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Gain Without Pain: Glucose Promotes Cognitive Engagement and Protects Positive Affect in Older Adults

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Abstract

When faced with a cognitively demanding task, older adults tend to disengage and withdraw effort. At the same time, their usual processing preference for positive information disappears. Providing glucose as an energy resource is known to improve cognitive performance and reinstate older adults' positivity preference. Here, we examined whether glucose can help older adults to exert more effort under high difficulty conditions, and if so, whether such increase is accompanied by a change in positive affect. Fifty-three young and 58 older adults consumed a glucose or a placebo drink and completed a memory-search task at three levels of difficulty. Cognitive engagement was measured through changes in heart rate and self-reported effort. After each memory-search block, participants completed an implicit emotion-assessment task. In both age groups, glucose produced increased heart rate (indicating higher task engagement) relative to placebo. In older but not in young adults, glucose also improved cognitive performance and increased positive affect. Subjective effort, in contrast, did not differ between the older-glucose and older-placebo groups. These results suggest that in older adults, glucose improves cognitive performance by promoting higher cognitive engagement while mitigating the subjective costs of effortful exertion.

Keywords: aging, cognitive engagement, glucose, heart rate, affect

Word count: 5313

Gain Without Pain: Glucose Promotes Cognitive Engagement and Protects Positive Affect in Older Adults

The ability to initiate effortful behavioral strategies and persist even when success seems unlikely is a fundamental human attribute that has been linked to positive health and social outcomes, especially in aging (Rowe & Kahn, 1997). Recent evidence suggests that cognitive engagement and participation in intellectually stimulating activities contribute to the maintenance of cognitive skills and the attenuation of age-related cognitive decline (for review, see Hertzog, Kramer, Wilson, & Lindenberger, 2009). However, the neuroanatomical and cognitive changes that occur naturally in the course of healthy aging (for reviews, see Antonenko & Flöel, 2014; Rossini, Rossi, Babiloni, & Polich, 2007; Salthouse, 2010) pose constraints on older adults' ability to maintain complex cognitive strategies and high levels of task engagement during cognitive exertion. Such age-related processing decrements make cognitive exertion more difficult for older adults (Hess & Ennis, 2012), as evidenced by the sharp decline in older adults' chances of success in high difficulty tasks compared with their young counterparts (for review, see Drag & Bieliauskas, 2010).

This pattern is observed not only in behavioral but also in physiological indices. Actively engaging in demanding cognitive tasks mobilizes the sympathetic nervous system (Wright, 1996) and increases the activity of peripheral physiological mechanisms linked to myocardial sympathetic function (Richter, Friedrich, & Gendolla, 2008). Therefore, cardiovascular (CV) indices such as heart rate and systolic blood pressure responsivity during cognitive performance might reflect objective measures of cognitive engagement (for review, see Richter, Gendolla, & Wright, 2016).[1] Recent studies measuring young and older adults' CV changes in response to cognitive tasks of increasing difficulty found age-related differences in the effect of task demands on physiological reactivity. In both young and older adults, CV reactivity increases strongly in relatively easy tasks where success seems attainable and within the participants' control, but it increases substantially less in tasks that surpass their cognitive capabilities (i.e., participants exerting submaximal cognitive effort). However, this relative reduction in the increase of CV responsivity during difficult cognitive tasks is more pronounced in old age, suggesting that the threshold for reducing one's task engagement is lower in older than in young adults (Ennis, Hess, & Smith, 2013; Hess, Smith, & Sharifian, 2016).

Such lower threshold might reflect an adaptive mechanism aimed at safeguarding energy resources available for cognitive processing (Hess, 2014). The physiological underpinnings of energy availability and utilization can be traced back to the regulation of glucose, the main energy fuel subserving all biological functions. Supporting the notion that cognitive effort is glucose dependent, moderate increases in peripherally circulating blood glucose have been shown to facilitate cognitive performance (for reviews, see Messier, 2004; Riby, 2004; Smith, Riby, van Eekelen, & Foster, 2011), particularly in more demanding tasks (Gagnon, Greenwood, & Bherer, 2010; Macpherson et al., 2015; Mantantzis, Schlaghecken, & Maylor, 2017; Scholey et al., 2013; Scholey, Sünram-Lea, Greer, Elliott, & Kennedy, 2009; Sünram-Lea, Foster, Durlach, & Perez, 2002). With increasing age, the efficiency of glucoregulation deteriorates: typical aging is accompanied by impaired peripheral and cerebral glucose metabolism (Biessels, Bravenboer, & Gispen, 2004; Blesa et al., 1997; Kuhl, Metter, Riege, & Hawkins, 1984; Messier & Gagnon, 1996), reduced insulin sensitivity (Chang & Halter, 2003; Melanson et al., 1998), and higher glucose depletion and slower replenishing rates following performance on cognitively challenging tasks (Gold, 2005). Given such inherent age-related difficulties in the mobilization and restoration of energy resources, it is perhaps not surprising that older adults would be more cautious than young adults about spending energy on activities that would compromise the availability of these valuable resources. If a task requires high energy expenditure but promises little benefit (i.e., costs outweighing potential gains), it makes intuitive sense that older adults would show a more pronounced effort withdrawal than their young counterparts, as evidenced by the steeper reduction of CV responsivity with increased task difficulty in aging (Ennis et al., 2013; Hess et al., 2016). In view of evidence suggesting that older adults often benefit more from glucose administration than young adults, whose glucoregulatory mechanisms are usually intact and who do not necessarily require external glucose administration to perform at the peak of their cognitive skills (e.g., Hall, Gonder-Frederick, Chewning, Silveira, & Gold, 1989; Macpherson et al., 2015; Manning, Parsons, Cotter, & Gold, 1997), it is likely that older adults' cognitive engagement patterns are modulated by glucose availability.

