Exp Brain Res (2017) 235:1107–1118
DOI 10.1007/s00221-017-4873-z

RESEARCH ARTICLE

Effort provides its own reward: endeavors reinforce subjective expectation and evaluation of task performance

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Received: 11 July 2016 / Accepted: 2 January 2017 / Published online: 25 January 2017

Abstract Although many studies have investigated the relationship between the amount of effort invested in a certain task and one's attitude towards the subsequent reward, whether exerted effort would impact one's expectation and evaluation of performance feedback itself still remains to be examined. In the present study, two types of calculation tasks that varied in the required effort were adopted, and we resorted to electroencephalography to probe the temporal dynamics of how exerted effort would affect one's anticipation and evaluation of performance feedback. In the high-effort condition, a more salient stimulus-preceding negativity was detected during the anticipation stage, which was accompanied with a more salient FRN/P300 complex (a more positive P300 and a less negative feedback-related negativity) in response to positive outcomes in the evaluation stage. These results suggested that when more effort was invested, an enhanced anticipatory attention would be paid toward one's task performance feedback and that positive outcomes would be subjectively valued to a greater extent.

Keywords Effort · Reward · Anticipation · Event-related potential · Stimulus-preceding negativity · Feedback-related negativity

Introduction

> "Effort is its own reward if you allow it to be." (Seth Godin quotes).

Imagine that you have been working hard on two different projects and have just finished them. One of the projects is really difficult, and you spared no effort to accomplish it. Comparatively, the other one is easy to handle, and you completed it with great ease. Now your boss is evaluating your task performance on these projects and will get back to you soon. Which of the two projects do you care for more? Compared with your success in the project that lacks challenge, will you be happier if you discover that you have done a good job on the harder one? According to our own experience, most people are more concerned with their performance in tasks that require greater effort, as motivation must be aroused to match the level of effort we have expended, and we are eager to know whether our effort has paid off (Brehm and Self 1989). In our daily life, generally we have to invest a certain degree of effort before obtaining a reward. According to Brehm and Self, effort refers to the motivational arousal associated with the prospect that a certain behavior would lead to desirable outcomes (Brehm and Self 1989). Since effort is a motivational state, it can affect our affective and motivational responses toward rewards. Previous studies have shown that as greater effort has been invested into work, people would generally look forward to receiving relatively larger rewards (Janssen 2000; Siegrist et al. 2004; Kroemer et al. 2014). Emotional distress is a

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byproduct of the mismatch between perceived costs and benefits. In the work setting, some researchers have found that an effort-reward imbalance will result in depression of the employees, and will cause other adverse effects for both employees and the affiliated company as a whole (Siegrist et al. 2004; Nielsen et al. 2013).

Recognizing the significance of the effort-reward balance, in recent years, an increasing number of studies are showing research interests in probing how mental effort modulates subsequent reward evaluation, especially on the neural level. There are two opposing views on the effect of effort on reward evaluation. One group of researchers considers exerted effort as a cost, which will result in the devaluation of the subsequent reward (Botvinick et al. 2009; Croxson et al. 2009; Vassena et al. 2014; Apps et al. 2015). This is referred to as effort discounting, meaning that a reward's value gets diminished if it is achieved at the expense of a larger amount of effort (Kivetz 2003; Rudebeck et al. 2006; Phillips et al. 2007; Botvinick et al. 2009). Several neuroimaging studies have found neural correlates of effort discounting. For example, Botvinick et al. (2009) applied functional magnetic resonance imaging (fMRI) to measure brain activities in response to monetary rewards following tasks demanding either high or low level of effort. It was found that the nucleus accumbens (NAcc) was less activated when processing a reward after greater mental effort investment. Similarly, by conducting an fMRI experiment in which cues on the amount of effort required and the reward to be obtained were presented to the participants at the beginning of the task, Croxson et al. (2009) focused on how the cost of exerted effort was processed and its effect on the evaluation of the course of action's net value. Brain activation in the ventral striatum and midbrain in response to the cues revealed that the expected value of the reward decreased when more effort was demanded.

