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Emotionally Arousing Pictures Increase Blood Glucose Levels and Enhance Recall

Treena M. Blake, Connie K. Varnhagen, and Marise B. Parent

Department of Psychology, University of Alberta, Edmonton, Alberta, Canada T6G 2E9
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Arousal enhances memory in human participants and this enhancing effect is likely due to the release of peripheral epinephrine. As epinephrine does not readily enter the brain, one way that peripheral epinephrine may enhance memory is by increasing circulating blood glucose levels. The present study investigated the possibility that emotionally arousing color pictures would improve memory and elevate blood glucose levels in human participants. Blood glucose levels were measured before, 15 min, and 30 min after male university students viewed 60 emotionally arousing or relatively neutral pictures. Participants viewed each picture for 6 s and then had 10 s to rate the arousal (emotional intensity) and valence (pleasantness) of each picture. A free-recall memory test was given 30 min after the last picture was viewed. Although the emotionally arousing and neutral picture sets were given comparable valence ratings, participants who viewed the emotionally arousing pictures rated the pictures as being more arousing, recalled more pictures, and had higher blood glucose levels after viewing the pictures than did participants who viewed the neutral pictures. These findings indicate that emotionally arousing pictures increase blood glucose levels and enhance memory, and that this effect is not due to differences in the degree of pleasantness of the stimuli. These findings support the possibility that increases in circulating blood glucose levels in response to emotional arousal may be part of the biological mechanism that allows emotional arousal to enhance memory.

Key Words: arousal; blood glucose; emotion; human; memory; recall.

Substantial experimental evidence indicates that emotional arousal enhances memory. In studies of human memory, researchers have found that memory is enhanced by increasing arousal, either through muscular contraction (Nielson & Jensen, 1994) or by increasing the emotional content of the information that is to be remembered (Bradley, Greenwald, Petry, & Lang, 1992; Cahill, Prins, Weber, & McGaugh, 1994; Heuer & Reisberg, 1990; Parent, Varnhagen, & Gold, 1999). The stress hormone epinephrine, which is released

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Address correspondence and reprint requests to Marise B. Parent, Ph.D., Department of Psychology, Georgia State University, University Plaza, Atlanta, Georgia 30303. Fax: (404) 651-3929. E-mail: psymbp@langate.gsu.edu.

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from the adrenal medulla in response to arousing experiences (Gerra et al., 1996; Gold & McCarty, 1981), has been implicated in the effects of emotion on memory storage. For example, in rats, administration of epinephrine following training enhances memory and retention is impaired by adrenergic antagonists or by adrenal demedullation (McGaugh, 1989). Similarly, administration of beta-adrenergic receptor antagonists prevents the enhancing effect of emotion on memory in humans (Cahill et al., 1994; Nielson & Jensen, 1994; van Stegeren, Everaerd, Cahill, McGaugh, & Gooren, 1998).

Although the influence of arousal and epinephrine on memory is well established, the neurobiological mechanisms underlying their effects are not as clearly understood. Since epinephrine is not able to cross the blood–brain barrier to any significant extent (Weil-Malherbe, Axelrod, & Tomchick, 1959), it is likely that epinephrine regulates memory formation indirectly through a secondary mechanism. One possible way that epinephrine may enhance memory is via the activation of peripheral adrenergic receptors in the liver. According to this hypothesis, the effects of epinephrine on memory are mediated, at least in part, by the role epinephrine plays in the release of glucose into the bloodstream (Korol & Gold, 1998; Wenk, 1989). Support for the role of glucose as a memory modulator is derived from studies of both rodent and human learning and memory. Poor glucose regulation is associated with memory deficits in aged human and animal subjects (Gold & Stone, 1988). In rats, injections of epinephrine and glucose, at doses optimal for enhancing memory, result in comparable increases in blood glucose concentrations (Gold, 1995). Like epinephrine, glucose administration enhances memory (Flint & Riccio, 1999; Gold, 1986; Kopf & Baratti, 1996; Messier, 1997) and attenuates memory deficits in rodents (Flint & Riccio, 1997; Stone, Croul, & Gold, 1988; Stone, Rudd, & Gold, 1995; Winocur & Gagnon, 1998). In humans, glucose administration improves declarative memory in healthy young and elderly participants, as well as in participants with Alzheimer's disease, Down syndrome, and schizophrenia (Benton & Owens, 1993; Craft, Murphy, & Wenstrom, 1994; Foster, Lidder, & Sünram, 1998, Korol & Gold, 1998; Hall, Gonder-Frederick, Chewning, Silveira, & Gold, 1989; Manning, Parsons, Cotter, & Gold, 1997; Manning, Stone, Korol, & Gold, 1998; Messier, Pierre, Desrochers, & Gravel, 1998; Newcomer et al., 1999).

