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Heart rate variability reflects the effects of emotional design principle on mental effort in multimedia learning

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ABSTRACT

Recent studies have indicated that there are benefits to be derived from incorporating emotional design principles into multimedia lessons. However, the results of how this principle affects the amount of mental effort that is exerted in learning have been mixed. In this study, the effect of the emotional design principle on individuals' mental effort investment was examined using effort-related physiological measures (i.e., heart rate variability). Sixty college participants, of whom 30 were in a positive emotional design group and the remaining 30 in a neutral emotional design (control) group, received a six-minute-long set of biology multimedia instructions. Compared to the participants in the neutral design group, the participants in the positive emotional design group performed better on a subsequent retention test and had a stronger decrease in the high-frequency band of heart rate variability in the instruction session. These findings are consistent with the affective mediation assumption of *Cognitive Affective Theory of Learning with Media* and indicate the potential importance of including affective and motivational factors in multimedia learning research.

1. Introduction

The emotional design principle of multimedia instruction involves the redesign of graphics in a lesson with warm colors and round shapes with face-like characters (Plass, Heidig, Hayward, Homer, & Um, 2014; Um, Plass, Hayward, & Homer, 2012). According to the emotional design hypothesis (Um et al., 2012), redesigned graphics with warm colors and face-like shapes in multimedia instructions induce the learner's positive affectation and therefore facilitate learning outcomes. Previous studies have indicated the benefits of implementing positive emotional design materials in multimedia lessons, such as induced positive feelings, increased motivation, decreased perceived task difficulty, and facilitated learning outcomes (Mayer & Estrella, 2014; Park, Knörzer, Plass, & Brünken, 2015; Plass et al., 2014; Um et al., 2012). This article addresses the question of whether the positive emotional design materials influence mental effort investment in multimedia learning.

1.1. Emotion and multimedia learning

Studies on emotional design principles (Um et al., 2012) are primarily guided by the Cognitive Affective Theory of Learning with Media (CATLM; Moreno, 2006; Moreno & Mayer, 2007), which extended the Cognitive Theory of Multimedia Learning (CTML; Mayer, 2005) by further integrating affective and motivational factors with cognitive processes. CATLM maintains the assumptions of the CTML that the learner selects, and then organizes and integrates the learning contents with prior knowledge to build a coherent mental modal (Mayer, 2005). In addition, CATLM proposes three new assumptions. First, affective and motivational factors mediate learning by increasing or decreasing cognitive engagement. Second, metacognitive factors (e.g., self-regulation) mediate learning by regulating cognitive and affective processes. Third, the efficiency of learning with multimedia is affected by individual differences (e.g., prior knowledge, cognitive style).

Recently, Plass and Kaplan (2016) presented the Integrated Cognitive Affective Model of Learning with Multimedia (ICALM) on the basis of CTML and CATLM to further explain the interconnection between emotions and cognitions in multimedia learning. The central theme in ICALM is that affective processes and cognitive processes are entangled with each other throughout the learning process and that cognitive-affective processing makes demands on cognitive resources (Plass & Kaplan, 2016). Specifically, ICALM proposes that the experienced affect during learning is both impacted by and impacts the information

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learners select from the multimedia environment. Affect that involves appraisal is experienced by the learner as interest and motivation also impacts and impacted by the organization of visual and verbal mental representations in working memory. Meanwhile, the experienced affect influences the integration process to build a coherent affective-cognitive mental model.

The present study focuses on the affective mediation assumption of the CATLM to investigate whether and how positive affective factors influence the learning process in a multimedia environment. In particular, we consider the question of how positive affect influences cognitive engagement.

1.2. Positive emotion, cognitive engagement, and mental effort investment

According to the affective mediation assumption of the CATLM (Moreno, 2006), positive emotion plays a central role to increase the level of learners' cognitive engagement. So that learners can think deeply to understand the learning content and to thereby improve learning outcomes (e.g., Blumenfeld & Rogat, 2006). Cognitive engagement during learning can be identified by the invested mental effort (e.g., Balumenfeld & Rogat, 2006; Fredrick, Blumenfel, & Paris, 2004), and mental effort has been defined as “the amount of resources actually allocated to accommodate task demands.” (Paas, 1992). Thus, the facilitation effect of positive emotions on cognitive engagement proposed by the affective mediation assumption (Moreno, 2006) can be simply explained as more mental effort (cognitive resources) being allocated by the learner to carry out a given task. This prediction is consistent with various theoretical models. For example, the broaden-and-build theory (Fredrickson, 2001) that is to explain the role of positive emotion in promoting mental health suggests that more cognitive resources are available when individuals are in a positive mood, allowing better coping with different adversities. In addition, the strength model of self-regulation (Baumeister, Vohs, & Tice, 2007) suggests that positive affect motivates individuals to continue to invest mental resources (common resources used for self-control, working memory, planning, and decision-making) and thereby avoid the ego depletion effect, that is, “the state of reduced self-regulatory capacity stemming from prior exertion of self-control” (for a review, see Baumeister, 2014).

