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Food for Thought: the Efficiency of Glucose Metabolism Predicts the Self-generation of Temporally Distant Cognition

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Abstract The generation of thought independent of environmental input occupies almost half of mental life and is important for skills such as creativity and planning. To understand how this ubiquitous cognitive process relates to the brain's 'energy budget', a cross-sectional study is carried out to examine how the capacity for mental time travel relates to the efficiency with which adults metabolize glucose, the brain's primary source of fuel. On day 1 the ability of a group of 36 younger and 36 older individuals to metabolize glucose was assessed using the gold standard two-hour glucose tolerance test. Twenty-four hours later, the same group of participants returned to the laboratory to perform a non-demanding choice reaction time task during which experience sampling was used to assess the frequency with which they generated thoughts that were unrelated to the here and now. Analysis indicated that younger individuals who were the most efficient at metabolizing glucose exhibited mental time travel that spanned longer time periods. Given the importance of self-generated thought in daily life these results suggest that the capacity to mentally simulate events not present in the immediate environment is highly dependent on efficient glucose metabolism.

Keywords: *glucose, glucose tolerance, mind wandering, attention, cognition, self-generated thought*

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1. Introduction

Although continually bathed in sensory input, the mind spends a significant proportion of time occupied with thoughts that are unrelated to the events taking place in the here and now [1]. Such self-generated thoughts [2] reflect the mind's capacity to produce mental contents that do not depend upon sensory input. These processes are important in the human capacity to consider events from the past and anticipation of events that may take place in the future which together affords individuals the chance to engage in mental time travel [3]. Although it can disrupt ongoing tasks, when self-generated thought occurs under benign conditions it can be associated with important capacities such as creativity [4], delaying gratification [5], and planning [6]. A common way to examine self-generated experiences is to ask participants to perform a task under laboratory conditions and to examine the occurrence and content of self-generated thoughts that are unrelated to the task being performed.

Engaging in self-generated thought is a complex cognitive act that depends on several component processes [5,7]. Episodic memory is important in providing the mental content of self-generated thought [8] and this allows individuals to mentally simulate events unrelated to perceptual input. Control processes (such as working memory capacity) are also thought to be important in buffering and sustaining the internal train of thought over time [5,9]. Given its complexity, the neural basis of self-generated thought has been found to engage a wide network of brain regions including medial and lateral regions of the frontal cortex, lateral regions of the parietal cortex, areas of cingulate cortex and parts of the medial temporal lobe [10,11,12].

Particularly relevant to the present investigation, a large body of research has shown that glucose metabolism is important for one of the major elements of self-generated thought; episodic memory [13,14]. Impairments in episodic memory has been observed in healthy younger individuals with poor glucose regulation [15], in middle aged adults [16] and also poor gluco-regulating adolescents after consuming a glucose containing drink [17,18,19], in older adults with and without Mild Cognitive Impairment [20] and in those individuals with impaired glucose tolerance and diabetes (see [14,21] for reviews). Efficient glucose regulation may be particularly important for episodic memory ability. Indeed, Riby and colleagues [22] administered a battery of cognitive tasks (including episodic) to older adults whilst blood glucose was measured during the testing session. Consistent relationships were observed between elevated blood glucose (indicator of poor control) for tasks involving episodic memory (immediate and delayed verbal recall; verbal recognition) compared to other domains of cognition such as short-term and semantic memory. Moreover, increasing the availability of glucose via the administration of a glucose containing drink (typically 25 or 50 g) particularly benefits episodic memory or more demanding memory retrieval operations (see [23] for meta-analysis).

Although not the primary concern of the present investigation, we were also interested in understanding the association between self-generated thought and ageing. One common observation in studies of a self-generated thought is that it is typically reduced during the ageing process. Giambra [24,25] demonstrated an inverse relationship between age and the frequency of task unrelated thoughts, suggesting there may be age-related declines in self-generated thought. In a recent study, McVay and colleagues [26] found that during both sustained attention and working memory tasks mind wandering, specifically task-unrelated, declined with age. In that study although task related thoughts associated with concerns about ongoing performance increased they did not reach the level of task-unrelated thoughts exhibited by younger adults (see also [27]). Although it is now well documented that task unrelated thoughts decline with age, there is no agreement on the mechanism underlying this effect. As glucose metabolism also decreases with age (see [13] for links to cognitive performance), by adding a factor of group we were able to explore whether the decline in self-generated thoughts in older individuals could be explained by age related differences in the capacity to metabolize glucose.