In contrast to the effort discounting view, several studies have found that high effort can lead to increased valuation of the reward (Zink et al. 2004; Vostroknutov et al. 2012; Hernandez Lallement et al. 2014; Ma et al. 2014). For instance, Hernandez Lallement et al. (2014) examined the effect of exerted effort on reward processing using fMRI. In their study, varied calculation tasks were adopted to manipulate different levels of effort required. Participants would first complete the calculation and, only after they provided a correct answer, would they gain a reward. Subsequently, they would go through a forced donation and lose certain proportions of their just-gained rewards. The results showed that after high effort involvement, activity in reward-related brain regions, including the subgenual anterior cingulate cortex (sgACC) and NAcc, was positively modulated by reward magnitudes. In other words, participants became more sensitive to discrepancies in reward magnitudes after hard work, and the unearned money was valued differently than the hard-earned money. On the behavioral level, participants tended to reduce the donation behavior and the amount of money to be spent after high effort (Muehlbacher and Kirchler 2009; Hernandez Lallement et al. 2014). In another study adopting the event-related potential (ERPs) approach, we investigated how mental effort thrown into tasks would influence subsequent reward processing and outcome evaluation (Ma et al. 2014). In our experiment, participants were asked to finish a number of high versus low-effort tasks. After participants responded to a specific calculation assignment, the correctness of their response would be shown. If the given response was correct, then performance feedback would be followed by reward feedback. Half of the successful trials were accompanied with a fixed reward, while participants gained nothing in the rest of the winning trials. A more pronounced feedback-related negativity loss-win difference wave (d-FRN) toward the reward feedback was elicited in the high-effort condition. Since the amplitude of the d-FRN is well recognized to reflect the motivational significance of feedback information (San Martín 2012; Meng and Ma 2015), we concluded that exerted effort might increase subjective evaluation of subsequent monetary rewards (Ma et al. 2014).

While a large number of pioneering studies have examined the modulation of mental effort on the evaluation of associated monetary rewards (Hernandez Lallement et al. 2014; Ma et al. 2014), fewer researchers have explored the positive effect of effort itself. In fact, effort itself may result in beneficial outcomes. Effort, especially effort voluntarily thrown into tasks, may contribute to the positive mental state of individuals (Patall et al. 2008; Meng and Ma 2015). Specifically, greater effort followed by successes may lead to a sense of self-efficacy, which refers to one's perceived self-worth, competence and effectiveness (Bandura 1977; Myers 2006). Recent neuroscience studies began to examine brain activations associated with the anticipation of effortful tasks (Boehler et al. 2011; Krebs et al. 2012; Kurniawan et al. 2013; Vassena et al. 2014, 2015). By applying a perceptual task, Krebs et al. (2012) probed the neural activation underlying effort processing. It was found that the ACC responded not only to the reward but also to the effort. In another pioneering study, Vassena and colleagues (Vassena et al. 2014) adopted varied mental arithmetic tasks to probe brain activities underlying the anticipation of reward and effort in a high-level cognition scenario. In their study, the anticipation of effort and reward was found to activate the same network, including the ACC and the striatum. Taken together, these results reveal that the ACC plays a significant role in experiencing and anticipating effort, indicating a potential motivational effect of greater effort on one's mental preparation for the tasks.

After reviewing relevant studies, we found that while a few pioneering studies have explored the positive effect of effort itself, the influence of exerted effort on task performance anticipation and evaluation remains to be examined. The common wisdom suggests that, the harder people have worked, the more curious they are about their task performance. Once they have obtained ideal results, the happier and more fulfilled they will be (Myers 2006). Recently, this logic link received provisional support from a relevant electrophysiological study (Meng and Ma 2015). However, it is worth noting that effort level was not directly manipulated in this ERP study but was only a byproduct of the opportunity to choose granted to participants.

To fill this research gap, in the present study, we aim to manipulate the required effort in a direct manner and probe the temporal dynamics of how exerted effort would affect one's subjective anticipation and evaluation of task performance applying the ERP approach. Our experimental task can be divided into five stages, including Task Cue, Task Assignment, Result Selection, Feedback Anticipation and Performance Feedback (Fig. 1). Participants who participated in this study were asked to solve a certain number of calculation tasks. Once they provided their answers to a given task, they had to wait for a brief period of time before receiving feedback of their task performance. If participants provided a wrong answer or did not solve the task in time, they would get "×" as feedback. Two different categories of operation tasks were adopted: multiplication and addition. In line with previous studies as well as one of our own (Ma et al. 2014), multiplication was deemed as a high-effort task, while addition was defined as a low-effort one. Distinct from our previous design (Ma et al. 2014), task cues were provided at the beginning of each trial so that participants could be mentally prepared for the upcoming task. Notably, as we aimed to focus on the effect of exerted effort on subsequent performance evaluation rather than reward evaluation, only performance feedback (correct or not) was provided to the participants. In the current performance feedback stage, the positive feedback itself signified an additional reward of a fixed amount, and participants who succeeded were no longer awarded with a 50% probability as was the case in our previous study (Ma et al. 2014). To distinguish from our previous experimental design, we used performance feedback instead of reward feedback to describe the outcome evaluation stage of this study.