1.3. Problem statement

Previous studies of the emotional design principle have measured the amount of mental effort individuals exert in lessons by using the single-item *Perceived Mental Effort Questionnaire* (Paas, 1992), which has been widely used in educational research (for a review, see Van Gog & Paas, 2008). According to the affective mediation assumption of the CATLM (Moreno, 2006; Moreno & Mayer, 2007), the materials designed to induce positive emotions in a multimedia lesson can increase the level of learners' cognitive engagement. Studies of the emotional design principle (Mayer & Estrella, 2014; Park et al., 2015; Plass et al., 2014; Um et al., 2012; Uzun & Yıldırım, 2018) extrapolated that participants who learned with positive emotional design materials may exert greater mental effort to carry out a task compared to their counterparts in the neutral emotional design group. However, such an extrapolation has not been validated in previous studies.

According to our knowledge, only one study to date has found that participants in a positive emotional design group report greater mental effort than participants in the corresponding control group (see Experiment 1, Mayer & Estrella, 2014). Conversely, a recent study, showed that the positive emotional design materials (e.g., anthropomorphic design and sound effects) result in less experienced mental effort investment as compared to the materials designed with bright and saturated colors (Uzun & Yıldırım, 2018). In addition, other studies have reported equivalent levels of mental effort between the positive emotional design group and the neutral emotional design group (see Experiment 2, Mayer & Estrella, 2014; Park et al., 2015; Plass et al., 2014; Um et al., 2012).

The abovementioned inconsistency of the empirical findings can be attributed to the fact that participants might have made inaccurate judgments about how much effort they invested in the positive emotional design condition (Uzun & Yıldırım, 2018). Learners' perceptions of mental effort investment are affected by their appraisal of task demand (e.g., Paas, Van Merrienboer, & Adam, 1994; Raaijmakers, Baars, Schaap, Paas, & van Gog, 2017). Previous studies have indicated that the positive emotional design materials can reduce perceived task difficulty (see Experiment 1, Mayer & Estrella, 2014; Plass et al., 2014; Um et al., 2012). Following the idea that decreases in perceived task difficulty lead to less effort investment, participants in the positive emotional design group could underestimate their mental effort investment in such tasks due to the lower perceived task demand. This prediction is consistent with the literature showing that positive affect can reduce the appraisal of task demand and therefore reduce experienced mental effort investment (e.g.,Raaijmakers et al., 2017; Venables & Fairclough, 2009; Wright & Brehm, 1989).

Overall, previous studies of the emotional design principle have not arrived at a clear consensus about how the positive emotional design principle influences mental effort investment. Thus, we argue that a more direct measure of learners' actual mental effort investment during learning would provide clarification on how positive emotional design influence mental effort investment.

1.4. The present study

In this study, we are interested in how positive emotional design materials affect learners' actual mental effort investment during learning. To this end, we introduce effort-related psychophysiological measures (i.e., heart rate variability) as objective indices of mental effort investment.

1.4.1. Measuring mental effort through heart rate variability

From a psychophysiology perspective, mental effort investment has been defined as the energy mobilization at cerebra sites in the service of cognitive goals (Fairclough & Mulder, 2011). To support the energy consumption, the brain requires a constant supply of energy (glucose and oxygen) via the cardiovascular system. Thus, mental effort investment can be identified by an increase of cardiovascular activity (Mulder, 1986, 1992).

In this study, spectral band analysis of heart rate variability (HRV) was conducted to investigate the effect of the positive emotional design principle on mental effort investment, which has been widely used in both laboratory tasks and applied situations (Fairclough & Mulder, 2011). Two ranges of spectral bands of HRV changes were analyzed in the present study: the middle-frequency (MF) band (0.07–0.14 Hz), and the high-frequency (HF) band (0.15–0.40 Hz; Mulder, 1986).

In general, MF and HF HRV have been found to decrease with increase of mental effort investment (Fairclough & Mulder, 2011). The MF band reflects short-term changes in blood pressure, which are associated with the influence of both the sympathetic (SNS) and the parasympathetic (PNS) nervous system (e.g., Task Force, 1996). A large body of evidence indicate that mental effort investment has strong effects on the MF component, which is particularly sensitive to task demand (for a review, see Reyes del Paso, Langewitz, Mulder, van Roon, & Duschek, 2013). The HF band reflects the effect of respiration on heart rate, also referred to as respiratory sinus arrhythmia (RSA). It has also been suggested that the HF component reflects vagal inhibition (Porges, 2007). Reduction of HF power is often considered to be a physiological indicator of an individual's engagement in regulated behavior, such as attentional regulation, inhibitory control, and working memory (for a review, see Holzman & Bridgett, 2017).

