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How stress influences creativity in game-based situations: Analysis of stress hormones, negative emotions, and working memory

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A B S T R A C T

This study aims to integrate neuroscientific techniques into a behavioral experimental design to investigate how stress stimuli may influence stress hormones and negative emotions, subsequently affecting working memory (WM) and creativity in game-based situations. Ninety-six college students participated in this study, in which a game-based experiment lasting 90 min was employed. The main findings were that (1) the employed stress stimuli influence creativity during gaming through two routes: enhancing creativity through cortisol concentration and WM and decreasing creativity by provoking promotion-focused negative emotions (frustration and anger); and (2) the subjective negative emotions and objective cortisol responses do not consistently predict WM and creativity in game-based situations. Accordingly, appropriate challenges or stressors that help increase the cortisol concentration to an attentional level without provoking a strong sense of promotion-focused negative emotions should be considered when designing games aimed at teaching creativity.

Creativity has been considered one of the required abilities for success in this epoch of emphasizing knowledge economics and technology. Although numerous studies on creativity have been conducted over the past decade (Hennessey & Amabile, 2010), only a few studies have investigated the cognitive process of creativity in game-based situations by integrating neuroscientific techniques. Games are considered an effective educational tool because they provide tasks with multiple difficulty levels for the adaptation of prior knowledge and skills of learners (Gentile & Gentile, 2008). Therefore, games are suitable for exploring the cognitive process of complex thinking processes such as creativity.

According to the creative cognition approach (Ward, Smith, & Finke, 1999), which serves as an important basis for experimental studies on the cognitive process of creativity, working memory (WM) plays a critical role in the creative process. Researchers have also recently suggested that creativity is the result of continuously repetitive processes of WM that are learned as cognitive control models in the cerebellum. Accordingly, the efficiency of memory routines plays a central role in the creative process (Vandervert, Schimpf, & Liu, 2007). To date, some studies have focused on studying the relationship between WM and creativity (e.g., Chrousos, 2009; De Dreu, Nijstad, Baas, Wolsink, & Roskes, 2012; Takeuchi et al., 2011). However, few studies have employed WM tasks that are connected to tasks involving creativity in game-based situations. Creative performance is largely dependent on the retrieval, activation, and operation of task-related knowledge (Ward et al., 1999; Yeh, 2011). Therefore, the first aim of this study was to investigate the relationship between WM and creativity in game-based situations.

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Among the variables that have been shown to predict creativity, mood is one of the most widely studied predictors (Baas, De Dreu, & Nijstad, 2008). Over the last 30 years, negative emotions have been widely studied from the perspective of valence (positive vs. negative) or activation (low vs. high). However, negative emotions are seldom investigated from the viewpoint of regulation focus (prevention vs. promotion). In addition, it has been suggested that stress hormones and negative emotions are closely related (Sudheimer, 2009). However, the mechanisms explaining how stress hormones influence creativity are rarely studied. Accordingly, our second aim was to investigate the relationships among negative emotions, WM, and creativity and the relationships among stress hormones, WM, and creativity during gaming.

In summary, the aims of this study are two-fold. First, this study tries to depict the relationships among negative emotions, stress hormones, WM, and creativity in game-based situations. Second, this study attempts to answer a question that has not been previously studied: do subjective negative emotions and objective hormonal responses consistently predict WM and creativity in game-based situations?

1. WM and creativity

Numerous definitions of creativity have been proposed (e.g., Kampylis, Berki, & Saariluoma, 2009; Zeng, Proctor, & Salvendy, 2011). A more recent consensus about the definition of creativity states that creativity is a process of producing original/novel and appropriate/valuable products within a specific context (Mayer, 1999; Yeh, 2011). It has also been noted that a predominant approach to creativity is more focused on everyday activities (Simonton, 2012). Therefore, this study focuses on these types of creativity and defines creativity as the ability to come up with novel and appropriate solutions to everyday problems.

Over the past few decades, the proposed definitions of creativity have changed from one-dimensional to multidimensional planes and have transitioned from the cognitive to the affective domain. Important theories of creativity have emphasized that multiple components must converge for creativity to occur (Amabile, 1996; Csikszentmihalyi, 1999; Gardner, 1993; Sternberg & Lubart, 1996). Accordingly, we have included both cognitive and affective factors (WM, emotion, and stress hormones) in this study to investigate how they may influence creativity during gaming.

WM is considered an online cognitive process through which the learner acquires and processes new information (Baddeley & Logie, 1999; Cowan, 1999). WM also allows an individual to hold in his/her mind the knowledge that is relevant to solving a particular problem (Dietrich, 2004). According to Baddeley's (2003) multicomponent model, WM is composed of the following four subcomponents: the central executive, the phonological loop, the visuospatial sketch pad, and the episodic buffer. Notably, the central executive is an attentional-control system that is responsible for directing attention to relevant information and suppressing irrelevant information.

It has been suggested that a WM buffer is required for creative thinking and that the operation and storage of WM affects creative problem solving (Baddeley, 2003; Lin & Lien, 2013; Thomas, 2013). Along the same lines, creativity-related experiments have shown that the efficiency of WM has significant effects on figural elaboration (Kaufmann & Vosburg, 1997). WM capacity is considered to be a prerequisite for cognitive flexibility, abstract thinking, strategic planning, and processing speed in long-term memory (Baddeley, 2000; Dietrich, 2004); it benefits creativity for it enables the individual to maintain attention on the task and prevents undesirable mind wandering (De Dreu et al., 2012). Based on the dual-process theories that propose the analytic system involved logical and rule-based processes execution relies on cognitive resources, researchers (Lin & Lien, 2013) found that increased the WM load hindered participants' performance in closed-ended creative problem-solving.