The task assignment and result selection stages can be regarded as periods of mental effort investment. We focused on the two subsequent stages, including feedback anticipation and performance feedback, and hypothesized that greater effort exerted on solving the current calculation task may reinforce anticipatory attention toward performance feedback during the first stage and then enhance subjective evaluation of performance feedback during the second stage. Stimulus-preceding negativity (SPN) is a sustained, negative shift that occurs when participants anticipate the presentation of relevant stimuli, whose magnitude reliably mirrors anticipatory attention paid to important information (Brunia et al. 2011), such as performance feedback (Meng and Ma 2015; Meng et al. 2016; Zheng et al.

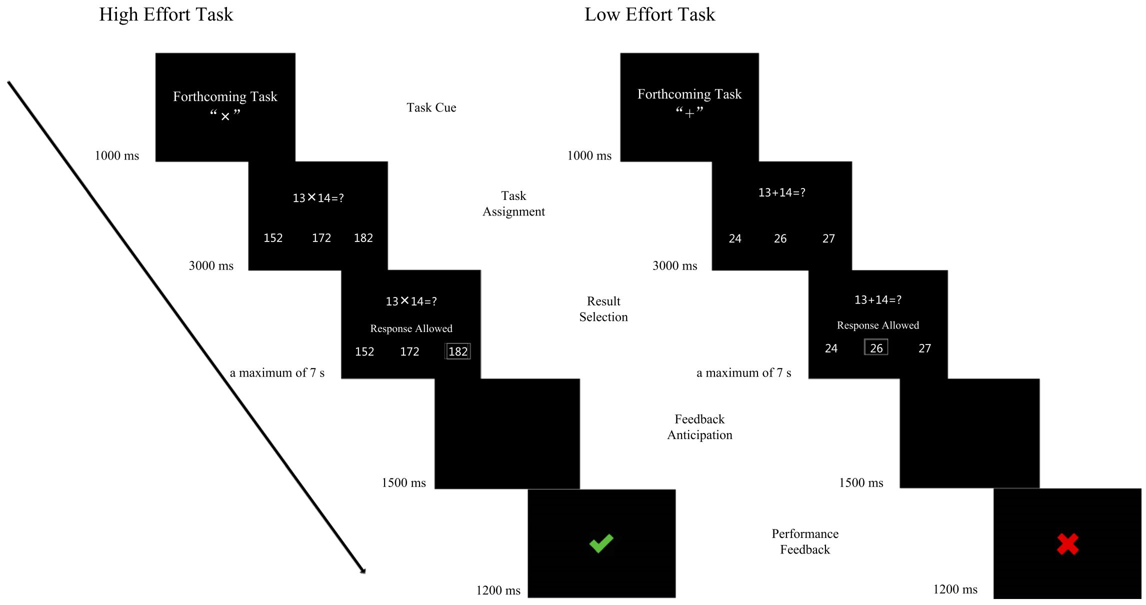

Fig. 1 Experimental task. Participants were instructed to accomplish 40 high effort tasks and another 40 low effort tasks. After the cue indicating either multiplication or addition tasks disappeared, they were allocated 3 s to read the assigned task and a maximum of 7 s to choose the correct answer. After a short delay, the correctness of their responses would be revealed during performance feedback

2015). As performance feedback draws nearer, the magnitude of the SPN gradually increases. According to dipole modeling analyses, the SPN is generated in the insular cortex, which can be activated by the motivational information delivered (Böcker et al. 1994; Masaki et al. 2006). Previous studies have consistently shown that the amplitude of the SPN is sensitive to the affective/motivational significance of anticipated stimuli (for a recent review, see Brunia et al. 2012). For instance, Novak and colleagues found that during outcome anticipation, the SPN was enlarged in incentivized trials compared to that in neutral trials (Novak et al. 2016). When it comes to effort, it has been commonly suggested to enhance participants' emotional and motivational relevance to feedback information (Ma et al. 2014; Schevernels et al. 2014, 2016). In the current study, multiplication tasks were considered to demand more mental effort than addition tasks. We hypothesize that investment of greater effort would render the participants care more about their task performance during multiplication. Since previous studies have found that enhanced anticipation of the outcome was reflected in the more pronounced SPN (Brunia et al. 2012; Kotani et al. 2015; Meng et al. 2016; Pei and Meng 2016), we predicted that a larger SPN would be observed in the high-effort condition compared with in the low-effort one.