The above evidence suggests that increases in circulating blood glucose levels in response to emotional arousal may be part of the biological mechanism that allows emotional arousal to enhance memory. One prediction that arises from this hypothesis is that circulating blood glucose levels should increase in response to memory-enhancing emotionally arousing stimuli. Indeed, research has shown that blood glucose levels increase in rats trained to avoid footshock (Hall & Gold, 1986) and in humans following an emotionally arousing experience (Armario, Marti, Molina, de Pablo, & Valdes, 1996; Parent et al., 1999). In particular, Parent, Varnhagen, and Gold (1999) recently demonstrated that circulating blood glucose levels increased after participants viewed a slide show accompanied by a memory-enhancing, emotionally arousing narrative. Blood glucose levels did not increase in participants who heard a closely matched, but relatively neutral, narrative.

To the best of our knowledge, the study by Parent, Varnhagen, and Gold (1999) was the first to examine the interaction between glucose and emotional memory in human participants. The results demonstrate that findings derived from studies of rodent learning and memory apply to human memory. However, the results have also raised many questions. For example, it is not known whether these findings are restricted to the specific

narratives or can be generalized to other emotionally arousing stimuli. If increases in blood glucose are part of a general mechanism involved in the memory-enhancing effects of emotional arousal, then blood glucose levels should increase following the presentation of different types of emotionally stimuli. Second, because the emotionally arousing narrative used in the Parent et al. (1999) study described a young boy critically injured in a car accident, it is not known whether the increases in blood glucose levels were associated with the negativity of the narrative (i.e., valence) or the degree of arousal that it produced. Finally, because the participants in the Parent et al. (1999) study were given saccharin as a control for glucose administration, it is not known whether emotionally arousing stimuli increase blood glucose levels in the absence of saccharin.

Consequently, the goal of the present study was to determine whether emotionally arousing pictures would improve memory and elevate blood glucose levels in human participants. The stimuli used were derived from the International Affective Picture System (IAPS; CSEA-NIMH, 1997), a collection of standardized colored pictures that have been previously shown to enhance memory independent of valence (Bradley et al. 1992; Bradley, Cuthberg, & Lang, 1996; Hamann, Cahill, & Squire, 1997). Two sets of pictures that varied in degree of arousal but were comparable in valence were created. Participants viewed either the arousing or neutral pictures and then their blood glucose levels and memory were tested. If the effects found by Parent, Varnhagen, and Gold (1999) are independent of valence and are part of a general biological mechanism involved in the memory enhancing effects of emotional arousal, then the participants who view the emotionally arousing pictures should have higher circulating blood glucose levels and better memory for the pictures than should participants who view the neutral pictures.

METHODS

All of the procedures used were approved by the University of Alberta Human Ethics Review Committee and the University of Alberta Environmental Health and Safety Biosafety Office.

Participants

Thirty-seven male University of Alberta undergraduate students ($M = 19.4$ years, $SD = 1.3$ years) participated in order to fulfill a course requirement. Participants avoided food and drink, except for water, after midnight the night before they were tested.

Procedure

All participants were tested individually between 7:00 and 10:00 a.m. Upon arrival, the participants completed a medical questionnaire indicating any history of diabetes or other blood sugar abnormalities and signed a consent form explaining the procedure. The participant was told that the goal of the experiment was to investigate the effects of emotions on physiological responses; no mention of a memory test was made.

A between-subjects experimental design was employed in which participants were randomly assigned to view 60 colored pictures whose content was either emotionally arousing (High Arousal) or relatively emotionally neutral (Low Arousal). The IAPS

pictures were divided into Low Arousal and High Arousal sets using previously established emotional arousal ratings for male participants (Lang, Bradley, & Cuthbert, 1997). The rating scale used to establish the normative ratings ranges from 0 to 9, with a higher score indicating a higher emotional arousal rating. The mean normative emotional arousal rating of the Low and High Arousal Pictures sets were 2.65 and 6.46, respectively, and the mean normative valence ratings were 5.17 and 5.37. Contents of the High Arousal picture set included, for example, nude females, an aimed gun, skydivers, and a bloody hand. Examples of Low Arousal stimuli included pictures of a fork, farmland, a cow, and neutral faces.