Neuropsychological findings have also suggested that different WM and neural operations account for differences in creative performance (e.g., Donkin, Nosofsky, Gold, & Shiffrin, 2013; Navas-Sánchez et al., 2014; Takeuchi et al., 2011; Vartanian, 2012). Attention can be the main mechanisms that connect WM and creative performance. It has been found that selective attention which involved the ability to focus cognitive resources on information relevant to goals influenced working memory (WM) performance (Gazzaley & Nobre, 2012), and both modality-dependent WM mechanisms and modality-independent attention control mechanisms influenced insight problem solving (Chein & Weisberg, 2013). Creative processes largely comprise the retrieval, integration, and retention of knowledge as well as close connections between cues and the activation of knowledge (Yeh, 2011). When WM has more available resources and greater efficiency, creative solutions should be enhanced. Accordingly, we propose the following hypothesis:

Hypothesis 1: WM will have positive effects on creativity during gaming.

2. The relationship between negative emotions, stress hormones, and WM

2.1. Negative emotions and stress hormones

To date, few studies have examined the relationship between negative emotions and stress hormones. Kleinginna and Kleinginna (1981) integrated existing definitions of emotion and concluded that emotion is composed of subjective and objective factors. The subjective factors include emotional experiences (e.g., pleasant, unhappy) and cognitive processes (e.g., perception and evaluation of emotions), whereas the objective factors are related to physical arousal. Moreover, the subjective and objective factors influence each other through neural and hormonal systems. In this study, we used cortisol to represent stress hormones. Cortisol is the principal end-product steroid hormone produced by the hypothalamic–pituitary–adrenal (HPA) axis. The HPA is highly sensitive to context and is highly responsive to stress; it helps individuals adapt their physiological activity to meet the demands of a constantly changing environment (Van Hulle, Shirtcliff, Lemery-Chalfant, & Goldsmith, 2012).

Regarding the relationship between emotion and cortisol, Cahill and McGaugh (1998) proposed that emotional experiences affect the endogenous release of the hormone and influence long-term retention intervals. Measures of endogenous cortisol levels have also been shown to correlate with depressed mood (von Langen, Fritzemeier, Diekmann, & Hillisch, 2005). Along the same lines, it has been reported that endogenous cortisol levels are related to activity in a variety of subcortical brain regions that are thought to process emotion such as the amygdala (Drevets et al., 2002), insula, and subgenual cingulate cortex (Liberzon et al., 2007). Accordingly, negative emotions and cortisol may be related through some cerebral mechanisms.

2.2. Negative emotions, stress hormones, and WM

The investigation of the effect of emotional stimuli on WM performance has produced contradictory findings. Both emotion-dependent facilitation and impairment are reported in the literature. For example, Gyurak, Goodkind, Kramer, Miller, and Levenson (2012) found that emotional regulation did not affect WM. However, Lindstrom and Bohlin (2011) used a modified visual 2-back task with high-arousal positive, high-arousal negative, and low-arousal neutral stimuli and found that compared with the neutral stimuli, the arousing emotional stimuli facilitated WM performance with regard to response accuracy and reaction times. Similarly, Gray (2001) found that a withdrawal-motivated negative emotional state enhanced spatial WM performance. These studies suggest that highly activated negative emotions may influence WM performance, but the direction of influence requires further exploration.

Conversely, stress hormones such as noradrenaline (NA) and cortisol have been found to influence memory processes (Tollenaar, Elzinga, Spinhoven, & Everaerd, 2009). It has been shown that cortisol inhibits the memory retrieval of stored information (de Quervain, Roozendaal, & McGaugh, 1998; de Quervain, Roozendaal, Nitsch, McGaugh, & Hock, 2000). Functional MRI studies also support the notion that WM is impaired by acute and chronic psychological stress. For example, Liston, McEwen, and Casey (2009) found that medical students undergoing stressful exams showed weakened functional connectivity in the prefrontal cortex. However, it has been suggested that the corticosteroid hormones secreted by the adrenal cortex protect the brain against adverse events and are essential for cognitive performance (Cahill & McGaugh, 1998; de Kloet, Oitzl, & Joëls, 1999). Some researchers have provided evidence supporting the positive relationship between stress (hormones) and WM from the perspective of attention. For example, Joëls, Pu, Wiegert, Oitzl, and Krugers (2006) suggested that stress hormones can induce focused attention and improve the memory of relevant information.

Because the effect of stressors on cognitive performance depends on the severity of the stressor and the type of stress (Byron, Khazanchi, & Nazarian, 2010), and because the effects of negative emotions and stress hormones on WM remain controversial, this study proposes the following hypotheses in an exploratory manner:

H2: Highly activated negative emotions will influence WM during gaming.
H3: Stress hormones will influence WM during gaming.

3. The relationship among negative emotions, stress hormones, and creativity

Over the last decade, emotion has been the most widely studied predictor of creativity (Baas et al., 2008). Many systematic empirical studies have examined the relationships between the valence of emotion and creativity (Zenasni & Lubart, 2008); many studies have found that negative emotions enhance creativity (Baruch, Grotberg, & Stutman, 2008; Carlsson, 2002; Hirt, Devers, & McCrea, 2008; Jones & Kelly, 2009; Zenasni & Lubart, 2009). More recently, a three-dimensional theory, developed by Baas et al. (2008), has been proposed to explain the relationship between emotion and creativity. The three dimensions proposed are valence (positive vs. negative), level of activation (activating vs. deactivating), and regulatory focus (promotion vs. prevention). It has also been reported that high levels of negative emotions and arousal can decrease the production of original ideas (Zenasni & Lubart, 2008). Moreover, De Dreu, Baas, and Nijstad (2008) argued that activating moods (e.g., angry, happy) lead to more creativity than do deactivating moods. Therefore, a negative emotion with a high level of activation may decrease the performance of creativity. On the other hand, emotional states that are related to a promotion focus (e.g., anger, happiness) will lead to an expanded attentional scope and therefore facilitate creative performance, whereas emotional states that are associated with a prevention focus (e.g., fear, relaxation) will generate a more constricted attentional scope and therefore impede creative performance (Baas et al., 2008).