In regard to temporal substrates of outcome evaluation after varied effort investment, existing ERP studies resorting to Feedback-related negativity (FRN) and P300 have reported preliminary findings. FRN, an ERP component generally observed during outcome evaluation, is typically regarded as a negative, frontal deflection (Miltner et al. 1997). It generally peaks approximately 250 ms after feedback onset and is found to originate from the ACC (Miltner et al. 1997; Gehring and Willoughby 2002; San Martín 2012). Recent studies begun to show that FRN mainly reflects a positive deflection after favorable outcomes rather than a negative deflection after unfavorable ones (Foti et al. 2011; Wardle et al. 2013; Weinberg et al. 2014). For instance, a recent study reported that offers proposed out of perceived good intentions led to a significantly less pronounced FRN (Ma et al. 2015). In order to better capture this characteristic, several groups of researchers named it as reward positivity (RewP) instead (Proudfit 2015; Threadgill and Gable 2016). Regarding the positive outcomes (feedback of correct answers) in this study, the greater extent they are being favored, the more positive FRN would be manifested. Thus, even though only winning trials were analyzed, we predicted that successes would be assigned greater subjective value and treasured more in the high-effort condition, leading to a less pronounced FRN.

The FRN is followed by a positive, central-parietal ERP component termed the P300. Typically, it peaks approximately 300–600 ms after the onset of feedback (Nieuwenhuis et al. 2005) and has been found to be related to various aspects of outcome evaluation (Yeung et al. 2005; Hajcak et al. 2007; Zhou et al. 2010). Previous studies consistently reported that the P300 is sensitive to the magnitude of outcomes. To be specific, the P300 is more positive toward larger outcomes than smaller ones. (Wu and Zhou 2009; Bellebaum et al. 2010; San Martín 2012). This magnitude effect has been suggested to be attributed to increased motivational significance of larger rewards (Yeung and Sanfey 2004; San Martín 2012). According to previous studies, more attentional resources would be allocated to elaborately process motivationally significant stimuli, eliciting a larger P300 (Kok 2001; Schupp et al. 2004). Besides outcome magnitude, the motivational significance of outcomes can be influenced by other factors as well, such as one's subjective expectancy, action, and exerted effort (San Martín 2012). For example, it was reported that an individual's action can increase the motivational significance of positive outcomes, which leads to an enlarged P300 compared to that in a non-action condition (Zhou et al. 2010). More relevant to the current research, in several related studies, it was reported that, when participants had to put in great amounts of effort, positive feedback would be valued to a greater extent, which contributed to a significantly larger P300 (Schevernels et al. 2014, 2016). In a similar manner, in this study, we postulate that participants would be better motivated for the outcome after devoting greater effort. As a consequence, the presentation of positive feedback is hypothesized to elicit a more positive P300 in high-effort tasks.

Materials and methods

Participants

20 healthy, right-handed participants participated in this study (7 females, age = [18–25], $M = 22.06$ years, $SD = 1.66$ years). All participants were students of Zhejiang University who reported no history of neurological disorders or mental diseases. Prior to formally participating in this study, written informed consent was obtained according to the procedure approved by the Institutional Review Board of Zhejiang University Neuromanagement Lab. As the electrophysiological data of two participants showed excessive recording artifacts, those data were discarded from the dataset. Therefore, the final analysis included data from 18 valid participants.

Stimuli and procedure

Participants were comfortably seated in a dimly lit, sound-attenuated and electrically shielded room. Stimuli were presented at the center of a computer screen situated 100 cm away from participants, with a visual angle of 8.69° × 6.52° (15.2 × 11.4 cm, width × height). Before recording, participants read the instructions to understand rules and procedures of the experimental task. The experiment consisted of 2 blocks, each containing 20 trials of high-effort tasks (two-digit multiplication tasks) and 20 trials of low-effort tasks (two-digit addition tasks). Calculation tasks were meticulously selected from those adopted in our previous study (Ma et al. 2014). The arithmetic operations were elaborately designed to ensure a certain difficulty level so that the participants could not easily guess the correct answers. In addition tasks, the three alternative answers were an arithmetic progression shown in a random order, and the distance of the progression was 2. In multiplication tasks, the three alternative answers were approximate arithmetic progressions shown in a random order. In most cases, the distance was 10. However, we deliberately adjusted the distance to 20 in some cases for fear that participants might discover rules adopted for the setting of correct answers. Notably, correct answers appeared in the left, right and central option with approximately equal probabilities. In addition, calculation tasks appeared in a random order within each run. Participants were instructed to use the keypad to make their choices. If they decided to choose the left option, they were instructed to press the "1" key. The "2" and "3" keys corresponded to the central and the right option of the task respectively. It is worth noting that, during the experiment, the participants were allowed to complete the 80 operation tasks only by mental calculation.