The pictures were shown on an IBM ThinkPad laptop computer using Microsoft PowerPoint software. The participant sat approximately 60 cm from the 30-cm monitor, which ran at 800 $\times$ 600 screen resolution in 16-bit high color. Each slide was displayed for 6 s followed by a 10-s interstimulus interval, during which the screen went black and the slide number was displayed.

Five additional neutral pictures were used to familiarize the participant with the rating procedure. The participant was instructed to attend continuously to the picture for the entire time it was on the screen and to use the intervening period to rate the arousal (emotional intensity) and valence (degree of pleasantness or unpleasantness) of the picture using a pen-and-paper version of the self assessment manikin (SAM) rating system (Lang, 1980).

The SAM system is the rating system that was used to establish the normative ratings for the IAPS pictures (Lang et al., 1997). SAM depicts the dimensions of arousal and valence with five ordinally scaled figures. The SAM figures for the arousal dimension range from a relaxed, sleepy figure to an excited, wide-eyed figure. For the valence dimension, the figures range from a smiling, happy figure to a frowning, unhappy figure. These two rating scales were displayed on each page of a ratings booklet. For half the participants, the upper scale assessed the valence dimension and the lower scale assessed the arousal dimension; for the other half, the scales were reversed. Participants were told to record their initial emotional reactions to the picture by placing an "x" on or between any of the five SAM figures on the dimensions of valence and arousal, producing a scale that ranged from one to nine.

After the participants viewed and rated the five practice slides, a baseline blood glucose measure was obtained using a Lifescan One Touch Basic blood glucose monitor. The participant's finger was pricked with a sterile lancet to obtain one drop of blood and a reflectance meter read the glucose concentration. The participant then viewed and rated the 60 High or Low Arousal pictures that were presented in one of three possible sequences. During this time, the researcher sat behind a divider and could not see or be seen by the participant. Blood glucose measures were obtained immediately following the slide show, and then 15 and 30 min later. These intervals were the same as those used by Parent, Varnhagen, and Gold (1999).

A free-recall memory test was given 30 min after participants viewed the last picture. The participant was asked whether he suspected a memory test and then was instructed to write down, in any order, a word or phrase describing the slides that he could remember. The participant was given as much time as needed to complete the task. At the conclusion of the session, the participant was debriefed as to the intent of the study, thanked, and given breakfast and participation credit.

The number of pictures correctly recalled was computed for each participant. Two

independent judges scored a participant's description as correct if it could be linked clearly to a particular picture and if it did not correspond to more than one slide. Because of the obvious differences in the pictures, it was not possible to score the results of the recall test blind to the arousal condition. Reliability of scoring, which was determined as the ratio of agreements divided by the number of recalls scored, was 98%. Disagreements were resolved by discussion.

Statistical Analyses

An average arousal and valence rating for the 60 pictures was computed for each participant in the Low Arousal condition. The mean of these values was then compared with the mean ratings of participants in the High Arousal condition. It was expected that the High Arousal stimuli would be rated as more arousing and would produce better recall than the Low Arousal stimuli. Consequently, one-tailed independent samples *t* tests were used to compare the mean arousal ratings and recall scores of participants in the Low and High Arousal conditions. As no hypothesis was made regarding differences in the degree of pleasantness of the pictures, mean valence ratings were compared using a two-tailed independent samples *t* test.

To determine whether the emotionally arousing stimuli affected blood glucose levels, circulating blood glucose levels were expressed as percentage change of baseline. These data were analyzed using a two-factor mixed analysis of variance (ANOVA), with arousal condition (Low and High Arousal) as the between-subjects factor and time since viewing the pictures (0, 15, 30 min) as the within-subject factor. This was followed by post hoc comparisons with Bonferroni corrections where appropriate. An alpha level of .05 was used as a criterion of statistical significance.