On the other hand, cortisol may influence creativity. Corticotrophin-releasing hormone (CRH) is critical to behavioral and neuroendocrinological adaptations to stress; it is the neuropeptide primarily responsible for HPA axis activation. It has been suggested that one of the most consistent behavioral correlates of CRH system activity is the manner in which an individual approaches novel and unfamiliar events (Barr et al., 2008). Novelty is a critical indicator of creativity (Mayer, 1999).

The findings of previous studies (De Dreu et al., 2008) suggest that stressors increase arousal, which enhances the use of creative thoughts and motivates persistence toward finding solutions. Moreover, stressors may enhance engagement in focused problem-solving strategies, leading to enhanced creativity. Alternatively, some researchers have proposed that stress may be related to creativity in a curvilinear fashion (Byron et al., 2010). Byron et al. (2010) conducted a meta-analysis of experimental studies and found that the effect of stressors on creative performance depends on the severity of the stressor and the type of stress that is induced.

Because the findings of previous studies on how negative emotions and stress hormones influence creativity are not consistent, and because few related studies have been conducted in game-based situations, this study proposed the following hypotheses in an exploratory manner:

H4: Highly activated negative emotions will influence creativity during gaming.
H5: Stress hormones will influence creativity during gaming.

4. Methods

4.1. Participants

In this study, all experimental tasks and data collection were conducted via a computer system. Thirty-four university students were included to test the validity of the experimental tasks and time controls in the computer system. After revising the system, 19 university students were included to revise and confirm the validity of the cortisol manipulation used in this study. Finally, 102 university students (35 males and 67 females) with a mean age of 19.78 years ($SD = 2.75$ years) participated in the formal experiment. They were randomly assigned to either the high- or low-stress groups. All participants received $10 for their participation.

4.2. Instruments

4.2.1. Situation-based creativity task

In this study, the Situation-based Creativity Task (SCT) (Yeh, 2012) was employed to evaluate the participants' creativity. The SCT includes situation- and game-based creative problem solving tasks. It has been proven to be an effective tool for evaluating creativity (Lin, Yeh, Hung, & Chang, 2013). Developed using Flash, the SCT consists of 3 runs of situational tasks in which the goal is to escape from a living room, kitchen, and bathroom. Each run of the situational task consisted of 10 insight problems. To solve each of the problems, 2 instruments that were provided in the situation had to be correctly combined (Fig. 1). Moreover, to increase the degree of difficulty and amusement, different sequences of problem solving were allowed in each run. An incorrect answer received 0 points, and a correct answer received 1 point. The highest total score attainable was 30 points (10 points in each run).

4.2.2. Situation-based WM task

Previous studies that focused on exploring the relationship between WM and creativity generally used WM tasks that were not related to creativity tasks. As mentioned above, the efficiency and effectiveness of specific WM should be closely related to creativity. In this study, we employed the Situation-based WM Task (SWMT), which is related to the SCT (Lin et al., 2013; Yeh, 2012). The SWMT consists of 3 runs of WM tasks, corresponding to the creativity tasks involving the living room, kitchen, and bathroom. Each run included 5 trials. In each trial, 3 pairs of a key item and an accessory item (e.g., garbage can + razor; garbage can + clothes hanger; garbage can + bath sponge) were displayed on the screen (Fig. 2). With a total of 5 key items, 15 pairs were displayed for the participants to memorize. To test their WM capacities, a matrix of 20 items with one key item was then displayed. The participants had to indicate the 3 accessory items that were shown from the matrix. Five matrices in total were displayed. During each run, an incorrect answer received 0 points, and a correct answer received 1 point. The highest score attainable was 45 points (15 points in each run).

4.2.3. Inventory of three-dimensional emotions

The Inventory of Three-dimensional Emotions (I3E), developed based on the theory of Baas et al. (2008), included 3 dimensions: valence (positive vs. negative), activation (high vs. low), and regulatory focus (prevention vs. promotion). Therefore, the I3E was composed of 8 types of emotions, each of which included 2 items. Each item was scored from 1 to 4 points, indicating “highly disagree” to “highly agree,” respectively. There was no time limit to complete the I3E. In terms of validity, a confirmatory factor analysis (CFA) indicated that the negative emotion model had good construct validity: $\chi^2(N = 301) = 29.151$ ($p = .015$); GFI = .976, AGFI = .944, RMSEA = .056, RMR = .017; NFI, NNFI, CFI, and IFI were all above .94. As for reliability, the Cronbach's α coefficient for the I3E was .839 (Yeh, Lin, Yeh, & Lin, 2012). Based on our experimental purpose, two types of negative emotions were employed in this study: (1) the highly activated and prevention-focused emotion (nervous and anxious) and (2) the highly activated and promotion-focused emotion (frustrated and angry).

4.2.4. Cortisol collection

In this study, saliva from healthy subjects was collected and the cortisol concentration was measured via an enzyme-linked immunosorbent assay (ELISA). To minimize interference from the baseline cortisol levels, participants were instructed to refrain from the following: stay up late the night before the experiment; drink alcohol 12 h before the experiment; brush teeth, perform extreme exercise, eat meals, smoke, or drink anything with sugar 2 h before the experiment. They were also requested to rinse their mouths thoroughly with water 10 min before the experiment began.