Based on these lines of evidence, the current study examined whether glucose regulation (measured with the 'gold standard' glucose tolerance test) is associated with the capacity for self-generated experiences. In particular, we recruited a cohort of old and young individuals and explored whether (i) the efficiency with which an individual processes glucose was associated with their capacity for self-generating thought (much like the association we find between glucose and episodic memory), specifically the temporal focus of the thoughts that they generate (past or future) as well as the temporal distance of these thoughts from the here and now (near or far) and (ii) whether age related differences exist in relationship between the occurrence of self-generated experiences and glucose regulation.

2. Method

2.1. Ethics Statement

We confirm that the research was conducted in accordance with APA standards for ethical treatment of subjects. Written consent was given by all subjects. The study and consent procedure were approved by the Department of Psychology, Northumbria University Ethics Committee.

2.2. Participants

Thirty-six healthy older adults were recruited from the Northumbria University North East Age Research (NEAR) database and from older adult organisations in the North East of England. Ages ranged from 65-82 years (Mage = 72.72 years, S.D. = 5.64). The thirty-six young adults (19-29 years, Mage=19.75, S.D. = 2.23) were recruited from Northumbria University Psychology department undergraduate population who received course credit for their participation. All participants were in good health (Older Adults; MeanBMI = 26.55 S.D. = 5.19; Younger Adults; MeanBMI = 21.79 S.D. = 3.17) and the groups did not differ in the number of years of education (MeanOLDER = 13.97 S.D. = 3.05; MeanYounger = 15.28, S.D. = 1.60, p >. 05). The blood glucose area under the curve (AUC) for older (Mean = 698.71 mmol/l x min, S.D. 329.98) and young adults (Mean = 363.88 mmol/l x min, S.D. = 253.55) was significantly different (t (70) = 4.83, p <.001). Four participants were excluded from the study, three for non-compliance with fasting instructions and one who failed to attend both testing sessions.

2.3. Design

A between-subjects design was employed with age group as the single independent variable.

2.4. Materials

2.4.1. Blood Glucose Measurement

The glucose treatment consisted of 75 g of glucose (dextrose) dissolved in 200 ml of water plus 30 ml of diluteable sugar-free orange squash for flavour. Seventy-five grams is the standard dose given during an oral glucose tolerance test for the detection of glucose abnormalities and diabetes. One drop of capillary blood was obtained from the fingertip using an Accucheck Single-Use Auto-Lancing device. Blood glucose concentration was measured using an Optimum Xceed diagnostic machine and Optimum Plus test strips (Abbott Laboratories Ltd). A separate glucose tolerance test rather than blood glucose measurement during cognitive testing is considered the ideal method for examining the relationship between glucose regulation and cognition and mimics investigations of diabetes status and cognitive ability (see [13] for discussion).

2.4.2. Reaction Time Task

The reaction time task (hereafter referred to as the O/Q) involved the presentation of either the letter 'O' or 'Q' on the computer screen at lengthy irregular intervals (a monotonous nature to promote off task thought). Participants were required to press the left mouse button when the 'O' appeared and the right mouse button when the 'Q' appeared (80 trials in total). On screen prompts reminded participants of the response choices. Interstimulus duration ranged from 2000 – 15000 ms with a fixation cross on screen during the gaps in stimuli presentation. Thought probes also appeared in randomised order. These asked two questions both of which required a response on a Likert scale (1-5) on the computer keyboard; First, participants were asked about the temporal focus, 1=the distant past, 2 = near past, 3= here and now, 4 = near future, 5=distant future; The second asked about the level of detail of the thoughts, 1=mind completely blank to 5=as rich subjective experience. There were twenty-four probes in total. Task duration was approximately 20 minutes.

2.5. Procedure

Participants attended two testing sessions. They were required to attend the first session between 8.30 and 9.30 am having fasted from 10.00 pm the previous evening. Height and weight were recorded by the experimenter and the National Adult Reading Test (all participants) and Mini Mental Sate Examination (older group only) administered. Total duration of the pre-test procedure was approximately 15 minutes, followed by the baseline fingerprick blood sample for recording of glucose level and consumption of the glucose drink. Participants were given 5 minutes in which to consume the whole drink and then required to sit quietly and relax. Four further pinprick blood glucose samples were recorded at 30-minute intervals post-treatment (+30, +60, +90, +120 mins). This blood glucose sampling enabled an area under the curve (AUC) measure to be calculated.