RESULTS

The Tietjen and Moore (1972) outlier test identified two blood glucose measurements as outliers. Consequently, the data from these two participants were excluded from the statistical analyses. In addition, the data from one participant were excluded because he had suspected a memory test during the session. This resulted in a final group size of 17 participants in the High Arousal condition and 17 participants in the Low Arousal condition.

The results indicated that the High Arousal stimuli were considered to be more emotionally arousing than were the Low Arousal stimuli. Mean arousal ratings were significantly higher for participants in the High Arousal condition than they were for participants in the Low Arousal condition ($t(32) = 5.64$, $p < .001$; see Fig. 1A). However, the stimuli were considered to be comparable in terms of pleasantness. Mean valence ratings did not significantly differ between participants in the High and Low Arousal conditions ($t(32) = 1.78$, $p > .05$; see Fig. 1B).

The results further indicated that emotional arousal enhanced recall. Participants who viewed the High Arousal picture set recalled more pictures than did participants who viewed the Low Arousal picture set ($t(32) = 1.80$, $p < .05$; see Fig. 2).

In addition to enhancing recall, emotional arousal also affected circulating blood glucose levels ($F(1, 31) = 6.69$, $p < .05$; see Fig. 3). Baseline blood glucose levels ranged from 81 to 107 mg/dL, consistent with expected fasting values (Krall & Beasner, 1989). Post

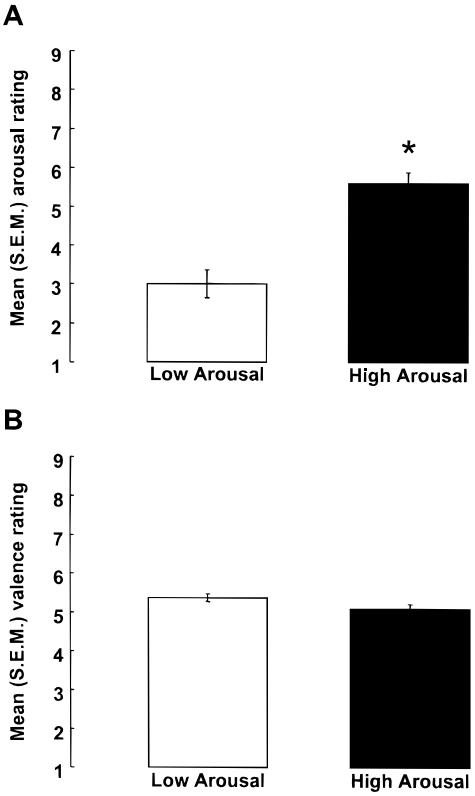

FIG. 1. (A) Mean (SEM) arousal and (B) valence ratings for participants who viewed the Low and High Arousal pictures sets ($n = 17$ per group; *$p < .001$ versus Low Arousal).

hoc analyses revealed that circulating blood glucose levels increased from baseline for participants in the High Arousal condition ($p < .05$). However, circulating blood glucose levels were not different from baseline for participants in the Low Arousal condition ($p > .05$). This effect of emotional arousal on circulating blood glucose levels also varied as a function of time since viewing the pictures ($F(2, 62) = 4.93$, $p < .05$). Changes in blood glucose levels were significantly greater for participants in the High Arousal group than for participants in the Low Arousal group 15 and 30 min after they viewed the pictures ($p <.001$ for both comparisons).

DISCUSSION

Our findings indicate that circulating blood glucose levels increased after young, healthy participants viewed emotionally arousing pictures, but did not change in participants who viewed relatively neutral pictures. Moreover, this increase in blood glucose levels was paralleled by the finding that memory was better for the emotionally arousing stimuli than for the relatively neutral stimuli. These findings are consistent with research showing that emotional arousal enhances memory in humans (Bradley et al., 1992; Cahill et al., 1994; Heuer & Reisberg, 1990; Nielson & Jensen, 1994; Parent et al., 1999). These findings are also in agreement with those of previous studies indicating that emotional arousal increases blood glucose levels in rodents (de Boer, Koopmans, Slangen, & van