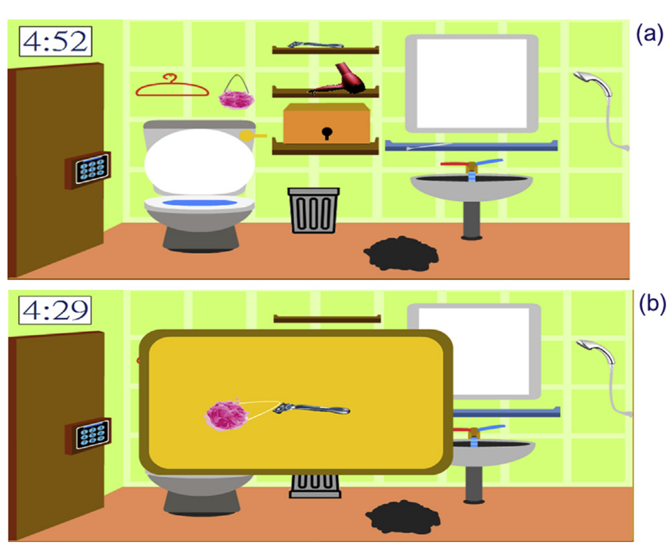

Fig. 1. An example of the situation-based creativity tasks.

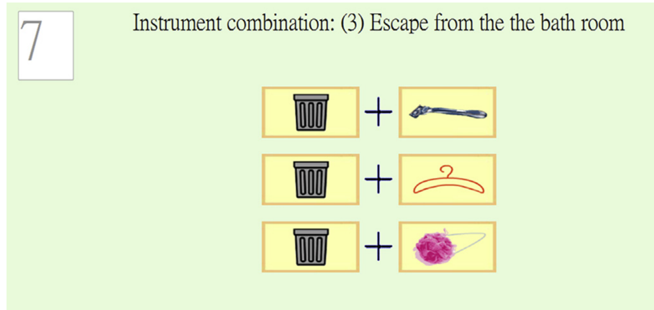

Fig. 2. Example of instrument combination.

During the experiment, four saliva samples were collected using commercially available disposable droppers. The collected saliva was placed into 1.5 mL polypropylene tubes. Each tube was immediately labeled with the participant's ID number, date, and time. Saliva samples were stored at −20 °C prior to analysis (Casals, Foj, & de Osaba, 2011; Tollenaar et al., 2009). On the day of testing, saliva samples were thawed, vortexed, and centrifuged at 1500 g for 15 min. An adequate amount of supernatant was pipetted into the wells of a 96-well plate for cortisol measurement using a salivary cortisol enzyme immunoassay kit (Salimetrics, PA, USA).

4.2.5. Experimental design and procedures

This study used desktop computers to collect data. Meanwhile, the salivary cortisol and emotional responses were collected. Because the salivary cortisol concentration can vary greatly during the day, the experiment was conducted in late afternoon. All study procedures were approved by the university's Institutional Review Board (IRB). To increase validity and reliability, the data were collected individually in the laboratory. The experimental procedure was as follows. (1) The experimenter explained the procedure of the experiment. (2) The participants filled out an informed consent form and watched a demonstration video about salivary cortisol collection. (3) The participants were randomly assigned to either the high- or low-stress group. Then, the Time 1 cortisol and emotion tests were administered. (4) The high-stress group was requested to memorize a short paragraph (10 min) and then recite it in front of a video camera (5 min), whereas the low-stress group was asked to watch a series of landscape pictures accompanied by relaxing music. (5) The participants then received the Time 2 cortisol and emotion tests. (6) The participants started to complete all of the experimental tasks and received the Time 3 and Time 4 cortisol and emotion tests at the end of the first and last games, respectively. The timeline of the procedure is illustrated in Fig. 3.

5. Results

5.1. Preliminary analyses

5.1.1. Changes in cortisol

To understand the effects of stress manipulation, we first analyzed the group differences in terms of changes in cortisol concentration. The cortisol concentration was measured in ng/dL. In testing for changes in cortisol, we used the manipulation group as the between-group

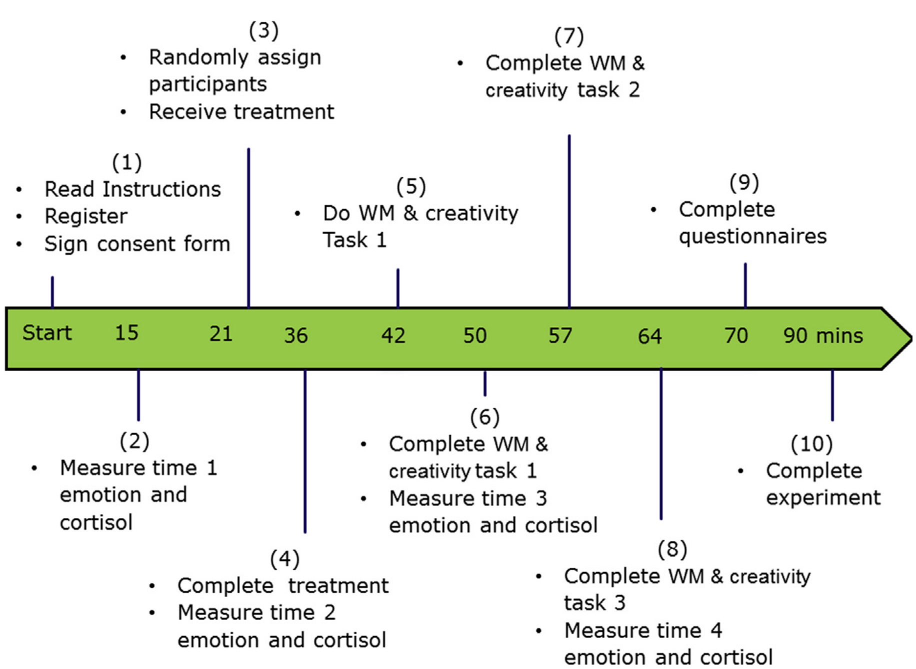

Fig. 3. Experimental procedures.

variable (Group: high-stress vs. low-stress) and took the time point of cortisol measurement as the within-group variable (Cortisol: T_1, T_2, T_3, and T_4) to conduct a 2 × 4 repeated measures of analysis of variance (see Fig. 4a for *M*s and *SD*s).