1.4.2. Research objective and hypothesis

This study was conducted with the objective of replicating and extending the findings in previous emotional design studies (Mayer & Estrella, 2014; Plass et al., 2014; Um et al., 2012; Uzun & Yıldırım, 2018) using different materials. Specifically, physiological measures (i.e., HRV) were adopted to investigate the effect of the positive emotional design principle on learners' mental effort investment during learning. In addition, according to the emotional design hypothesis (Um et al., 2012), specially designed visual elements (with appealing colors and face-like shapes) facilitate learning by increasing learners' motivation. To better replicate previous findings and investigate the underlying mechanism for the effect of the emotional design principle, motivational factors were also measured in the present study. Based on the extant research, the following hypotheses were made:

Hypothesis 1. Positive emotional design (PD) materials will induce more positive emotions than neutral emotional design (ND) materials, and learners in a PD group will perform better on retention and transfer tasks than participants in an ND group.

Hypothesis 2. Participants in a PD group will have higher situational interest, higher perception about learning achievement, and lower perceived task difficulty than participants in an ND group.

Hypothesis 3. The materials designed to induce positive affectation may facilitate greater mental effort investment (Um et al., 2012) during learning, and therefore a stronger reduction of HRV (i.e., MF and HF) will be observed in the PD group.

2. Method

2.1. Participants

The participants ($N = 60$) were first year undergraduate students from a university in east China, each of whom received $5 USD for their participation. The sample included 17 men and 43 women and had an average age of 18.79 years ($SD = 1.20$). Participants were randomly assigned to one of the two groups, one constructed by positive emotional design (PD), and the other neutral emotional (ND) design.

2.2. Design of materials

A multimedia learning lesson about the influenza virus served as the learning material. These learning materials incorporated text and pictures, and were accompanied by narration. The program consisted of three sections, entitled "The morphological structure of the virus," "Virus infection process," and "Mutation of the virus," for a total duration of 6 min. The learning course was system-paced, and the learner could not control the progress. The positive emotional design materials followed the emotional design principle presented by Um et al. (2012) without changing the basic learning content. Specifically, the *positive emotional design* materials used saturated and analogous warm color and face-like round shapes. The *neutral emotional design* materials used monochromatic grayscale and rectangular shapes (see Fig. 1).

2.3. Subjective measures

Two control measures were used to assess the following: (1) *Prior knowledge* was measured with a seven-item self-report checklist, in which the learner indicated his or her level of knowledge on the topic of virus (e.g., "I can explain the difference between virus and bacteria."). Participants received one point for each item. The total score was obtained by summing the points from all seven items, with scores ranging from 0 to 7. Cronbach's α was 0.85 in the present study. (2) *Individual interest* was measured using a four-item questionnaire, adapted from the Individual Interest Questionnaire (Mitchell, 1993). Individual interest is conceptualized as a relatively stable predisposition toward a particular topic or domain (e.g., Renninger, 2000). Previous studies have indicated that individual interest can influence how participants evaluate and respond to a given task (for a review, see Hidi & Harackiewicz, 2000). In the present study, participants responded on a five-point Likert scale ranging from "1" (*strongly disagree*) to "5" (*strongly agree*). The average score of the ratings for the four items was obtained, ranging from 1 to 5. In the present study, the Individual Interest Questionnaire was translated into Chinese by the first author, with the word "mathematics" in the original questionnaire being replaced with "biology." For example, "I have always enjoyed studying mathematics in school," was changed to "I have always enjoyed studying biology in school." A high internal consistency was found with Cronbach's $\alpha = 0.90$.

Positive emotions were measured via the Positive Affect Scale (PAS) from the Positive and Negative Affect Schedule (PANAS; Watson, Clark, & Tellegen, 1988). Ten positive emotions (interested, excited, strong, enthusiastic, proud, alert, inspired, determined attentive, active) were measured using a five-point Likert scale, ranging from "1" (*very, slightly, or not at all*) to "5" (*very much*). Previous studies have shown that the Chinese version of the PAS is reliable and valid (e.g., Weidong, Jing, & Schick, 2004). Cronbach's α was 0.89 (PAS 1) and 0.88 (PAS 2) in the present study.