Although a facilitative effect of glucose on older adults' cognition has been observed in previous studies, recent evidence suggests that glucose does not necessarily lead to improved cognitive performance but can be used by older adults to prioritize other aspects of their performance. For instance, glucose ingestion makes older adults more likely to prioritize positive over negative information (Positivity Effect; for reviews, see Mather & Carstensen, 2005; Scheibe & Carstensen, 2010), whereas young adults use it to optimize their overall performance (Mantantzis et al., 2017). It is possible that the purpose of this positivity bias is to help older adults maintain their positive affect (e.g., Isaacowitz, Toner, & Neupert, 2009; Kappes, Streubel, Droste, & Folta-Schoofs, 2017), although the relationship between the positivity effect and positive affect has been contested (Isaacowitz & Blanchard-Fields, 2012).

Overall, the picture that emerges is that older adults' performance deficits in cognitively demanding tasks are driven by the dual disadvantage of increased cognitive difficulty (due to age-related neural decline) and decreased efficiency in utilizing and replenishing physiological resources, potentially leading older adults to reduce their cognitive engagement in difficult tasks at a lower threshold than young adults. So far, however, this scenario is merely intuitively plausible. No study has yet directly investigated the relationship between not only age, task difficulty, and availability of physiological resources, but also their combined effects on cognitive engagement, task performance, subjective effort and affect. The present experiment aimed to address these issues. We asked young and older adults to consume a glucose or a placebo drink and to perform a memory-search task consisting of three blocks of different levels of difficulty, calibrated so as to be centered on each participant’s individual memory span. We measured participants’ heart rate (HR) at rest and during task performance, and calculated task-related HR change as a measure of task engagement. At the end of each block, participants rated their effort on a self-report scale and completed an implicit emotion-assessment task to assess their levels of positive or negative affect.

We expected the following pattern of results: First, in view of findings suggesting that older adults prioritize the preservation of processing resources, we expected older adults to perform less well in the memory-search task than young adults despite the individually calibrated difficulty levels, and to show greater signs of disengagement at high task difficulty. It should be noted that we operationalize cognitive engagement as HR change, assumed to reflect the level of effort exerted in a task, irrespective of whether this results in improved cognitive performance (Hess, 2014). Second, based on the assumption that age-related constraints in neural processing capacity and energy metabolism make cognitive tasks more effortful for older than for young adults, we expected older adults to give higher subjective effort ratings than young adults. Third, in line with evidence showing that task engagement increases with more challenging tasks but decreases when success seems unattainable, we expected HR changes to be largest in the medium difficulty condition and to decrease from the medium to the high difficulty condition, particularly in older adults. The question of interest was how glucose would affect these measures, particularly in older adults. If the scenario outlined above is correct, that is, if additional energy resources enable older adults to increase task engagement without compromizing their resource balance, then we should expect older adults in the glucose group to show greater task-related HR change and improved memory-search performance, without feeling that they have exerted more effort. We also expected that older adults' positive affect might be reduced with increasing task difficulty. We hypothesized that glucose could help older adults retain their positive emotionality by increasing their ability to successfully perform the task without compromizing resource availability.

Method

Design and Drinks

We employed a between-subjects 2 (Age: young vs. older) × 2 (Drink: glucose vs. placebo) randomized, placebo-controlled, double-blind design. All drinks were prepared and labelled by assistants to ensure that the experimenter was unaware of the composition of the drinks. Participants assigned to the glucose condition were asked to consume a drink containing 25 g of glucose. The placebo groups were given a non-glucose drink of equivalent sweetness (five aspartame tablets). Both drinks were dissolved in 300 ml of water and 25 ml of sugar-free orange-flavored cordial (to improve palatability). The glucose dose was chosen based on previous studies indicating that 25 g of glucose is sufficient for observing cognitive enhancement in both young and older adults (Parsons & Gold, 1992; Riby, 2004; Sünram-Lea, Owen, Finnegan, & Hu, 2011). The drink composition used in the current study does not lead to differences in palatability ratings between glucose and placebo (see Mantantzis et al., 2017).

Participants

The sample consisted of 54 healthy first-year undergraduate students (age range 18-27) and 58 healthy community-dwelling older adults (age range 65-82). The study was approved by the Psychology Department’s Research Ethics Committee at the University of Warwick and all participants provided written consent. Older adults were compensated £10 and young adults were offered course credit in exchange for their participation. Exclusion criteria included self-reported history of recent neurological or psychiatric disorders, diabetes, CV disease and use of medication that could potentially affect CV reactivity (e.g., β-blockers). The sample size was determined based on previous work indicating that age-related differences in task engagement (i.e., changes in CV responses) can be identified with a sample of 50-55 participants per age group (Ennis et al., 2013; Hess & Ennis, 2012; Smith & Hess, 2015), and glucose studies requiring approximately 25 participants per drink condition (Gagnon et al., 2010; Macpherson et al., 2015). One young participant failed to complete the testing session, leaving 53 young adults in the final sample. HR data from six older adults (four glucose, two placebo) were excluded from further analysis because of artifacts affecting accurate heart-beat detection,[2] leading to a final sample of 52 older adults for HR analysis. The full sample of 58 older adults was used in all other analyses (see Table 1 for characteristics of the final sample).