The findings of our experiment revealed that the main effect of cortisol was significant, $F(3, 94) = 10.241$, $p = .002$, $\eta^2_p = .098$; the main effect of Group was significant, $F(1, 94) = 4.691$, $p = .028$, $\eta^2_p = .050$; and the Group × Cortisol interaction was significant, $F(3, 94) = 6.353$, $p = .013$, $\eta^2_p = .063$. Further analysis of simple main effects revealed that the change in cortisol was significant in the high-stress group, $F(1, 47) = 7.170$, $p = .008$, $\eta^2_p = .141$ and in the low-stress group, $F(1, 47) = 19.587$, $p = .000$, $\eta^2_p = .294$. Moreover, the cortisol concentration in the high-stress group was higher than that in the low-stress group at T_2, T_3, and T_4 ($ps < .05$). These results suggest that the manipulation of stress in this study was effective. Statistical analyses also show that, in the high-stress group, the cortisol concentration starts to increase significantly after the manipulation and starts to decline after the completion of the 2nd game task (T_3 is the highest and T_2 & $T_3 > T_4$). In other words, the cortisol concentration takes 35 min to reach its peak and then decreases. In the low-stress group, the cortisol concentration starts to decrease significantly and reaches its minimum after the manipulation ($T_1 > T_2 > T_3 > T_4$). Moreover, except for T_1, the cortisol concentration in the high-stress group is significantly higher than that in the low-stress group (Fig. 4).

5.1.2. Changes in emotions

To understand the effects of stress manipulation, we also analyzed the group differences for changes in emotions at the time points corresponding to the cortisol measurements (see Fig. 4b and c for *M*s and *SD*s). The emotions measured in this study included the highly activated, prevention-focused and highly activated, promotion-focused emotions. In testing for each of the emotional changes, we considered the manipulation group to be the between-group variable (Group: high-stress vs. low-stress) and considered the time point of emotions to be the within-group variable (Emotion: T_1, T_2, T_3, and T_4) to conduct a 2 × 4 repeated measures analysis of variance.

The results showed that the main effect of the prevention emotion was significant, $F(3, 94) = 59.176$, $p = .000$, $\eta^2_p = .386$; however, neither the main effect of Group, $F(3, 94) = .344$, $p = .559$, $\eta^2_p = .004$, nor the interaction effect, $F(3, 94) = .003$, $p = .956$, $\eta^2_p = .000$, was significant. Comparisons of means revealed that T_2 had the strongest prevention-focused emotion whereas T_1 had the weakest emotion among the 4 measures, suggesting that the stress manipulation significantly increased the participants' feelings of nervousness and anxiety.

The results showed that the main effect of the promotion emotion was significant, $F(3, 94) = 122.777$, $p = .000$, $\eta^2_p = .566$; the main effect of Group was not significant, $F(3, 94) = .449$, $p = .505$, $\eta^2_p = .005$; and their interaction was not significant, $F(3, 98) = .263$, $p = .609$, $\eta^2_p = .003$. Comparisons of the means revealed that T_2 had the strongest promotion-focused emotion, whereas T_1 has the weakest emotion among the 4 measures, suggesting that the stress manipulation significantly increased the participants' feelings of anger and frustration.

5.1.3. Descriptive analyses of cortisol concentration, emotion, and WM scores

We employed a two-way (treatment group × personal characteristics group) analysis of variance (ANOVA) to examine the proposed hypotheses of this study. In these analyses, we divided each of the personal characteristics groups into three subgroups (Low, Medium, and High) based on their levels of cortisol concentration (mean score of the four measures), emotions (mean score of the four measures), or WM ability according to the cut-off points defined as the lower 27% and upper 27% (Kelley, Ebel, & Linacre, 2002). We then used these groupings separately as the independent variable to test their effects on the relevant dependent variables (WM or creativity). The *M*s and *SD*s of cortisol concentration, emotion scores, and WM ability scores are shown in Table 1.

5.2. Effects of cortisol on WM and creativity

The preliminary analyses revealed that the manipulation is effective in increasing the concentration of cortisol. To further understand the effects of treatment and cortisol on WM and creativity, we conducted a 2 (Group: high-stress vs. low-stress) × 3 (Cortisol: Low, Medium, and High) ANOVA separately (see Fig. 5 for *M*s and *SD*s).

The results revealed that the main effect of cortisol on WM was significant, $F(2, 90) = 5.061$, $p = .008$, $\eta^2_p = .101$. Scheffé's post hoc test revealed that the high-cortisol participants had better WM than did the medium-cortisol participants. Moreover, the main effect of Group

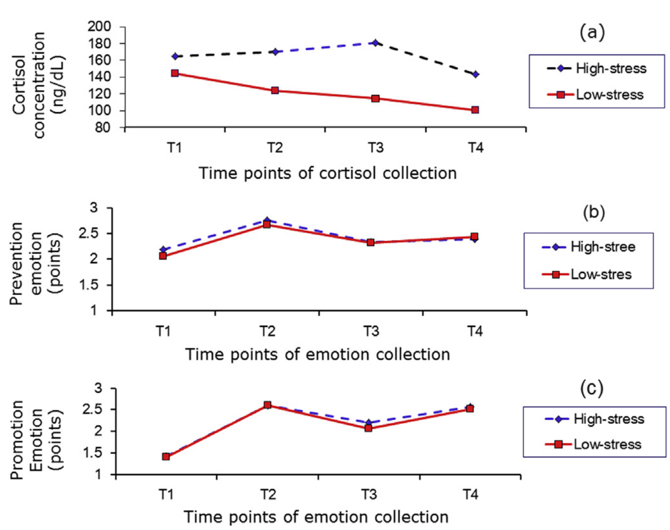

Fig. 4. Mean cortisol concentration and emotion scores of different groups at different time points.

Table 1
The means and *SD*s of cortisol concentration, emotion, and WM scores in different groups.