Learning outcome was measured via *retention* and *transfer* tests. The retention test was comprised of 15 multiple-choice questions measuring the learners' understanding of the key concepts in the multimedia lesson. For example, "Which kind of antigen will help the virus intrude into the normal cell?" Participants received one point for each correct answer, with the total score ranging from one to 15 points (Cronbach's $\alpha = 0.73$). The transfer test consisted of four questions, measuring the learners' ability to apply the knowledge learned to solve problems (e.g., "Try to explain why a person who was vaccinated with the influenza vaccine still became infected with the flu."). Participants received 2 points for each question if their answer was completely correct, otherwise they received 1 or 0 points. The total score was obtained by summing the points received for the individual items on the test, resulting in a range of scores from 0 to 8. These four questions were rated by two independent raters who resolved differences in scores by discussion, Cronbach's $\alpha = 0.66$.

Subjective rate of mental effort was measured via a Cognitive Load Subjective Experience Questionnaire (Paas, 1992). One question was

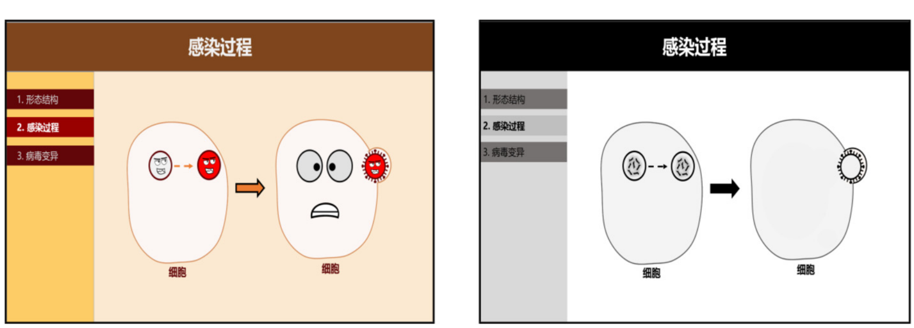

Fig. 1. Screen shots of multimedia learning materials, positive emotional design materials (left) and neutral emotional design materials (right).

asked, “How much mental effort did you invest in studying the previous material?” A nine-point Likert scale was used for the measurement. Participants also completed a nine-point Likert style questionnaire on their perceptions of task difficulty by asking, “How difficult was the material to understand?” (e.g., Kalyuga, Chandler, & Sweller, 2000).

Situation interest was measured using a 10-item situational interest questionnaire (Flowerday & Schraw, 2003). Situational interest is conceptualized as a form of externally controlled motivation that is generated by certain conditions and/or stimuli in the environment (for a review, see Hidi & Harackiewicz, 2000). Participants responded on a five-point Likert scale ranging from “1” (*strongly disagree*) *to* “5” (*strongly agree*). The average score of the ratings of the ten items was obtained, ranging from 1 to 5. In the present study, the situational interest questionnaire was translated into Chinese by the first author (e.g., “I got caught-up in the learning material without trying to.”). Cronbach's α = 0.87 in the present study.

Perception of learning achievement was measured using a seven-point Likert style scale (Um et al., 2012; “How well do you think you did in the preceding tests?”) ranging from “1” (*very bad*) to “7” (*very good*).

2.4. Physiological measures

Each learner's heart rate was obtained using a Nexus-32 physiological monitoring system with Biotrace +2009 software (Mind Media B.V. Netherland). The body signal was digitized at 128 Hz derived from a blood volume plus (BVP) sensor. The inter-beat interval (IBI) sequences were automatically and manually inspected, and the data considered as artifacts were replaced by interpolated data. The HRV spectrum (0–0.4 Hz) used a nonparametric fast Fourier transform (FFT; 1024 points) on detrended IBI values, interpolated at 4 Hz. The data from the spectral analysis were transformed with a natural logarithm for statistical analysis.

2.5. Procedure

The study was conducted in a single session, lasting approximately 45 min using a computer system. Participants were first tested for prior knowledge and individual interest. Then the experimenter attached the BVP sensor to participants who sat quietly for 6 min while the baseline data were collected. After the baseline period, participants completed the first positive affect schedule (PAS1). Next, the multimedia instructions were presented to the participants on the computer while psychological data were collected for 6 min. After completing the learning task, the BVP sensor was removed. Participants were given approximately 25 min to finish the remaining questionnaires related to mental effort, perceived task difficulty, the second PAS (PAS2), situational interest, learning performance (retention and transfer), and the perception of learning achievement.

3. Results

The means and standard deviations of all the variables across the conditions are presented in Table 1.

3.1. Control variables

The first step was to determine whether there are group differences in the control variables. For each variable (i.e., prior knowledge and individual interest), a one-way ANOVA was conducted with group as the between-subject factor. The results revealed no main effect for either control variable, for prior knowledge, F (1,58) = 1.20, p = 0.27; for individual interest, F (1,58) = 0.68, p = 0.41.