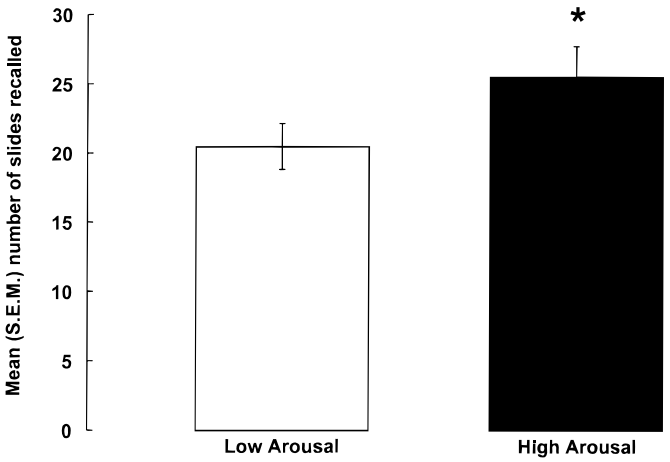

FIG. 2. Mean (SEM) number of slides recalled by participants who viewed the Low and High Arousal pictures sets ($n = 17$ per group; $*p < .05$ versus Low Arousal).

der Gugten, 1990; Gold & Stone, 1988; Hall & Gold, 1986) and in humans (Armario et al., 1996; Parent et al., 1999). The present results show that, in addition to orally presented narratives (Parent et al., 1999), emotionally arousing pictures also increase blood glucose levels. This supports the possibility that increases in glucose may be part of a general response to emotional arousal.

The present findings also show that the effect of emotional arousal on blood glucose levels and recall is independent of the valence of the stimuli. Although the Low and High Arousal stimuli used in the current study differed in terms of their perceived emotional arousal, the stimuli did not differ in terms of ratings of pleasantness and unpleasantness.

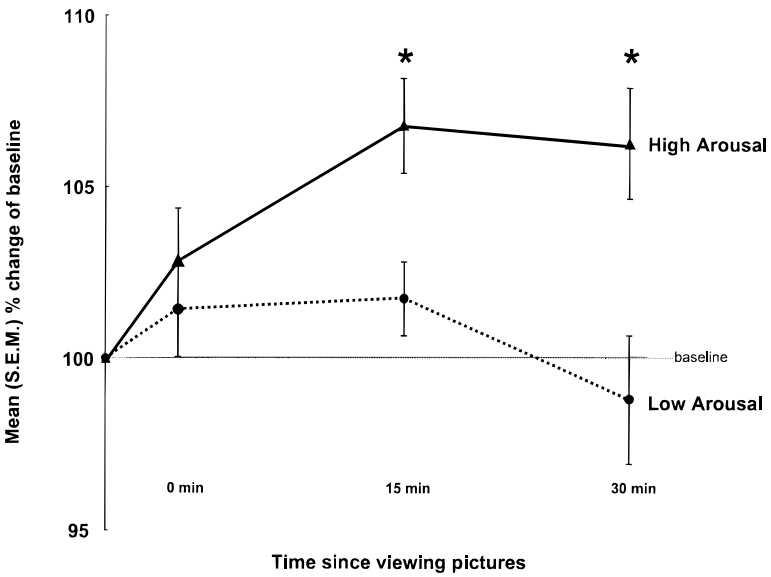

FIG. 3. Percentage change in circulating blood glucose levels for participants who viewed the Low and High Arousal pictures sets. The baseline measure was taken 5 min before participants viewed the pictures ($n = 17$ per group; $*p < .001$ versus Low Arousal).

This suggests that the increase in blood glucose levels that was previously observed by Parent and colleagues (1999) was more likely related to the degree of emotional arousal the narrative produced rather than its negativity.

The present results also show that emotional arousal increases blood glucose levels in the absence of saccharin consumption. The magnitude of the increase in blood glucose levels observed in the present study is comparable to that reported by Parent, Varnhagen, and Gold (1999). This suggests that the increase in blood glucose levels that was observed in control participants who ingested saccharin prior to hearing an emotional narrative (Parent et al., 1999) was not likely influenced by the saccharin consumption.