Both young and older adults completed background measures of short-term memory (forward digit span; Wechsler, 1981), processing speed (Digit Symbol Substitution task; Wechsler, 1981) and vocabulary knowledge (Mill Hill vocabulary test; Raven, Raven, & Court, 1988). As expected, older adults had lower speed scores, $t(109) = -8.29$, $p < .001$, higher vocabulary scores, $t(109) = 12.06$, $p < .001$, and more years of formal education, $t(109) = 5.39$, $p < .001$, compared with young adults. Young adults had lower digit span scores compared with older adults, $t(109) = -2.71$, $p = .008$. Further examination of education, digit span, speed, and vocabulary differences between the glucose and placebo groups within each age group revealed that the young-placebo group had marginally higher speed scores compared with the young-glucose group, *t*(51) = 1.96, *p* = .056. No other differences were identified (all *p*s > .37).

Cognitive Tasks and Equipment

CV responsivity. Heart rate was continuously measured throughout the testing session using a standard 3-lead ECG electrode placement configuration. Disposable Ag/AgCl pre-gelled ECG electrodes were placed on the participant's right wrist ('negative'), left wrist ('ground') and left ankle ('positive'), and connected to a BIOPAC MP36 data acquisition system (BIOPAC Systems Inc., Goleta, CA, USA). The ECG signal was digitized at a 1,000 Hz sampling rate and filtered online with a low-pass filter of 35 Hz and a high-pass filter of 0.5 Hz. Stimulus delivery markers were sent to BIOPAC's Acq*Knowledge* recording software (version 4.2) through a parallel port, and saved in digital channels. The analog (ECG signal) and digital channels (event markers) were synchronized and visually displayed on Acq*Knowledge*. The 5-minute baseline and cognitive block segments were extracted from the raw ECG signal and subsequently entered into Kubios version 2.2 (Tarvainen, Niskanen, Lipponen, Ranta-aho, & Karjalainen, 2014), which allows for automatic detection of heart beats and HR calculations. To ensure that all heart beats were accurately detected, the raw ECG signal was visually inspected. Additionally, Kubios's medium artifact correction level was used to identify and correct potential artifacts. Across both age groups, less than 1% of identified heart beats were marked as artifacts and were corrected before analysis.

Memory search. Participants performed a memory-search task (Sternberg, 1966) consisting of three blocks at different levels of difficulty: low, medium and high. A set of pseudo-randomly selected consonants were presented on a 20-inch screen, with no single consonant appearing more than once in the same trial. White uppercase letters appeared in random positions on the edges of a 150 × 150 pixels square centered on the middle of the screen, and drawn on a black background. Each letter subtended a visual angle of 0.95^o at a 60-cm viewing distance. The consonants remained on the screen for 3 s and participants were asked to memorize them. After a 2-s retention period (blank screen), a single target letter appeared at the center of the screen and participants had to press a key as fast and accurately as possible to indicate whether the target letter was part of the set of consonants presented immediately before. The target remained on the screen for 2.5 s or until a response was made. Participants responded with their left and right index fingers (left 'Z' key for a new target, right 'M' key for a memory set target). After a response was recorded, the target disappeared and the screen remained blank for the rest of the 2.5-s period. All trials were preceded by a 1-s central fixation cross. The probability of the target letter being part of the memory set was 50%. Each block consisted of 36 trials and lasted for a fixed duration of approximately five minutes (8.5 s per trial) to allow for meaningful comparisons of CV responsivity across difficulty blocks, age and drink groups. The size of the memory sets (i.e., number of letters presented) was based on each participant's individual short-term memory capacity as measured by the forward digit span subscale of the WAIS (Wechsler, 1981). Blocks were created such that the medium difficulty level set size would match each participant's short-term memory capacity. The low difficulty level contained three fewer and the high difficulty level had three more items than each participant's short-term memory capacity. For example, a participant with a forward digit span of seven items was given a low difficulty block of four items, a medium difficulty block of seven items and a high difficulty block of 10 items. The presentation order of the difficulty blocks was counterbalanced.

Effort ratings. The 'effort' subscale of the NASA Task Load Index (NASA-TLX; Hart & Staveland, 1988) was used to evaluate subjective perception of effort expended in the task (question: 'how hard did you have to work to accomplish your level of performance?'). At the end of each block, participants were asked to give their rating by using the computer mouse to place the cursor on one field of a 10-point scale, displayed horizontally in the middle of the screen and ranging from 1 (‘very low’) to 10 (‘very high’).

Affective judgment. Affect was measured through an affective judgment task based on Bartoszek and Cervone's (2016) implicit emotion-assessment task. This task has been shown to accurately detect changes in affect following mood manipulation and exposure to emotional material (e.g., fear-inducing stimuli), and can be assumed to be more sensitive to small changes in emotionality compared with self-report/explicit affect-assessment tools (Abercrombie, Kalin, & Davidson, 2005; Quirin, Kazén, Rohrmann, & Kuhl, 2009).

At the end of each memory-search block, participants were asked to rate 10 abstract expressionist artworks. Participants were required to give a response by using the computer mouse to place the cursor on one field of a 7-point scale (displayed horizontally below the painting) ranging from -3 (‘very negative’) to 3 (‘very positive’). A set of 10 new paintings were presented after each block. Each painting remained on the screen until a rating was given. We opted for paintings depicting ambiguous abstract patterns and excluded paintings containing figures (e.g., human faces) or items that could influence emotional states because of familiarity. Paintings were retrieved from the internet. All stimuli were gray-scaled and resized to 500 × 400 pixels, and were presented one at a time at the center of the screen. A 1-s central fixation cross preceded each trial. Participants were asked to rely on their first impression of the painting and give their ratings immediately. This was done to ensure that their affective ratings were based on heuristic processes, which have been shown to accurately reflect participants’ affective state, rather than controlled processes, which could introduce processing biases, such as social desirability and situation-related beliefs about emotion, that can influence explicit measures of affect (Quirin, Kazén, & Kuhl, 2009).