At the beginning of each trial, a fixation was shown for 600 ms at the center of the screen. Afterwards, the task cue ("Forthcoming Task ×" or "Forthcoming Task +") would be presented for 1000 ms, which informs the participants of the type of the following task. After a corresponding operation task was randomly assigned, participants were allowed 3000 ms to carefully read the task assignment (an equation with three possible answers). Then, the prompt of "Response Allowed" would appear on the screen. Participants could only respond after the prompt appeared and had to respond within 7000 ms. Upon responding, a blank screen was displayed for 1500 ms, which was followed by the feedback information for the trial. If the input was correct, they would get a green "√". If they responded incorrectly instead, they would get a red "×" (Fig. 1). Sequential stimuli were separated by blank screens that lasted for 600–800 ms. Ten practice trials were implemented before the start of the formal experiment. Participants were told that they would receive ¥ 30 as compensation for their attendance, and ten trials would be randomly chosen from the whole 80 trials to determine their performance-based payment. For each correctly answered trial (regardless of the type of the calculation task) that was chosen, they would get an additional ¥ 1 as payment.

EEG recordings

Electroencephalogram data (EEG) were recorded (band-pass 0.05–70 Hz, sampling rate 500 Hz) from 64 scalp sites with Neuroscan Synamp2 Amplifier. We set the left mastoid as on-line reference and the electrode on the cephalic region as ground. Horizontal Electrooculogram (EOG) was recorded at the left versus right orbital rim while vertical EOG was recorded supra and infra-orbitally at the left eye. Electrode impedance was maintained below 5 kΩ during the whole experiment.

Data analysis

During offline EEG analysis, at the first step, we re-referenced the data to the average of the left mastoid and the right mastoid, which was followed by the removal of ocular artifacts by Neuroscan (Scan 4.3; Neurosoft Labs Inc., USA). Subsequently, ERPLAB (Lopez-Calderon and Luck 2014) was adopted to analyze the collected EEGs, and original data were band-pass filtered (0.1–30 Hz, 24 dB/octave). Trials containing amplifier clipping, bursts of electromyography activity, or peak-to-peak deflection exceeding ± 100 μV were excluded. For the amplitude of the SPN, the maximum differences between the high and low-effort conditions were shown at the frontal sites (see the topographical map in Fig. 2). Thus, data from the electrodes F1, Fz, F2, FC1, FCz, FC2, C1, Cz and C2 were analyzed. The 1200 ms time window before the onset of performance feedback was segmented, and the mean amplitude in the − 500 to −0 ms time window prior to the onset of performance feedback went into the analysis. The whole epoch was baseline-corrected by the 1200–1000 ms interval prior to feedback onset.

When it comes to performance evaluation, because the maximum P300 amplitudes were observed at parietal sites (see Fig. 3), data from C1, Cz, C2, CP1, CPz, CP2, P1, Pz and P2 were analyzed. Since the most positive peak of the P300 appeared approximately 360 ms post-onset of the feedback, mean amplitudes in the time window of 310–410 ms were calculated. As we observed an FRN-like component during the 210–310 ms time window, and its scalp topographic distribution was comparable to that of the classical FRN (Fig. 3), we defined it as the FRN in this study, and data from the electrodes F1, Fz, F2, FC1, FCz, FC2 went into the analysis. For both the P300 and the FRN, the whole epoch was baseline-corrected adopting the 200 ms interval prior to feedback onset.