Our findings are consistent with and extend the findings of previous experiments that have used the IAPS stimuli. Specifically, the arousal and valence ratings we obtained in the present study are comparable to those of the normative sample (Lang et al., 1997). As in the present study, previous researchers have shown that the emotionally arousing IAPS stimuli enhance memory and that the memory-enhancing effect of emotional arousal is independent of the valence of the pictures (Bradley et al., 1992; Hamann et al., 1997). However, in previous work with IAPS stimuli, participants were presented with a mixture of neutral and emotionally arousing pictures. We show here that similar effects are observed when different groups of participants view only the Low or High Arousal stimuli. We have also expanded the findings by showing that the emotionally arousing IAPS stimuli increase circulating blood glucose levels. This finding adds to the growing body of evidence indicating that specific physiological and behavioral indices of emotional responses reliably covary with the valence and arousal dimensions of the IAPS stimuli (Greenwald, Cook, & Lang, 1989; Lang, Greenwald, Bradley, & Hamm, 1993). Specifically, increased arousal ratings are positively associated with increases in skin conductance (Lang et al., 1993).

In the present study, blood glucose levels increased by approximately 6% after participants viewed the High Arousal pictures. Although this is comparable to the increase observed by Parent, Varnhagen, and Gold (1999), it is smaller than the increase Armario et al. (1996) observed in students about to write college exams (approximately 28%). Students in the latter study did not fast overnight and likely had higher baseline glucose stores. Therefore, participants in our study might have experienced larger emotion-induced increases in blood glucose levels had they not fasted. The differences in magnitude might also be related to differences in the degree of arousal experienced by the participants. It is likely that viewing or listening to emotionally arousing stimuli in an experimental situation is less arousing than studying for real-life exams. It would be interesting to determine whether pictures with higher emotional arousal ratings than those used in the present study would produce larger increases in blood glucose levels and enhance memory to a greater degree.

Our findings do not indicate whether the increases in blood glucose that were observed after participants viewed the High Arousal pictures directly contributed to the enhancing effect of emotional arousal on recall. Future experiments are needed to examine the effects of glucose administration. Specifically, it will be important to determine whether glucose administration, at a dose that increases blood glucose levels to concentrations similar to those seen after emotional arousal, will enhance memory of the neutral pictures.

Previous findings suggest that optimal memory-enhancing doses of glucose produce larger increases in blood glucose concentrations than were observed in the present experiment (Parsons & Gold, 1992). However, it is unlikely that an increase in blood glucose

levels is the sole mechanism underlying the memory-enhancing effect of emotional arousal. Evidence suggests that epinephrine also enhances memory via activation of vagal afferents projecting to brain stem regions such as the nucleus of the solitary tract (NTS). Reversible inactivation of the NTS prevents the memory-enhancing effects of peripherally administered epinephrine (Williams & McGaugh, 1993). Interestingly, recent findings from *in vivo* and in *in vitro* studies demonstrate that NTS neurons are sensitive to small changes in glucose levels (Dallaporta, Himmi, Perrin, & Orsini, 1999). Such evidence raises the possibility that epinephrine-induced increases in circulating blood glucose levels and adrenergic activation of the vagus nerve may both mediate their enhancing effects on memory via an influence on the NTS.

As memory was tested while blood glucose levels remained elevated, our results do not reveal whether the relationship between elevated blood glucose levels and enhanced recall reflects an effect on encoding, retrieval, or both. Existing evidence suggests that increases in blood glucose levels affect encoding processes. For instance, posttraining glucose administration enhances memory in humans and rodents (Gold, 1986; Manning, Parsons, & Gold, 1992). Also, we previously found that recognition memory was enhanced 2 weeks after glucose levels had been elevated by an emotional narrative (Parent et al., 1999). Further research is needed to assess whether retrieval processes are also influenced by elevated blood glucose levels.

The mechanisms through which glucose enhances memory require further investigation. Glucose may act by altering neural metabolism, neural activity, or neurotransmitter synthesis (Korol & Gold, 1998). Glucose is closely linked to the formation of acetylcholine in the central nervous system (Gibson & Blass, 1976; Gibson, Blass, & Jenden, 1978; Tucek & Cheng, 1974), and extensive evidence suggests that glucose may up-regulate mnemonic processes, at least in part, by up-regulating central cholinergic function (Kopf & Baratti, 1996; Micheau, Messier, & Jaffard, 1995; Pavone, Capone, Battaglia & Sansone, 1998; Ragozzino, Unick, & Gold, 1996; Ragozzino, Pal, Unick, Stefani, & Gold, 1998).

In summary, the findings of the present experiment indicate that emotionally arousing pictures increase circulating blood glucose levels and enhance recall. These findings in human participants confirm the results of non-human animal research and support the possibility that increases in blood glucose contribute to enhanced memory of emotionally arousing information.

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