Procedure

Participants were instructed to avoid consuming any food or drink for two hours before coming to the lab. All participants reported to have adhered to that condition. Upon arrival, participants signed a consent form, provided demographic information and completed the digit span test. After that, they were connected to the ECG equipment and given instructions on optimal testing conditions (e.g., avoid excessive movement). This was followed by a 7-minute period during which participants were asked to sit back and relax. The final five minutes of the 7-minute resting period were used as the HR baseline for each participant. At the end of the resting period, participants were given instructions on how to perform the cognitive tasks and were asked to consume the glucose or placebo drink within five minutes. After the drink, participants completed a short practice to familiarize themselves with the procedure and timings. The practice phase consisted of four memory-search trials per difficulty block (two target matches and two non-matches per block). At the end of each memory-search practice block, they completed the effort self-report scale and rated two paintings (different from the ones presented in the actual task). Following the end of the practice and 10 minutes after drink ingestion, participants were given the full cognitive task. At the end of the testing session, young participants completed the processing speed and vocabulary tests (older participants completed these during an earlier session). Finally, they were compensated for their participation and debriefed.

Results

Cognitive Performance

Two separate three-way mixed analyses of variance (ANOVAs) were conducted on mean correct reaction times (RTs) and error rates (Figures 1A and 1B, respectively), with age (young, older) and drink (glucose, placebo) as the between-subjects factors, and difficulty (low, medium, high) as the within-subjects factor. Follow-up *t* tests were used to further examine significant interactions between factors.

Overall, young adults were faster and more accurate than older adults ($F(1, 107) = 107.60$, $p < .001$, $\eta_p^2 = .501$, and $F(1, 107) = 13.55$, $p < .001$, $\eta_p^2 = .112$, for RTs and error rates, respectively). Responses were both slower and less accurate with increasing task difficulty (RTs: $F(2, 214) = 133.56$, $p < .001$, $\eta_p^2 = .555$; error rates: $F(2, 214) = 390.34$, $p < .001$, $\eta_p^2 = .785$), and this performance decline was steeper in older than in young adults, as reflected in Age × Difficulty interactions (RTs: $F(2, 214) = 25.58$, $p < .001$, $\eta_p^2 = .193$; error rates: $F(2, 214) = 8.49$, $p < .001$, $\eta_p^2 = .074$). RTs were shorter with glucose than with placebo, $F(1, 107) = 3.96$, $p = .049$, $\eta_p^2 = .036$, though the corresponding effect for error rates was not significant, $F = 1.88$, $p = .17$. However, the Age × Drink interaction was significant for both RTs, $F(1, 107) = 6.21$, $p = .014$, $\eta_p^2 = .055$, and error rates, $F(1, 107) = 5.70$, $p = .019$, $\eta_p^2 = .051$: whereas older adults in the glucose group were overall significantly faster ($t(56) = -3.64$, $p = .001$) and more accurate ($t(56) = 2.81$, $p = .007$) than those in the placebo group, no glucose effect was found in young adults (both *p*s > .50).

CV Responsivity and Subjective Effort

Heart rate. Percentage HR change from baseline was used as the physiological index of effortful exertion/task engagement in the memory-search task (see Figure 2A). Thus, change scores for the cognitive blocks were calculated individually for each participant as ([Raw HR during cognitive block / Raw HR during baseline] – 1) × 100.

Compared to young adults, older adults showed higher HR change, $F(1, 101) = 12.87$, $p = .001$, $\eta_p^2 = .113$. HR change varied with difficulty, $F(2, 202) = 13.49$, $p < .001$, $\eta_p^2 = .118$, being greatest in the medium difficulty block and smallest in the low difficulty block. Pairwise comparisons between difficulty conditions confirmed that they all were significantly different from each other, all *t*s > 2.6, all *p*s < .01. However, whereas young adults' HR change was comparable between medium and high difficulty, *t*(52) = -0.97, *p* = .339, HR reactivity in older adults was significantly smaller in the high than medium difficulty level, *t*(51) = -2.85, *p* = .006. Finally, glucose led to higher HR change during the cognitive task than did placebo, *F*(1, 101) = 11.82, *p* = .001, $\eta_p^2 = .105$. This was true for both age groups: *t*(51) = 2.76, *p* = .008, and *t*(50) = 2.06, *p* = .045, for young and older adults, respectively. There were no interactions (all *F*s < 2.08, all *p*s > .12).

Subjective effort. Subjective effort ratings (see Figure 2B) rose with increasing difficulty, *F*(2, 214) = 293.39, *p* < .001, $\eta_p^2 = .733$, and older adults rated their cognitive exertion as being more effortful compared with young adults, *F*(1, 107) = 3.99, *p* = .048, $\eta_p^2 = .036$. Glucose did not affect subjective effort perception, *F* < 1, nor were there any interactions between age, difficulty, and drink (all *F*s < 1.69, all *p*s > .18).