3.2. Positive emotion

To investigate whether the emotional deign principle induces positive emotions, an analysis of repeated measures (RM-ANOVA) with group as between-subject factors and PAS scores on the first (PAS 1) and second PAS (PAS 2) tests as repeated measures was conducted. The analysis indicated a significant main effect of the changes in PAS scores (PAS 1 vs. PAS 2), F (1,58) = 9.41, p = 0.03, η_p^2 = 0.14. Paired-sample t-tests indicated that the PAS score of the positive emotional design (PD) group significantly increased (ΔM = 3.03) during learning, t (29) = 2.47, p = 0.02, d = 0.46, but not for the neutral emotional design (ND) group (ΔM = 1.27), t (29) = 1.43, p = 0.17. In summary, the redesigned graphics in the PD group successfully induced learners' positive emotion, which is consistent with the emotional design hypothesis (Um et al., 2012).

Table 1
Means and standard deviations of all variables by conditions.

	Neutral design group (N = 30)		Positive design group (N = 30)	
	M	*SD*	*M*	*SD*
Prior-knowledge	3.17	0.65	3.35	0.68
Individual interest	3.48	0.70	3.64	0.80
PAS 1	27.40	7.88	26.70	6.09
PAS 2	28.67	6.36	29.73	7.58
Mental effort	7.10	1.32	7.20	1.32
Task difficulty	4.43	1.14	3.63	1.30
Situational interest	3.21	0.62	3.52	0.39
Retention	9.30	2.23	10.57	2.05
Transfer	4.23	1.41	4.76	1.66
Learning achievement	4.70	1.09	5.20	0.92
MF 1	6.14	0.72	6.27	0.98
MF 2	6.37	0.52	6.45	0.72
HF 1	6.79	0.79	6.67	0.89
HF 2	6.73	0.79	6.23	0.70

Note: PAS = positive affect score; MF = middle frequency band; HF = high frequency band HRV (i.e., MF & HF) is measured as ln(ms^2).

3.3. Retention and transfer performance

Because of the moderate correlation between retention and transfer measures (r = 0.47, p < 0.01), a MANOVA was conducted with the group (neutral vs. positive) as the between-subject factor and retention and transfer scores as dependent measures. The analysis revealed a marginally significant main effect for group, Wilks' Lambda = 0.92, F (2, 57) = 2.65, p = 0.08, η_p^2 = 0.09. Separate univariate analyses revealed a significant group difference in retention, F (1,58) = 5.25, p = 0.03, η_p^2 = 0.08, but not in transfer, F (1,58) = 1.54, p = 0.22. These results indicating that the participants in the PD group outperformed on the retention test (ΔM = 1.27).

3.4. Subjective ratings of mental effort and perceived task difficulty

For each of these measures, a one-way ANOVA was conducted with group as the between-subject factor. The ANOVA ran with *mental effort* as the dependent variable showed no main effect for group (ΔM = 0.10), F (1,58) = 0.10, p = 0.77. The ANOVA computed with perceived task difficulty as a dependent variable revealed a significant main effect for group, F (1,58) = 6.45, p = 0.01, η_p^2 = 0.10, indicating that the positive emotional design material reduced the perception of task difficulty (ΔM = −0.8).

3.5. Situational interest, perception of learning achievement

Because of the moderate correlation between situational interest and perception of learning achievement (r = 0.38, p < 0.01), a MANOVA was conducted with the group (neutral vs. positive) as between-subject factor and situational interest and learning achievement as dependent measures. The analysis revealed a significant main effect for the group, Wilks' Lambda = 0.89, F (2, 57) = 3.38, p = 0.04, η_p^2 = 0.11. Separate univariate analyses revealed a significant group difference in situational interest, F (1,58) = 5.40, p = 0.02, η_p^2 = 0.09, and a marginal difference in perception of learning achievement, F (1,58) = 3.68, p = 0.06, η_p^2 = 0.06. These results indicating that the participants in the PD group rated higher situational interest than the participants in the ND group (ΔM = 0.31) and a trend toward higher perception of learning achievement in the PD group (ΔM = 0.50).

3.6. Physiological measures

Three participants were excluded from the physiological dataset owing to a hardware malfunction during the experiment. Therefore, analyses were conducted based on n = 29 in the positive emotional design (PD) group and n = 28 in the neutral emotional design (ND) group.

We first examined whether the two groups differed during rest periods (i.e., baseline). A MANOVA was conducted with the group (neutral vs. positive) as between-subject factor and MF and HF power before learning as dependent measures. The analysis showed no significant main effect for group, Wilks' Lambda = 0.97, F (2, 54) = 0.81, p = 0.45. Separate univariate analyses also showed no main effect for either variable, for MF 1, F (1,55) = 0.32, p = 0.57; for HF 1, F (1,55) = 0.29, p = 0.59, suggesting that the two groups had similar baselines in their physiological activity.