Source	Low		Median		High	
	M	*SD*	*M*	*SD*	*M*	*SD*
Cortisol (ng/dL)	54.87	16.80	127.04	23.20	268.12	116.16
Prevention-focused emotion (points)	1.88	.23	2.46	.14	2.89	.15
Promotion-focused emotion (points)	1.68	.25	2.23	.17	2.74	.13
WM (points)	13.96	2.41	20.17	2.04	28.42	3.30

was significant, $F(1, 90) = 5.699$, $p = .019$, $\eta^2_p = .060$, and the high-stress group had better WM than did the low-stress group. However, the Group × Cortisol interaction was not significant. In addition, all main and interaction effects on creativity were not significant.

5.3. Effects of emotion on WM and creativity

To investigate the effects of the examined emotions on WM and creativity, we conducted a 2 (Group: high-stress vs. low-stress) × 3 (Emotion: Low, Medium, and High) ANOVA (see Fig. 6 for *M*s and *SD*s) separately. Again, the examined emotions were the prevention- and promotion-focused emotions. The results revealed that in the promotion-emotion condition, the main effects of Group on WM were significant, $F(2, 90) = 7.418$, $p = .008$, $\eta^2_p = .076$. Scheffé's post hoc test revealed that the high-stress group had better WM than did the low-stress group, suggesting that stress contributes to WM performance. However, the main effect of prevention emotions and the Group × Prevention Emotion interactions were not significant.

Conversely, the ANOVA results revealed that promotion emotions had a significant effect on creativity, $F(2, 90) = 17.821$, $p = .000$, $\eta^2_p = .284$. Scheffé's post hoc test revealed that participants with low levels of promotion-focused emotions had more creativity than did those participants with medium and high levels of promotion-focused emotions, suggesting that promotion-focused emotions harm creativity.

5.4. Effects of WM on creativity

To examine the effects of WM on creativity, we conducted a 2 (Group: high-stress vs. low-stress) × 3 (WM: Low, Medium, and High) ANOVA (see Fig. 7 for *M*s and *SD*s). The results revealed that WM has a significant effect on creativity, $F(2, 90) = 6.334$, $p = .003$, $\eta^2_p = .112$. Scheffé's post hoc test revealed that participants with high levels of WM ability exhibited more creativity than did those with medium and low levels of WM ability, suggesting that WM has an important influence on creativity.

6. Discussion and suggestions

6.1. Effectiveness of stress manipulation and inconsistencies of changes in emotions and cortisol

This study aimed to manipulate stress to further investigate the relationships among cortisol concentration, negative emotions, WM ability, and creativity in game-based situations. Two types of stress manipulation were employed in the experiment. As expected, in the low-stress group, the cortisol concentrations decreased to a minimum level, whereas in the high-stress group, the cortisol concentrations increased to a maximum level during the experiment. Interestingly, we found that the change curve for emotion was not the same as the curve for cortisol concentration. Specifically, in both groups, the negative prevention- and promotion-focused emotions increased after treatment. When we further examined the relationship between negative emotions and cortisol concentrations at the four time points, only

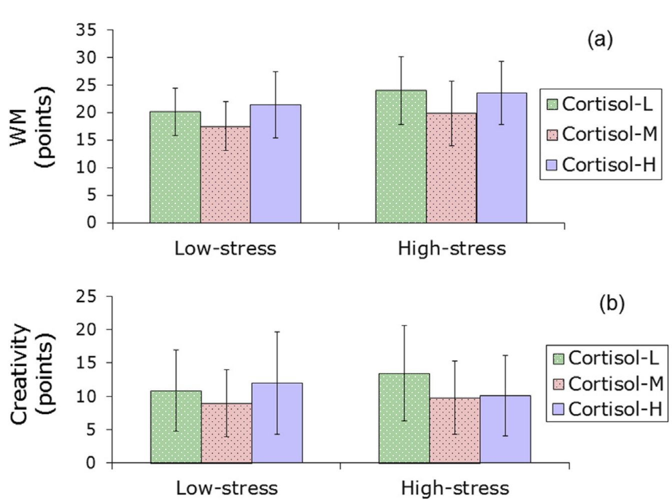

Fig. 5. Mean scores and standard deviations of WM and creativity in different manipulation and cortisol groups.

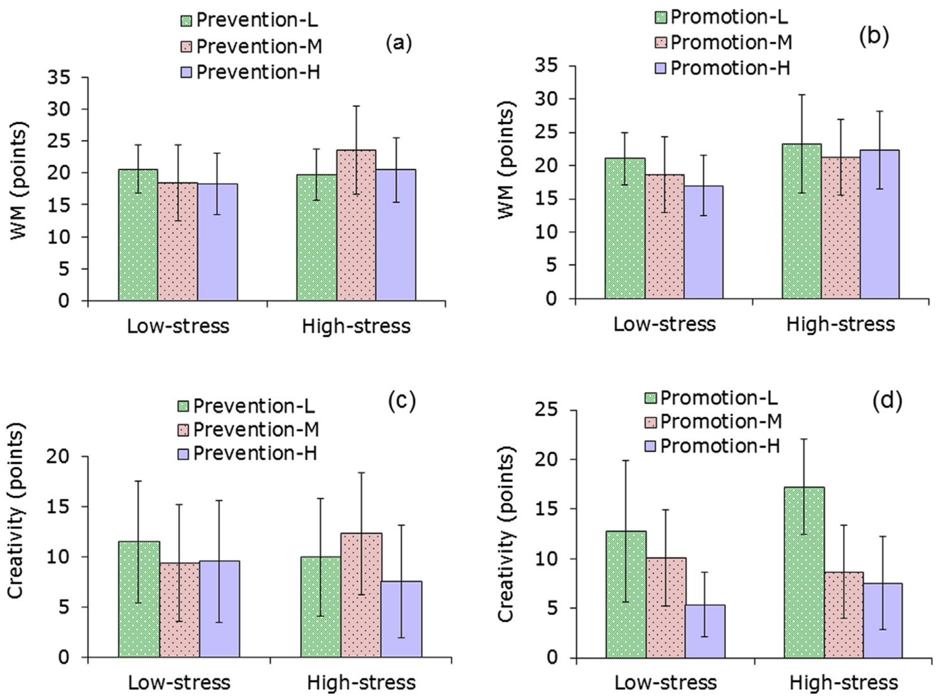

Fig. 6. Mean scores and standard deviations of WM and creativity in different manipulation and emotion groups.

the prevention-focused emotions and cortisol concentrations were positively correlated at T_1, $r(95) = .228$, $p = .026$. These findings suggest that subjective negative emotions and objective cortisol responses are not necessarily consistent during gaming tasks.