Affective Judgment

Figures 3A and 3B display participants' mean affective ratings and RTs, respectively. Older adults took longer than young adults to rate each painting, *F*(1, 107) = 94.15, *p* < .001, $\eta_p^2 = .468$. No other main effects or interactions were significant for RTs (all *F*s < 2, all *p*s > .16). Importantly, older adults rated the pictures more positively than did young adults, *F*(1, 107) = 9.96, *p* = .002, $\eta_p^2 = .085$. Moreover, this effect of age was qualified by an Age × Drink interaction, *F*(1, 107) = 5.01, *p* = .027, $\eta_p^2 = .045$: whereas young adults' ratings were not affected by drink, *t* < 1, older adults in the glucose group gave significantly more positive ratings compared with their placebo counterparts, *t*(56) = 2.53, *p* = .014. There were no other main effects or interactions for ratings (all *F*s < 2.53, all *p*s > .11).[3]

Discussion

The present study examined the relationship between task difficulty and availability of physiological resources, and their combined effects on older adults' cognitive engagement and task performance, including subjective effort and affect. As expected, older adults performed less well in the memory task than did young adults, especially as difficulty increased, and found their performance to be more effortful. Whereas both age groups showed maximal CV reactivity at the medium difficulty level, older adults' task disengagement at the high difficulty level was more pronounced than young adults' CV withdrawal. Although glucose did not affect cognitive performance in young adults, older adults in the glucose group performed better in the cognitive task, showed greater HR change, and their affect scores were more positive, compared with their placebo counterparts. Despite older-glucose participants outperforming older-placebo, the subjective effort ratings of the two groups were similar, indicating that the older-glucose group was able to exert more effort and improve their performance without feeling more challenged. In fact, the numerical trend showed that older adults in the glucose group rated their performance to be slightly less effortful compared with placebo, in line with their more positive affect scores.

In terms of cognitive performance, we predicted that glucose administration would significantly improve participants' RTs and error rates, and this effect would be more robust for older adults (e.g., Hall et al., 1989; Macpherson et al., 2015; Manning et al., 1997). As expected, we identified a glucose-related improvement in both RTs and error rates for older but not young adults. Given that previous studies have found glucose enhancement to be more pronounced under dual-task conditions that require the simultaneous coordination of multiple cognitive functions, and are less reliable when simply manipulating the difficulty of a single task (e.g., Sünram-Lea et al., 2002), the absence of glucose effects on young adults' performance is not surprising. In contrast, glucose improved older adults' performance on the memory task across all difficulty levels. It is worth recalling that task difficulty was calibrated for each participant individually. Therefore, one might have expected similar low effort ratings and lack of glucose effects in the ‘easy’ condition for both age groups. However, there is evidence to suggest that glucose can improve older adults’ cognitive performance even under relatively easy testing conditions (e.g., Manning et al., 1997; Manning, Parsons, & Gold, 1992; Manning, Stone, Korol, & Gold, 1998; Messier, Tsiakas, Gagnon, Desrochers, & Awad, 2003; Riby et al., 2006). Our results suggest that in the present task, even the individually calibrated ‘easy’ condition was substantially more effortful for older than for young participants, in line with the observation that aging is associated with increased subjective perceptions of difficulty (Hess & Ennis, 2012; Hess et al., 2016).

Consistent with previous findings (Ennis et al., 2013; Hess & Ennis, 2012; Hess et al., 2016; Smith & Hess, 2015), older adults showed higher task engagement than young adults during the memory-search task, reflected in higher CV responsivity and higher self-reported effort. Both young and older adults showed an increase in CV responsivity from the low to the medium difficulty condition. Similar to previous studies (Ennis et al., 2013; Hess et al., 2016), task disengagement from medium to high difficulty was more pronounced in older than in young adults (-1.37% and -0.42%, respectively, with only the former significant). This finding supports the role of CV reactivity as a measure of task engagement (Hess & Ennis, 2014; Richter et al., 2016).

The main question of interest was whether glucose would allow older adults to increase their level of task engagement, and how this would relate to cognitive performance, subjective effort ratings, and affect. As predicted, glucose administration increased effortful exertion irrespective of difficulty, with the glucose groups showing higher task engagement throughout the memory-search task compared with placebo. However, whereas older adults’ increased task engagement was associated with an improvement in cognitive performance, the same was not observed in young adults. Although ‘task engagement’ is defined as the individual’s willingness to invest resources in the task, irrespective of whether this results in improved cognitive performance (Hess, 2014), the question why increased engagement was associated with improved performance in older but not young adults cannot be answered on the basis of the present data, and will have to await future studies investigating the connection between CV indices, task engagement and cognitive performance.

As expected, despite older-glucose participants outperforming their placebo counterparts in the memory-search task, the effort self-report ratings of the two groups showed no differences. Not only did glucose administration increase task engagement and improve older adults’ cognitive performance, it also kept subjective perceptions of expended effort to levels comparable to those obtained from the placebo group. It has been shown that one of the main factors contributing to older adults’ willingness to exert effort is their subjective perception of the cognitive costs associated with performance on the task: if the cognitive cost of performing the task is seen as prohibitive, older adults are more likely to disengage and withdraw effort (Hess et al., 2016). The present results demonstrate that glucose administration enables older adults to maintain high levels of task engagement without subjective costs.

Furthermore, in line with reports of higher positive affect in older adults (Carstensen, 1995; Scheibe & Carstensen, 2010), in the implicit affect assessment task, older adults rated the paintings as more positive than did young adults. Importantly, whereas young adults’ affective ratings were not influenced by the drink condition to which they were allocated, older adults in the glucose group gave more positive ratings than their placebo counterparts despite expending more effort to perform the memory-search task. This effect might be task specific (i.e., decreasing a potential negative emotional impact of performing the memory-search task) or might be a non-specific increase in general positivity (as a by-product of ingesting glucose, unrelated to the task). However, the general conclusion remains the same:

glucose can protect older adults' positive affect. Together with previous findings from our laboratory showing that glucose can help older adults retain their positivity preference even under high cognitive load (Mantantzis et al., 2017), it appears that moderate increases in glucose availability are able to protect or even enhance both positive emotionality and positivity-related cognitive strategies in old age.[4]