3.6.1. Middle-frequency band

An RM-ANOVA was conducted with group as the between-subject factor and MF band power before (MF 1) and during learning (MF 2) as the repeated measure variable. The analysis results indicated a significant main effect of the change in the MF band from baseline to learning (see Fig. 2), F (1, 55) = 5.32, p = 0.03, η_p^2 = 0.09. No other significant effects were found. A paired-sample t-test indicated that the MF band of the ND group marginally increased from baseline to learning (ΔM = 0.23), t (27) = 1.86, p = 0.07, d = 0.36, but not for the PD design group (ΔM = 0.18), t (28) = 1.41, p = 0.17.

3.6.2. High-frequency band

An RM-ANOVA was conducted with group as the between-subject factor and HF power before and during learning as the repeated measure variable. The results indicated a significant interaction between the change of HF from baseline to learning and group (see Fig. 3), F (1, 55) = 6.76, p = 0.01, η_p^2 = 0.12. Paired-sample t-tests indicated that the participants in the PD group had a stronger reduction of HF power from baseline to learning (ΔM = −0.44), t (28) = 3.43, p < 0.01, d = 0.54, but not for participants in the ND group (ΔM = −0.07), t (27) = 1.07, p = 0.29. An individual sample t-test revealed that participants in the PD group had significantly lower HF power than participants in the ND group during the learning process, t (55) = 2.49, p = 0.02, d = 0.67.

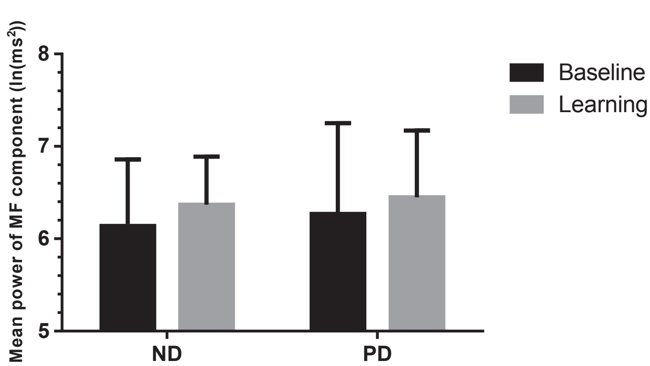

Fig. 2. Mean values and standard deviations for power of middle - frequency component from baseline to learning. ND = neutral emotional design. PD = positive emotional design.

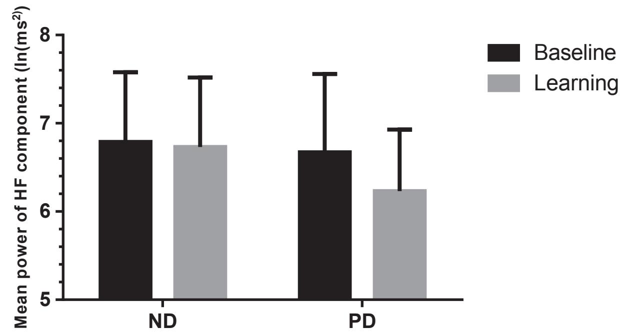

Fig. 3. Mean values and standard deviations for power of high - frequency component from baseline to learning. ND = neutral emotional design. PD = positive emotional design.

3.7. Mediation analyses

To assess the extent to which situational interest and HF changes (HF_Learning minus HF_Baseline) might be mediating the relationship between positive emotions and retention, we conducted a mediation analysis based on the procedure outlined by Hayes and Preacher (2013).

We first explored the role of situational interest in mediating the effect of positive emotions on retention control for the group. The analysis revealed a direct effect of positive emotions on situational interest (β = 0.44, p < 0.01). Situational interest had a direct effect on retention (β = 0.28, p < 0.01). Positive emotions had a marginally significant effect on retention (β = 0.25, p = 0.08). Upon using 1000 bootstrap resamples, the 95% confidence interval (CI) for the indirect effect of the mediator was 0.01–0.30, indicating that the indirect effect of situational interest on retention is greater than zero. Therefore, situational interest mediates the effect of positive emotions on retention outcomes.

Next, we explored the role of HF changes in mediating the effect of positive emotions on retention. The analysis revealed a direct effect of positive emotions on retention (β = 0.35, p = 0.01). HF changes had a direct effect on retention (β = −0.47, p = 0.04). Positive emotions did not have a direct effect on HF change scores (β = −0.04, p = 0.65), suggesting no mediation by HF changes. The bootstrap results showed that the 95% CI for the indirect effect of the mediator was −0.07 to 0.16, supporting the result that no mediation effect was found.