The findings of this study also support the notion that there is no direct cause-and-effect relationship between cortisol and negative emotions (Sudheimer, 2009). However, it has been suggested that cortisol can influence emotions and that the structure and physiology of neurons in certain brain regions may underlie emotional responses (von Langen et al., 2005; Liberzon et al., 2007; Sudheimer, 2009). In an fMRI study, Sudheimer (2009) concluded that cortisol specifically influences activities in the subgenual cingulate during times of sadness and affects the subjective emotional experience of sadness. Sudheimer suggested that endogenous hypercortisolemia could be responsible for changes in the subjective experience of emotion and for changes in subgenual cingulate brain activity patterns. Accordingly, cortisol and negative emotions may indirectly influence each other via brain functions. Further studies can employ a cognitive neuroscientific approach to investigate the underlying brain mechanisms in the relationships between different types of negative emotions and cortisol during gaming. Moreover, because a single measure of cortisol differentially reflects the confluence of momentary, rhythmic and individual difference factors (Adam, Hawkley, Kudielka, & Cacioppo, 2006), we collected the salivary cortisol at four time points in this study to investigate the effectiveness of manipulation as well as to explore how long an elevated cortisol concentration may be maintained. Laboratory studies employing the TSST von Dawans, Kirschbaum, and Heinrichs (2011), which involves subjects delivering a speech, demonstrate a reliable increase in cortisol secretions. The effectiveness of our stress manipulation lends support to the strength of a public speech in increasing cortisol concentration and the suggestion that exposure to psychosocial stress alters the functioning of the

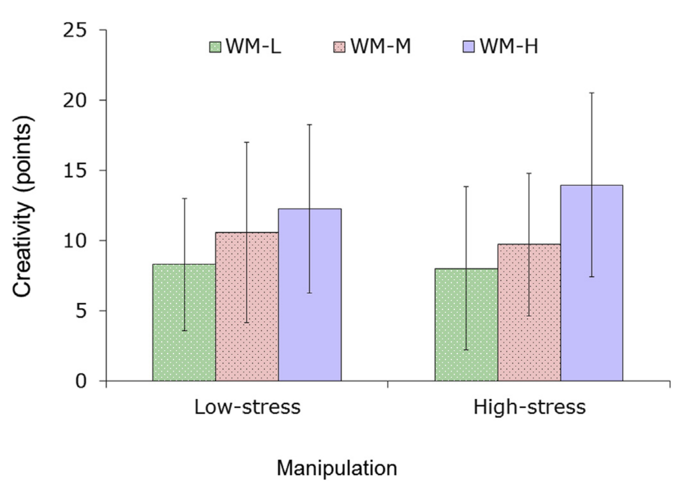

Fig. 7. Mean scores and standard deviations of creativity in different WM groups.

hypothalamic–pituitary–adrenal (HPA) axis, which regulates the release of cortisol (Chrousos, 2009). Moreover, in the high-stress group, the cortisol concentration takes 35 min to reach its peak level and then decreases, suggesting that the employed stress manipulation in our study strongly increases cortisol. Notably, the cortisol concentration declines during the day after wakening. As we try to elevate the cortisol concentration, its natural response is actually to continue decreasing. Accordingly, the actual increased cortisol concentration should be higher than what we measured.

6.2. Two routes in which stress stimuli influence WM and creativity during gaming

In this study, we hypothesized that the employed stress stimuli would influence cortisol concentration and negative emotions, subsequently influencing WM and creativity in game-based situations. To make our complex findings easy to understand, we present Fig. 8 as a framework for our interpretations. In Fig. 8, the black arrows are based on the findings of this study, and the dotted arrows are the possible underlying mechanisms suggested by previous findings. In summary, stress stimuli may influence creativity through two routes: (1) by enhancing creativity via cortisol concentration and WM and (2) by decreasing creativity via highly activated and promotion-focused negative emotions. Meanwhile, some brain mechanisms (e.g., the dopamine and the amygdala pathways) and some cognitive mechanisms (e.g., attention, motivation, perseverance, and flexibility) may serve as mediators.

In this study, we hypothesized that the levels of cortisol concentration would have an influence on WM ability and creativity. Interestingly, we found a U-shaped relationship between cortisol concentration and WM ability. Stress is not a unitary process; its effects on cognitive outcomes depend on its duration, intensity, or timing with regard to cognitive challenges (Luksys & Sandi, 2011). Compared with prior related studies, our stress manipulation and experiment lasted for a longer period of time, and our WM tasks were more difficult (they were 5-back tasks). These unique characteristics may explain why our findings differed from those of previous studies (e.g., Diamond, Campbell, Park, Halonen, & Zoladz, 2007). Moreover, some researchers have provided supporting evidence for a positive relationship between stress (hormones) and WM from the perspective of attention. For example, Joëls et al. (2006) suggested that stress hormones can induce focused attention and improve the memory of relevant information. It is worthwhile to investigate the mechanisms of how attention may mediate the relationship between stress hormones and WM.

