & Foster, J. K. (2011). Glucose enhancement of human memory: A comprehensive research review of the glucose memory facilitation effect. *Neuroscience and Biobehavioral Reviews*, *35*, 770–783.

St. Jacques, P., Bessette-Symons, B., & Cabeza, R. (2009). Functional neuroimaging studies of aging and emotion: Fronto-amygdalar differences during emotional perception and episodic memory. *Journal of the International Neuropsychological Society*, *15*, 819–825.

Sünram-Lea, S. I., Foster, J. K., Durlach, P., & Perez, C. (2002). Investigation into the significance of task difficulty and divided allocation of resources on the glucose memory facilitation effect. *Psychopharmacology*, *160*, 387–397.

Sünram-Lea, S. I., Owen, L., Finnegan, Y., & Hu, H. (2011). Dose-response investigation into glucose facilitation of memory performance and mood in healthy young adults. *Journal of Psychopharmacology*, *25*, 1076–1087.

Vadillo, M. A., Gold, N., & Osman, M. (2016). The bitter truth about sugar and willpower: The limited evidential value of the glucose model of ego depletion. *Psychological Science*, *27*, 1207–1214.

Warriner, A. B., Kuperman, V., & Brysbaert, M. (2013). Norms of valence, arousal, and dominance for 13,915 English lemmas. *Behavior Research Methods*, *45*, 1191–1207.

Wechsler, D. (1981). *WAIS-R manual: Wechsler adult intelligence scale-revised*. New York: Psychological Corporation.

Table 1

Characteristics of the Samples and Performance on the Secondary Task as a Function of Age and Drink

	Experiment 1				Experiment 2	
	Young		Older		Older	
	Glucose	Placebo	Glucose	Placebo	Glucose	Placebo
Characteristics						
N (M/F)[1]	20 (2/18)	20 (2/18)	21 (9/12)	21 (9/12)	20 (8/12)	20 (7/13)
Age	19.50 (2.54)	18.80 (0.77)	72.19 (3.43)	71.38 (4.78)	73.05 (3.83)	72.90 (3.84)
Years of education	14.20 (0.41)	13.60 (0.68)	16.62 (2.80)	17.00 (3.39)	16.40 (3.27)	15.90 (2.32)
Speed[2]	69.55 (9.12)	66.55 (11.36)	57.67 (14.26)	54.43 (10.91)	53.35 (10.49)	54.45 (11.25)
Vocabulary[3]	16.35 (2.46)	15.40 (2.95)	23.52 (3.01)	23.71 (4.44)	25.05 (3.40)	24.20 (4.15)
Secondary task						
Reaction time[4]	732.91 (93.71)	735.80 (92.50)	729.77 (90.90)	772.54 (79.34)	780.47 (119.92)	764.10 (100.7)
Accuracy[5]	83.52 (12.51)	83.29 (10.45)	90.58 (7.99)	87.88 (10.45)	87.86 (13.07)	87.62 (9.26)

Note. All values except for *N* (M/F) are given as means (with standard deviations).

[1] Number of participants in each age and drink group (male/female). [2] Processing speed as measured by the Digit Symbol Substitution task (Wechsler, 1981). [3] Vocabulary score as measured by the multiple-choice section of the Mill Hill vocabulary test out of a maximum of 33 (Raven, Raven, & Court, 1988). [4] Reaction time in milliseconds. [5] Percentage accuracy calculated as 100 × ((Number of correct hits ÷ Number of 1-back matches) – (Number of false alarms ÷ Number of non-matches)).

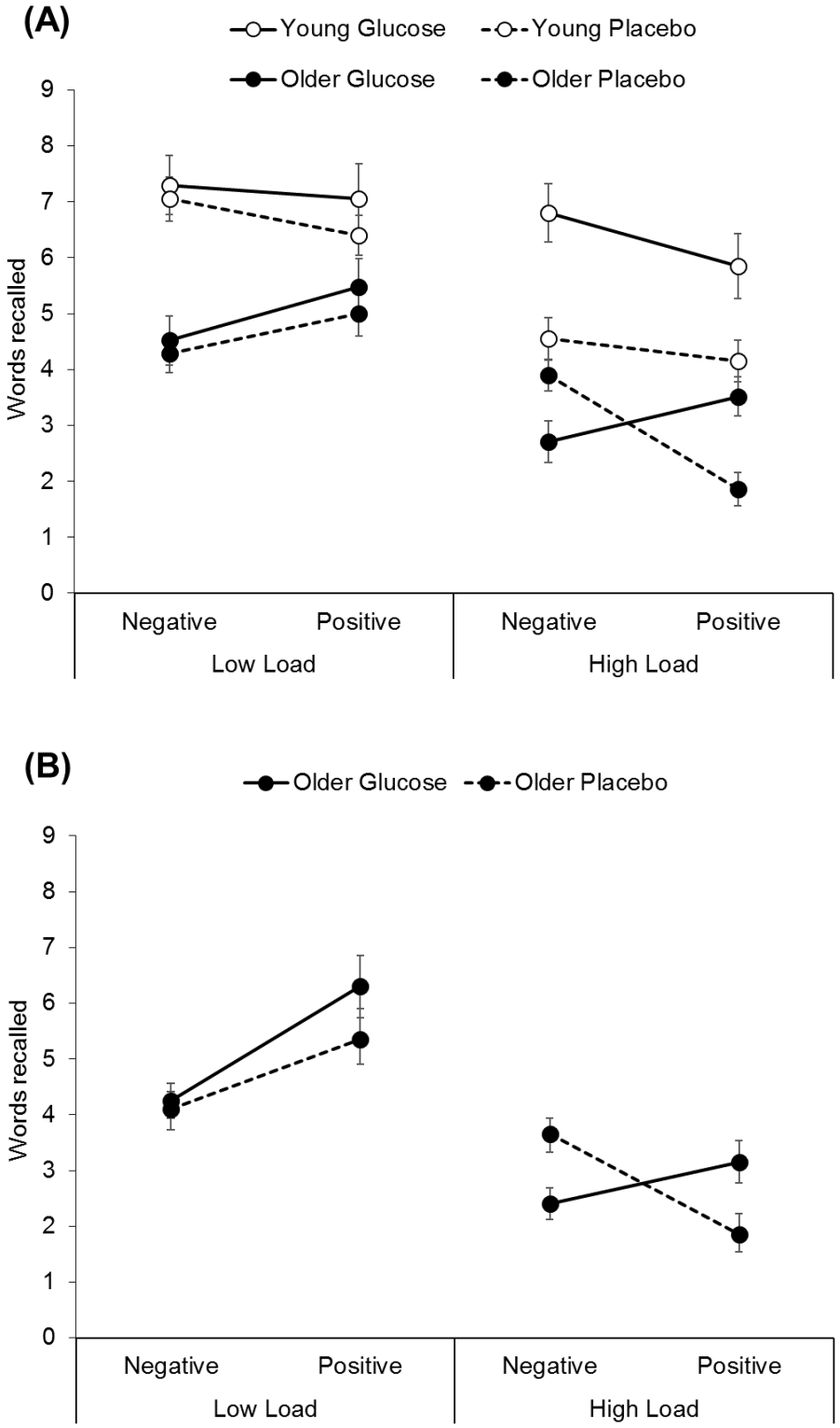

Figure 1. Mean number of words recalled out of 20 (± standard error of mean) as a function of drink (glucose/placebo), valence (negative/positive) and load (low/high) for (A) young and older adults in Experiment 1, and (B) older adults in Experiment 2.