4. Discussion

In this study, the effect of emotional design principle (Um et al., 2012) on mental effort investment was investigated using physiological measures (i.e., HRV) in order to replicate and extend previous findings. Some summary of your findings.

4.1. Learning outcomes

The results of the current study indicated that participants in the PD group outperformed the participants in the ND group on the retention test, partially supporting the first hypothesis. These results are consistent with previous findings suggesting that positive emotional design graphics improve retention performance. However, there was no evidence to support the conjecture that the positive emotional design graphics would improve learners' transfer test performance (Um et al., 2012). One possible interpretation is that positive emotion induced by the redesigned graphics may have affected retention and transfer test performance in different ways (Plass et al., 2014). Specifically, appealing colors and human-face characteristics in the positive emotional design group may have helped students to concentrate on the details of the information, and therefore facilitated the retention outcomes, that these features were not capable of fostering a deep learning than the version without these features (e.g., Park et al., 2015).

4.2. Subjective measures

As a partial support of the second hypothesis, the results demonstrated that the positive emotional design successfully induced positive emotions. The PAS score significantly increased from baseline during learning in the PD group with a small-to-medium effect ($d = 0.46$), but this was not the case of learners in the ND group. In addition, the results also indicated that positive emotional design increased situational interest and perceived learning achievement, as well as reducing perceived task difficulty among learners. These findings replicate previous results and are consistent with the emotional design hypothesis (Um et al., 2012).

However, the positive emotional design materials did not influence the subjective ratings of mental effort investment in this study. Consistent with previous studies (see Experiment 2, Mayer & Estrella, 2014; Plass et al., 2014; Um et al., 2012), no group difference was found between the PD and ND groups. Such a result did not support the affective mediation assumption of CATML (Moreno, 2006), which suggests that positive affect would facilitate mental effort investment. The null results of the subjective ratings of mental effort investment in the present study validates concerns that the single-item mental effort questionnaire (Paas, 1992) may not be an appropriate measurement to reflect the effort expenditure during emotional design research (e.g., Park et al., 2015).

4.3. Heart rate variability

There was partial support for Hypothesis 3, as participants in the PD group showed a larger decrease in HF power but not in MF power.

4.3.1. Middle-frequency band

Although the data indicated a marginal increase of MF power in the ND group, no significant group difference was found between the PD and ND group during learning. This result is inconsistent with our prediction that a significant difference in MF power would be observed between the PD and ND groups. One possible interpretation is that the MF component is only sensitive to relatively large differences in task demands (Paas et al., 1994). According to the emotional design principle (Um et al., 2012), the redesigned graphics were only used to induce positive emotions but did not change the basic learning content. Thus, the learning materials in the different groups (PD vs. ND) may only contribute to a subtle difference in their actual task difficulty, which may not be reflected by the MF component. A further possibility is that the MF component was influenced by the sustained time-on-task, which may have prompted effort investment to protect performance from the influence of fatigue, boredom, etc. (e.g., Mulder, 1986). Previous studies have indicated that the increase of the MF power represented a reduction of mental effort investment throughout task duration (e.g., Fairclough & Houston, 2004; Fairclough, Venables, & Tattersall, 2005). Following this viewpoint, the marginally increased MF power with a small-to-medium effect ($d = 0.36$) in the ND group may indicate a reduction of mental effort investment over time, whereas the PD group persisted to invest effort for a longer time; therefore, the MF power was not significantly changed. This is consistent with the idea that disinterested students will not maintain effort when compared to interested or emotional engaged students (Brehm & Self, 1989).

4.3.2. High-frequency band

The analysis of the HF component produced the expected finding, that the participants in the PD group had a larger decrease in HF power with a medium-to-large effect ($d = 0.54$), but this was not the case of learners in the control group (ND). This result can be interpreted by Porges' polyvagal theory (2007), that is developed within an evolutionary framework and suggest that the influence of central nervous system activity on HRV evolved owing to increasing engagement in social behaviors. According to the polyvagal theory (Porges, 2007), the reduction of HF power indicates the inhibition of parasympathetic nervous system activity, which is associated with the engagement in the controlled process (for a review, see Holzman & Bridgett, 2017). In line with the viewpoint that mental effort reflects the amount of controlled processing in which an individual is engaged (Mulder, 1986; Paas et al., 1994), the larger reduction of HF power in the PD group can be simply explained as greater mental effort investment. Thus, the results obtained for the HF component in this study support the prediction that the redesigned graphics to induce positive emotions in a multimedia lesson may facilitate mental effort investment. This is consistent with the affect mediation assumption of CATLM, namely, that affective factors influence learners' cognitive engagement (Moreno, 2006).