This study also found that WM positively influences creativity. WM fulfills two basic functions: (1) keeping novel information in a heightened state of activity and (2) discriminating between task-relevant and task-irrelevant information. These two functions are critical to creative performance (De Dreu et al., 2012). The findings in this study support the claims that WM span is related to the ability to solve difficult problems (Song, He, & Kong, 2011), high WM capacity is positively related to creativity, and WM capacity predicts original ideas because it allows for persistent (rather than flexible) processing (De Dreu et al., 2012). Moreover, it has been suggested that WM capacity benefits creativity because it enables the individual to maintain attention (De Dreu et al., 2012). Additionally, WM capacity facilitates problem solving because it helps individuals control their attention, resist distraction, and narrow their search through a problem space (Wiley & Jarosz, 2012). Accordingly, WM may influence creativity via attention on task-related information and persistence. Moreover, it has been suggested that executive control plays an important role in creativity. However scientific evidence on this topic is sparse (De Dreu et al., 2012). Recently, a few imaging studies have provided some evidence for the correlation between WM and creativity. For example, Gansler et al. (2011) found that the right parietal lobe contributes to visuospatial divergent thinking because this process draws more upon mental manipulation than on the monitoring aspects of WM. In addition, Takeuchi et al. (2011) found that reduced deactivation in the precuneus during a WM task was associated with creativity measured by the divergent thinking test. Future studies can focus on exploring how different neural components (e.g., executive control) and WM strategies may facilitate WM capacity via brain functions, subsequently stimulating creativity in game-based situations.

Regarding the relationship between negative emotions and WM, this study found that none of the examined types of emotion affected WM. This result is not consistent with a previous finding that cognition–emotion interactions are modulated by WM capacity (Strauss et al., 2012). However, it is also possible that emotion may influence WM indirectly via some brain functions. Cahill and McGaugh (1998) proposed a memory-modulating mechanism for emotionally arousing events, in which experiences are stored in various brain regions with little or no involvement of either stress hormone activation or the amygdaloid complex (AC). During periods of emotional arousal, stress hormone

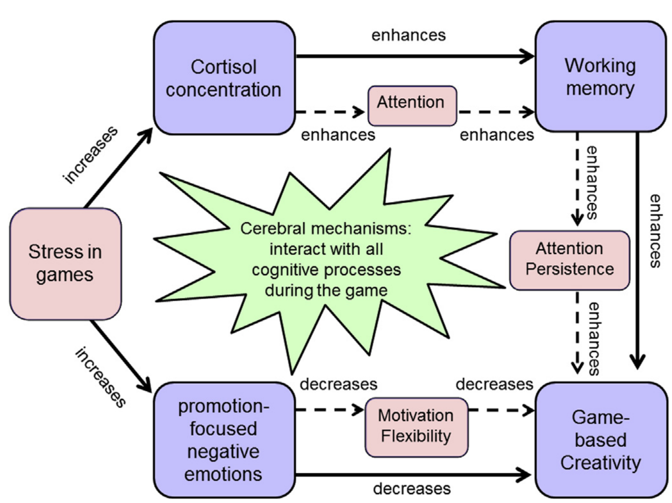

Fig. 8. A framework of interpreting findings in this study.

systems may interact with the AC to modulate memory storage processes occurring in other brain regions. Accordingly, it would be interesting to further investigate whether such emotion–brain interactions are found in game-based situations.

Notably, this study found that highly activated and promotion-focused negative emotions decreased creativity. This result is in line with Zenasni and Lubart's (2008) finding that as participants increased their state of arousal, they tended to feel their negative emotional experiences more intensely and generated fewer positive ideas. These emotions are most common in this task. It has been suggested that activating, rather than deactivating, mood states converge with greater motivation, higher levels of dopamine and noradrenaline, and enhanced WM capacity. As a result, these processes should facilitate cognitive flexibility, abstract thinking, processing speed, and access to long-term memory (Baas et al., 2008; Dietrich, 2004). Accordingly, it is likely that during gaming, highly activated and promotion-focused negative emotions may decrease motivation and cognitive flexibility for creative problem solving, and this decreased cognitive flexibility and motivation may decrease levels of dopamine and noradrenaline, further hindering creativity.

7. Conclusions

Creativity is a significant human strength, and game-based learning has become an important educational instrument. This study attempts to interpret the cognitive process of game-based creativity through the integration of neuroscientific techniques into a behavioral experiment. The variables included in this experiment were negative emotions, stress hormones (cortisol), and WM. This study had two major limitations. First, although we carefully excluded participants who were not suitable for this experiment and randomly assigned our participants to either the high- or low-stress groups, it is unknown whether the participants had potential diseases that might have influenced their cortisol concentrations. Second, a WM and creativity pretest was not administered because it may have caused negative emotions that could potentially interfere with the effects of our manipulation. Nevertheless, our original experimental design and the interesting findings that resulted help demonstrate the cognitive process of creativity in game-based situations.

This study found that cortisol concentration contributes to WM performance and that WM ability facilitates creativity during gaming. Meanwhile, negative emotions with a high level of activation and a promotion focus are detrimental to creativity. Such a contradictory finding suggests that WM can be a mediator of cortisol concentrations and creativity only when cortisol levels are high but also when highly activated and promotion-focused negative emotions are not perceived. Therefore, when designing games aimed at teaching creativity, it is important to provide appropriate challenges or stressors that can increase cortisol concentration to a level that contributes to attention and flexible thinking but to a level at which subjective highly activated and promotion-focused negative emotions are not provoked. Game designers can also focus on enhancing the function of executive control and WM strategies that may facilitate WM capacity and efficiency, and further, stimulating creativity in game-based learning. Moreover, the findings in this study suggest that changes in subjective negative emotions, and supposedly corresponding physical changes in cortisol, do not have a consistent change patterns or predictive power for WM and creativity during gaming. Therefore, integrating neuroscientific methods to understand the underlying mechanisms that influence creativity can provide concrete suggestions for game-based learning or designing games for creativity. To conclude, we proposed that stress stimuli may affect WM and creativity through two routes, which contributes to cognitive creation theory building in the area of game-based learning as well as provides valuable implications for designing games for the learning of creativity.

Acknowledgments

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