Closely examining the older-glucose group's behavioral performance and their physiological patterns of task engagement, it becomes obvious that glucose effects go above and beyond cognitive facilitation in aging. Glucose increased older adults' task engagement and cognitive performance without increasing subjective effort perception, instead even improving their affective state. Based on observations of heightened motivation following carbohydrate administration (e.g., Chambers, Bridge, & Jones, 2009; Kringelbach, 2004), our findings fit with the idea that glucose facilitation could be a result of both metabolic and motivational influences (see Beedie & Lane, 2012; Molden et al., 2012). Although the present results confirm the prediction that these facilitation effects are more pronounced in older than in young adults (in line with the notion that the former are more in need of 'metabolic support' than the latter), a note of caution is in order. Whereas our older adults sample was relatively balanced in terms of gender, the young adult groups consisted primarily of female participants and, therefore, the observed age effects might in part be driven by gender differences in glucose metabolism (for reviews, see Hedrington & Davis, 2015; Varlamov, Bethea, & Roberts, 2014). To investigate this possibility, we repeated our analyses using data collected from female participants alone (*n* = 82). The results of the subgroup analysis largely mirrored the ones obtained from the full sample, suggesting that the glucose facilitation effect observed in our study was not influenced by gender differences. Nevertheless, future studies should aim for balanced or single-gender samples to avoid potential confounds associated with gender-related differences in glucose metabolism.

The question of how glucose leads to cognitive facilitation, however, still stands. The cascade of cognitive and affective results observed in the older group points to an intricate relationship between energy availability, cognitive performance and affect, but we do not yet possess an in-depth understanding of the directionality of these effects. It could be that glucose motivates older adults to exert effort, which improves their cognitive performance, and this subsequently leads to more positive affect after successfully completing the task. On the other hand, if older adults use available energy resources to prioritize positivity-driven adaptive goals (see Mantantzis et al., 2017), it could be that the increase in energy availability enhances older adults' affect and this positivity motivates them to exert more effort and improve their cognitive performance. In light of recent evidence stressing the importance of cognitive engagement for maintaining cognitive functioning in aging (for review, see Hertzog et al., 2009), our results are an important first step toward understanding the physiological and behavioral mechanisms underlying cognitive engagement in old age. Finding ways to manipulate the effectiveness of these mechanisms (e.g., improving glucoregulation) could increase older adults' ability to engage in cognitive tasks and, potentially, improve their cognitive and emotional well-being.

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Footnotes

[1] Although heart rate is considered a less sensitive measure of cognitive engagement compared with systolic blood pressure because its function is modulated both by the sympathetic and the parasympathetic branch of the autonomic nervous system, it has been found to follow similar, albeit weaker, patterns to those observed for systolic blood pressure (e.g., Ennis, Hess, & Smith, 2013).

[2] HR data from four older adults were excluded because of movement artifacts affecting the accurate estimation of HR from the ECG signal. Additionally, ECG data from two older adults were discarded because of artifacts relating to heart conditions which participants failed to disclose during the screening stage.

[3] With the exception of CV responsivity, all analyses presented in the results section were conducted using the full sample of older adults (n = 58). Repeating the cognitive performance, subjective effort, and affective judgment analyses with the sample of older adults whose CV data were included in the HR analysis (n = 52) did not alter the significance of the main effects and the interactions reported in the results section. The only difference found was for the main effect of age on subjective effort ratings, with the effect being only marginally significant, $F(1, 101) = 3.32$, $p = .072$, $\eta_p^2 = .032$.

[4] It should be noted that no direct links have been established between the positivity effect and mood states (for review, see Isaacowitz & Blanchard-Fields, 2012), yet older adults’ motivation to prioritize positive material appears to be closely related to affective outcomes (e.g., Isaacowitz et al., 2009; Kappes et al., 2017).

Table 1

Characteristics of the Sample and Performance on Background Cognitive Measures for Each Age and Drink Group

	Young		Older	
Characteristics	Glucose	Placebo	Glucose	Placebo
N (M/F)[a]	26 (1/25)	27 (4/23)	30 (13/17)	28 (11/17)
Age	18.46 (0.65)	18.93 (1.73)	72.47 (4.06)	72.75 (4.01)
Years of education	14.08 (0.27)	14.19 (0.56)	16.40 (2.99)	16.25 (2.93)
Digit span[b]	8.46 (1.03)	8.26 (0.98)	9.00 (1.66)	9.11 (1.55)
Speed[c]	68.85 (9.45)	73.85 (9.16)	56.50 (10.28)	54.50 (10.84)
Vocabulary[d]	15.65 (3.56)	16.41 (3.19)	24.43 (3.67)	23.86 (3.77)

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

[a] Number of participants in each age and drink group (male/female). [b] Digit span score as measured by the forward digit span subscale of the WAIS (Wechsler, 1981). [c] Processing speed as measured by the Digit Symbol Substitution task of the WAIS (Wechsler, 1981). [d] 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).