On day two participants attended the lab at their convenience. Since we were concerned with participants' behavior under naturalistic conditions, there were no prior dietary restrictions and participants were asked to eat and drink as normal in advance of the session. All participants were asked to complete the general health and demographic information, the GDS, and Cognitive Failures Questionnaire (older group only) independently. They were seated in front of a standard flat screen computer (approx. 55 cm viewing distance) and had the structure of the session explained. Participants then completed the O/Q task.

3. Results

Performance on the O/Q task was examined using a univariate analysis of variance (ANOVA) in which age group [Young / Old] was included as a categorical variable and GlucoseAUC was included a continuous between subjects variable. This analysis indicated a trend for a shorter RT in young [M = 885ms, SE = 45] than in older individuals [M = 1075, SE = 43, F (1, 68) = 3.6, p =. 06]. No differences were observed for accuracy [all p-values >. 18].

The relationship between the content of thought, age and glucose metabolism was examined using an ANOVA with repeated measures on temporal distance [Near / Far] and temporal focus [Past / Future]. Age group [Young / Old] was included as a categorical between participant variable and GlucoseAUC was included as a continuous between participant variable. This analysis indicated two significant effects. First, there was a Temporal Focus X Group interaction [F (1, 64) = 3.92. p <. 05, ηp2 =. 06] with younger individuals reporting more future related thought [M = 4.2, SE =. 5] than older individuals [M = 3.7, SE =. 47, F (1, 68) = 6.48, p <. 01]. Past-related thought did not vary across groups [Young M = 2.4, SE =. 43, Old M = 3.1 SE =. 5, F (1,72) =. 857, p >. 3]. this replicates prior work demonstrating that older individuals tend not to engage in the same amount of self-generated thought as younger individuals, and suggests that this is in part because they do not engage in prospection to the same extent as younger indiviudals.

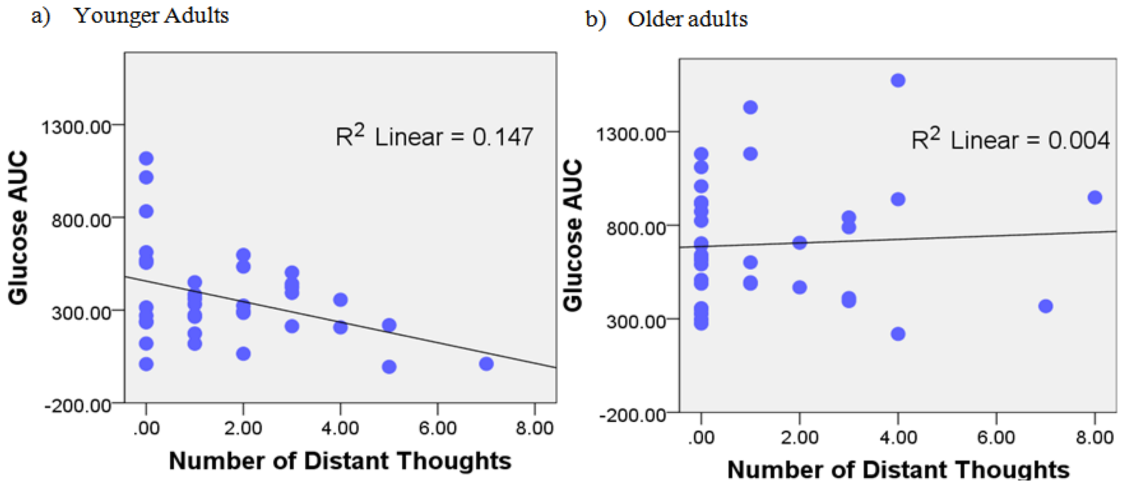

Figure 1. The relationship between the frequency of distant thoughts and blood glucose absorption (area under the curve) for (a) younger and (b) older adults and R^2 effect size