Moreover, the reduction of HF power in a given task has been recognized as an index of sustained attention (e.g., Porges, 1991; Ravaja, 2004; Weber, Van Der Molen, & Molenaar, 1994). Considering this viewpoint, the stronger suppression of HF power in the PD group may reflect greater attentional engagement. This is consistent with previous findings from an eye tracker study (Park et al., 2015), which indicated that positive emotion design graphics can induce an attention-arousing effect (e.g., Nummenmaa, Hyönä, & Calvo, 2006).

4.4. Mediation effect

Results from mediation analyses indicated that situational interest mediates the effect of positive emotions on retention outcomes. This is consistent with the emotional design hypothesis (Um et al., 2012) that the positive emotional designed materials facilitate learning by increasing learners' motivation (e.g., Park et al., 2015).

However, the analyses failed to find the meditation effect of HF changes. This is inconsistent with the affective mediation assumption (Moreno, 2006) that positive emotions mediate learning by increasing cognitive engagement. In the present study, no relationship was found between positive emotions and HF changes ($\beta = -0.04$, $p = 0.65$). This result could have been caused by the complex relationship between the subjective measurement of positive emotions (PNS) and psychophysiological measurement of invested mental effort (HRV). The relationship between self-reported measurements and psychophysiological measurements can often be quite fortuitous (Potter & Bolls, 2012). This is because the results of the self-reported measurements are often obtained afterwards, and they depend on participants' conscious perception of their emotion processes and/or cognitive processes, whereas psychophysiological measurements reflect the averaged data of dynamic mental activities (e.g., Cacioppo, Tassinary, & Berntson, 2007). Instantaneous changes in mental activity will influence the average data of psychophysiological measurements but may not be detected subjectively. Thus, the relationship between subjective results and psychophysiological results may or may not appear (Potter & Bolls, 2012, p. 185). In future study, objective measurements of learners' emotional states (e.g., by using facial electromyography or facial expression recognition) should be included to further investigate the relationship between positive emotion and mental effort investment from a dynamic viewpoint.

5. Limitations and future direction

As a preliminary study, there are some limitations in the present study that should be considered. Firstly, the 6 min learning duration in the present study is fairly short. A longer overall duration may highlight the effect of positive emotional design on sustained time-on-task.

Moreover, it has been suggested that psychophysiological (i.e., HRV) sensitivity of mental effort investment would be confounded by task demand and time-on-task together (Fairclough et al., 2005). In future work, these factors (i.e., task demand and time-on-task) should be manipulated to clarify the effect of positive emotional design on sustained time-on-task.

Secondly, in the present study, mental effort investment was identified and measured as energy mobilization (Fairclough & Mulder, 2011). However, such an identification is susceptible to the criticism of oversimplification (Fairclough & Houston, 2004). For example, Um et al. (2012) suggest that the mental effort investment in emotional design research may reflect the germane cognitive load, that is the learner's efforts to process and comprehend the learning contents (Sweller, Ayres, & Kalyuga, 2011). However, the current findings (i.e., HRV changes) may only reflect an overall energy mobilization but not directed to a specific type of cognitive load. Future work should combine different methods (e.g., HRV, eye-tracker) to differentiate the effects of emotional design principle on specific types of cognitive load (e.g., Korbach, Brünken, & Park, 2017). Furthermore, consider the one-to-many relation between physiological measures and psychological states (for a review, see Richter & Slade, 2017). The stronger reduction of HF power in the present study could also be interpreted as better self-regulation. For instance, in a recent meta-analysis, Holzman and Bridgett (2017) demonstrated that the high-frequency component of HRV is a valid index to broadly reflect self-regulation (e.g., emotional regulation, self-control, effortful control). According to CATLM, self-regulatory skills mediate learning by regulating cognitive and affective processes (Moreno, 2006), while self-regulation and cognitive load are theoretical different (e.g., Maranges, Schmeichel, & Baumeister, 2016). In future research, a joint research paradigm of cognitive load and self-regulation (e.g., de Bruin & van Merriënboer, 2017) should be adopted in emotional design research to clarify the effect of positive emotional design on specific cognitive process.

6. Conclusion

Our findings in this study replicate and extend the findings on the emotional design principle. Consistent with previous studies (Mayer & Estrella, 2014; Plass et al., 2014; Um et al., 2012), the benefits of incorporating positive emotion design graphics in multimedia instruction have been validated using different materials and have been extended to a Chinese population. The current findings also support the use of heart rate variability (i.e., high-frequency band) as an index to reflect the mental effort investment in emotional design research. The interaction effect of the HF component represented the expected suppression of the HF power, and is indicative of increased mental effort and energy mobilization in response to positive emotional design materials. The results in the present study provide further evidence for the affective mediation assumption of CATLM (Moreno & Mayer, 2007; Moreno, 2006) that affective and motivational factors in multimedia instructions encourage cognitive engagement during multimedia learning.

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