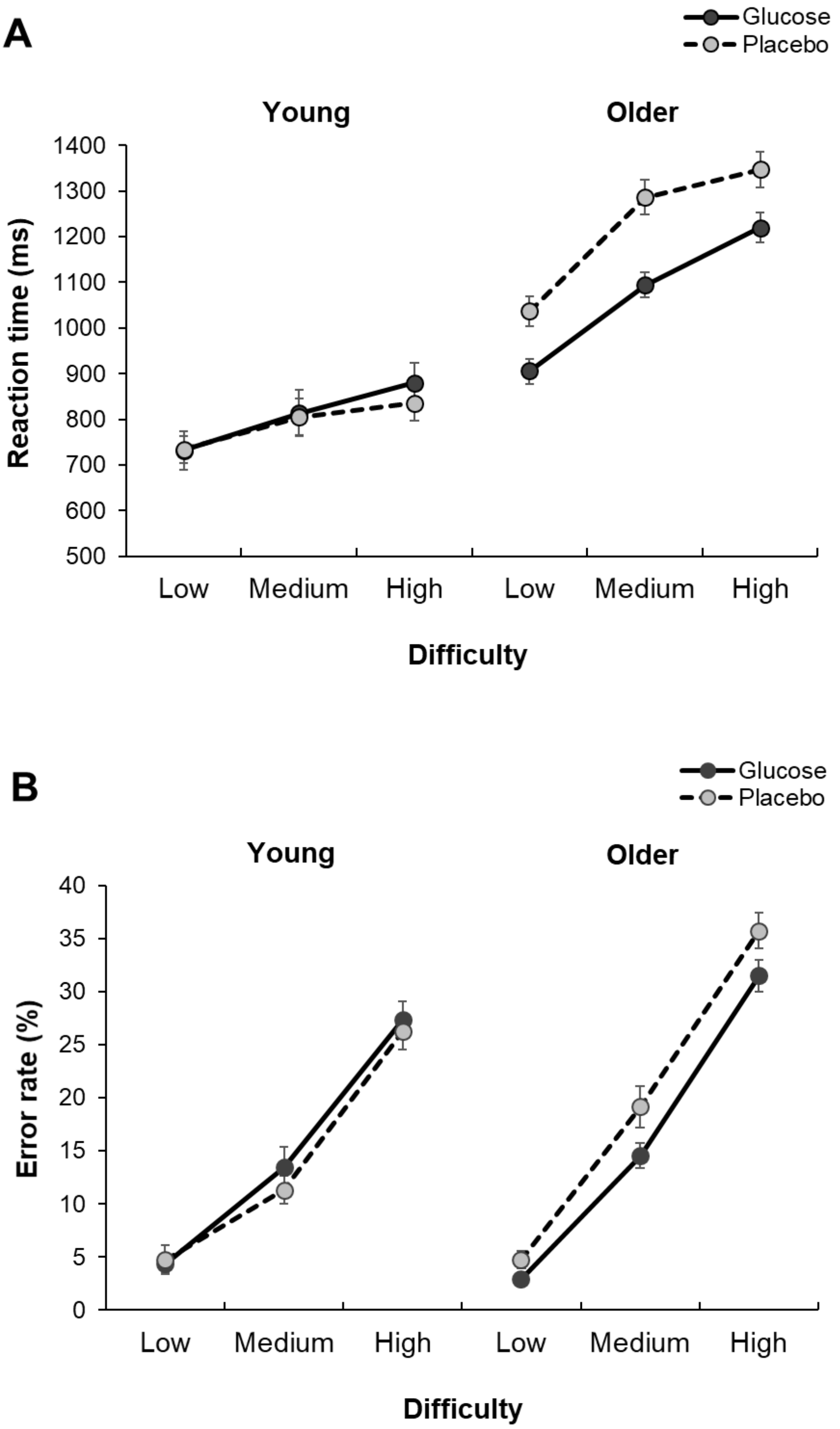

Figure 1. Performance on the memory-search task: (A) mean correct reaction times in milliseconds, and (B) mean percentage error rates, as a function of age (young/older), drink (glucose/placebo) and difficulty level (low/medium/high). Error bars denote ±1 standard error of the mean.