Secondly, there was a Temporal Focus X Temporal Distance X Age Group X GlucoseAUC interaction [F (1, 64) = 44.67, p <. 05, ηp2 =. 06] [1]. To follow up this interaction, separate Temporal Focus X Temporal Distance X GlucoseAUC ANOVAs were performed for younger and older adults. For younger individuals, the analysis of distant thoughts revealed a main effect of time period [F (1, 34) = 4.469, p <. 05] indicating thoughts of the distant past were more common [M = 1, SE =. 20] than the future [M =. 66, SE =. 12]. For analysis of temporally close thoughts, younger individuals reported more thoughts focused on the future [M = 8.5, SE =. 61] than the past [M = 4.2, SE =. 42, F (1, 34) = 17.3, p <. 001, ηp2 =. 34]. Interestingly, and the primary concern of the present investigation, a main effect of Glucose AUC [F (1, 34) = 5.85, p <. 05, ηp2 =. 15] indicated that distant thoughts were less common for younger individuals who could not absorb glucose effectively [t (34) = -2.4, p <.

05]. These data in comparison to older adults are displayed in the Figure 1. scatterplot. For older individuals, there were no significant effects of GlucoseAUC and no differences were observed for either close or distant thoughts.

Finally, the level of detail in thoughts was compared using a repeated measures ANOVA including both age group and GlucoseAUC. This revealed no significant association between age, GlucoseAUC, nor their interaction.

The abovementioned significant findings related to glucose regulation and distant thought across age group are summarized in Figure 1 scatterplot.

4. Discussion

Our novel study demonstrated that in younger individuals effective glucose metabolism was associated with a greater number of reports of temporally distant thoughts. We also replicated the age-related decline in self-generated thought seen in prior studies (e.g. [25,26]) and demonstrated that this was independent of age related changes in glucose metabolism. In light of this result we suspect that the low frequency of self-generated thought in older age arises from other types of deficit that could impair the capacity to simulate using episodic memory, reduce cognitive control or temper an older individual's motivation to engage in the experience. Clearly further work in an older population is warranted given that self-generated thoughts can be important in making future plans [6], generating creative solutions [4] and is a marker of patient decision making [5].

Given that self-generated thought, and in particular its capacity to allow mental time travel, depend on episodic memory [3] it has recently be suggested that the hippocampus may be important in the generation of self-generated thought [2]. Studies suggest that the impact of glucose metabolism may be targeted at the hippocampus, and so our data provides indirect support for this hypothesis. Neuroimaging studies suggest that a network of regions engaged during task unrelated self-generated thoughts [10,11,12] is similar to those activated by the recollection of personal and emotional memories [28], self-awareness [29], hypothetical moral decision making [30] and many other cognitive functions that can help an individual navigate the complex social environment in which they exist (see [31] for a review). The pilot data here will provide the groundwork for shedding the light on the importance of the hippocampus in mediating self-generated imaginative processes by exploring the link between glucose metabolism and the neural recruitment that occurs. Importantly, the present data are consistent with the hippocampal account of glucose facilitation reported during external task performance reported elsewhere (for a review of the hypothesis see [13]).

More generally our data suggest that the capacity to self-generate imaginative thoughts that are unrelated to the task in hand is an indicator of an efficient glucose regulation system, and it is worth considering the reason why this may be the case. There is an emerging literature suggesting that situations which require self-control result in depleted glucose levels (reviewed in [32]). Our results raise the intriguing (though speculative) possibility that the efficiency of glucose metabolism and the capacity for self-generated thought might underlie improved self-control by diverting attention from proximal stimuli and actions linked to more immediate gratification. Current research suggests that self-generated thought is implicated in skills that would be important in maintaining a healthy diet, such as delaying gratification [5] and that this is mediated by the integrity of grey matter in the medial pre-frontal cortex [33]. Our data is also consistent with the possibility that problems in mental simulation could lead to poor lifestyle choices, which in turn could further impair glucose metabolism. This is not an unreasonable proposition given elsewhere effective glucose utilization has been associated efficient self-control and several social behaviours (e.g. quitting smoking, emotional regulation; see [34]). The correlational nature of our design prohibits assessments of causality, and so further work is necessary to understand the link between self-generated thought and the lifestyle choices. Such investigations could seek to understand how conditions such as impaired glucose tolerance and type 2 diabetes develop over the life span, and whether these are related to the self-generated thoughts that people experience during everyday life. More generally, our findings extend the range of cognitive phenomena that are moderated by glucoregulation from experimentally initiated tasks to self-generated thought reported here.

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