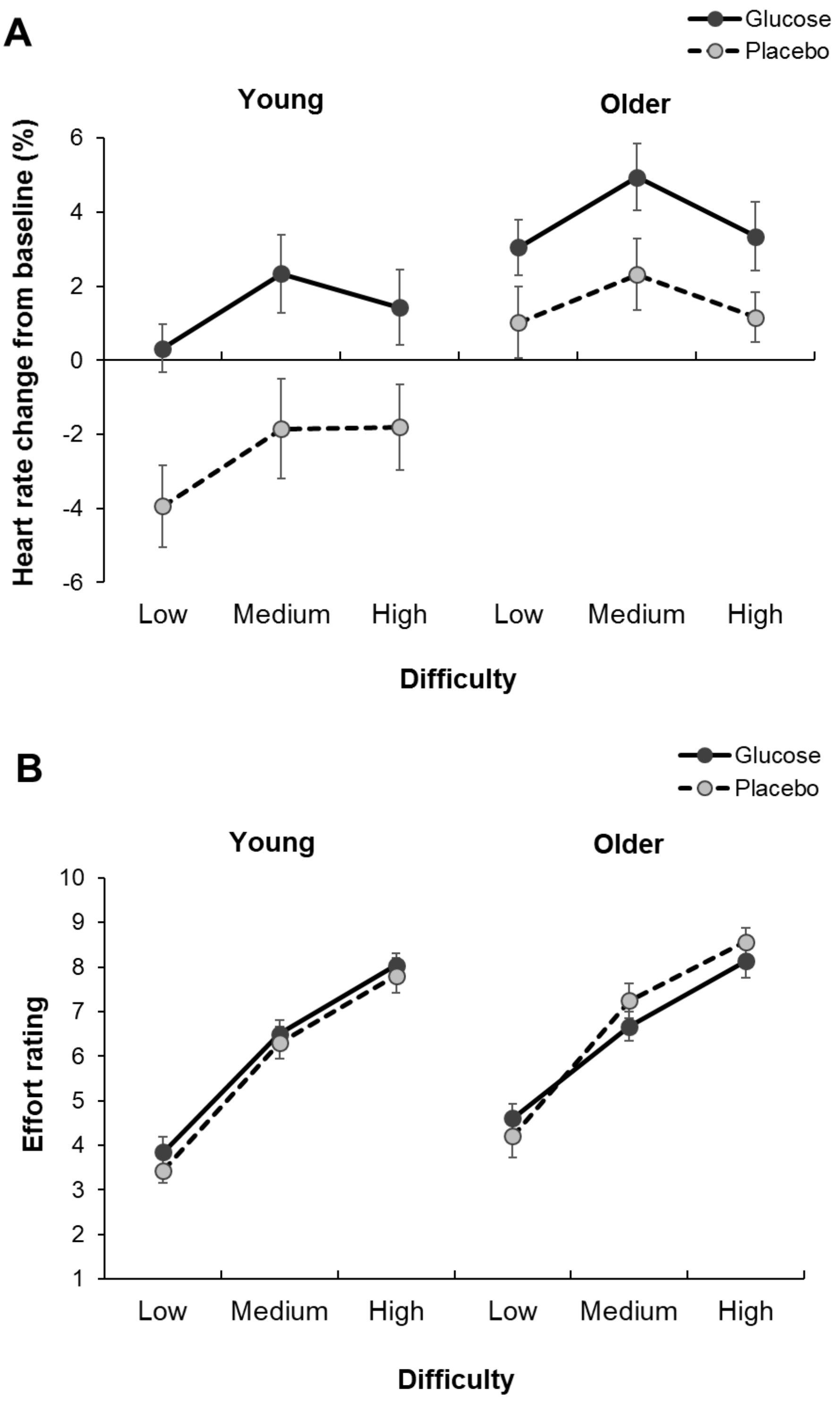

Figure 2. Participants' scores on measures of task engagement and effortful exertion: (A) mean percentage heart rate change from baseline, and (B) mean self-report effort scores on the NASA-TLX effort subscale, as a function of age (young/older), drink (glucose/placebo) and difficulty level (low/medium/high). Error bars denote ±1 standard error of the mean.

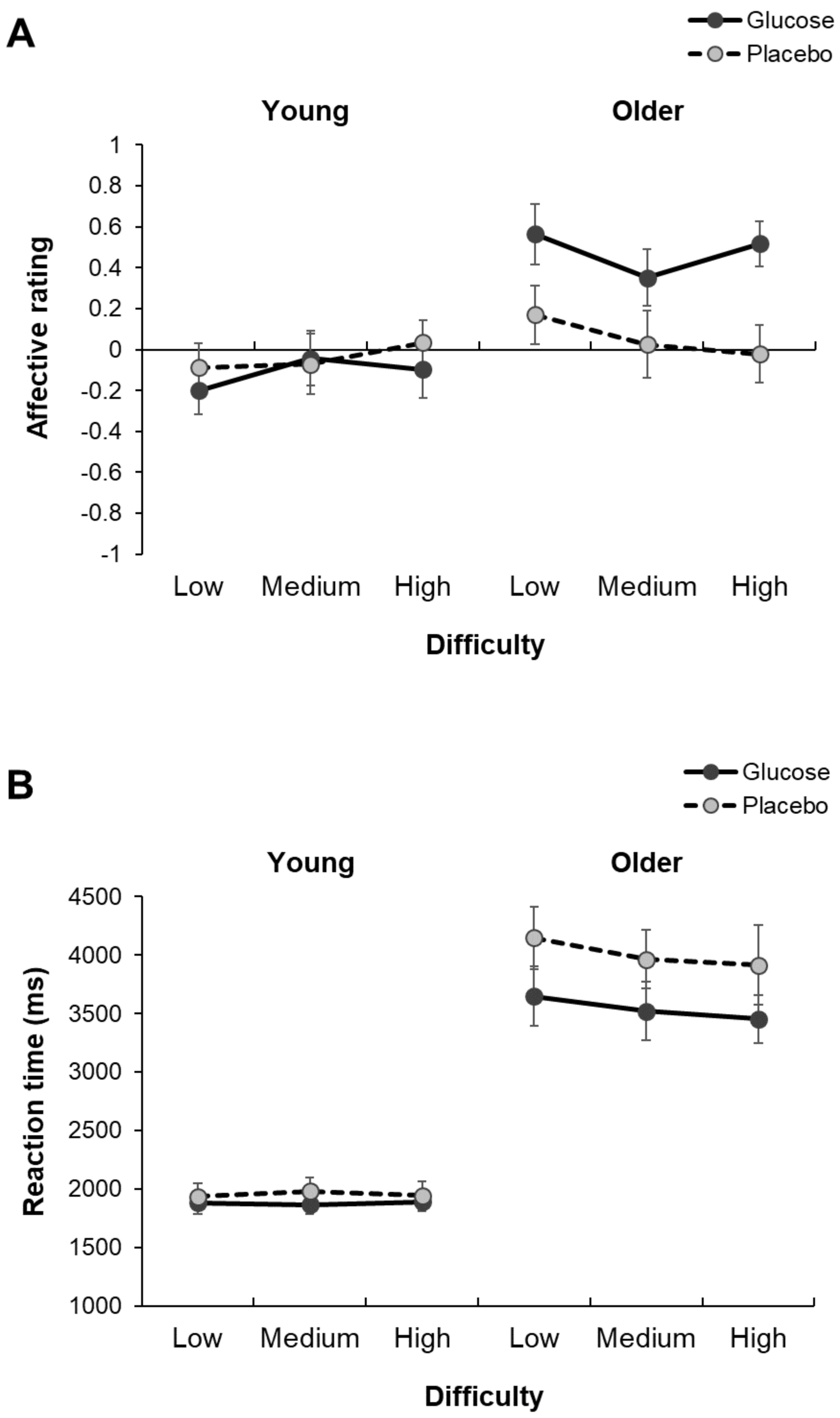

Figure 3. Performance on the affective judgment task: (A) mean affective ratings, and (B) mean reaction times, as a function of age (young/older), drink (glucose/placebo) and difficulty level (low/medium/high). Error bars denote ±1 standard error of the mean.