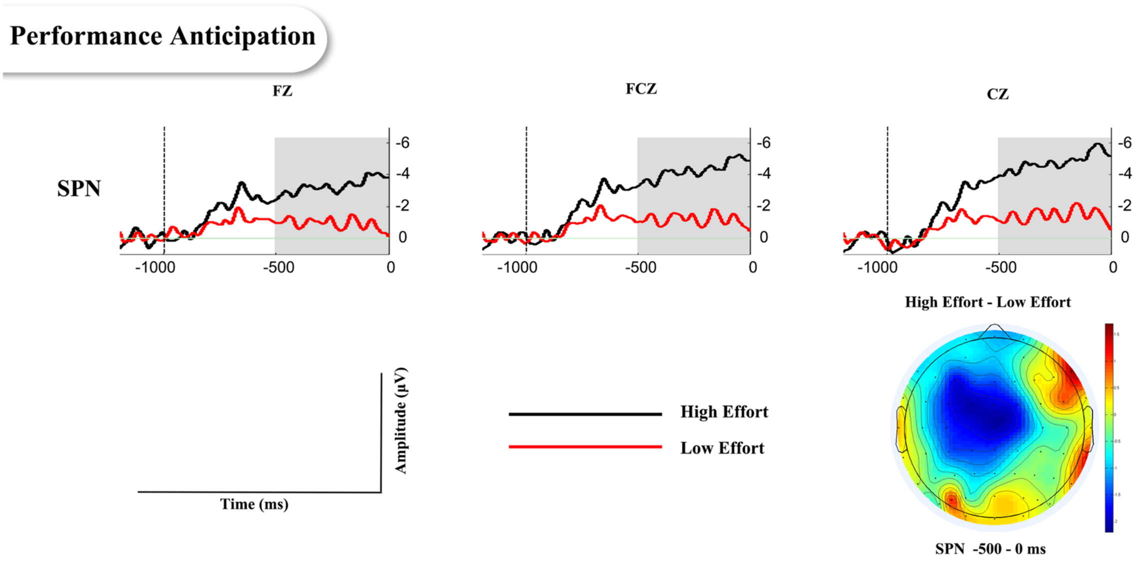

Fig. 2 Grand-averaged ERP waveforms during the anticipation stage of performance feedback. Waveforms of the SPN from three midline frontal electrodes (Fz, FCz, Cz) are shown in relation to effort (high effort versus low effort). The 1200 ms before the onset of performance feedback was segmented, during which participants were actively anticipating their performance feedback. Scalp topographic distribution of the SPN (amplitude in the low effort condition subtracted by that in the high effort condition during the time window −500 to −0 ms prior to performance feedback onset) is provided, and the bar for the topographic map ranges from +1.5 to −2 μV

For each subject, recorded EEGs were separately averaged over each recording site under each experimental condition. To be specific, EEG epochs were separately averaged for high effort versus low effort conditions, and we performed ANOVAs with within-subject factors of effort, caudality and laterality. Simple effect analysis was conducted when the interaction effect was significant. The Greenhouse–Geisser correction was applied in all statistical analyses when necessary. For the behavioral data, paired *t* test was adopted to compare accuracy rates across the two effort conditions.

Results

Behavioral performance

The accuracy of the high-effort tasks was 81.94%, while it was 99.86% in the low-effort condition. This result pattern demonstrated a significant effort effect on accuracy ($t = 6.158$; $P < 0.01$). In addition, the average reaction time was 3000.6 ms (SD = 738.3) in the high-effort condition. While it was 585.7 ms (SD = 292.2) in the low-effort condition, suggesting a significant effort effect on the average reaction time ($t = 14.938$; $P < 0.01$).

ERPs

SPN

Subjective anticipation toward performance feedback is mainly reflected in the amplitude of SPN. As presented in Fig. 2, the mean SPN amplitude was −2.681 μV in the high-effort condition, while it was −0.953 μV in the low-effort condition. With effort (high effort versus low effort), caudality (frontal: F1, Fz, F2; frontocentral: FC1, FCz, FC2; center: C1, Cz, C2) and laterality (left: F1, FC1, C1; middle: Fz, FCz, Cz; right: F2, FC2, C2) as within-participant factors of the ANOVA, it was found that the main effect of effort was significant ($F_{(1,\ 17)} = 21.291$, $P < 0.001$, $\eta^2 = 0.556$), while the main effects of caudality ($F_{(2,\ 34)} = 1.558$, $P = 0.225$, $\eta^2 = 0.084$) and laterality ($F_{(2,\ 34)} = 0.486$, $P = 0.619$, $\eta^2 = 0.028$) were not significant. No significant interaction effects of these factors were detected. The SPN in the high-effort condition was more pronounced than that in the low-effort condition, indicating that a greater amount of anticipatory attention might be devoted to the upcoming performance feedback in the high-effort condition. In other words, participants cared more about their task performance with greater exerted effort.

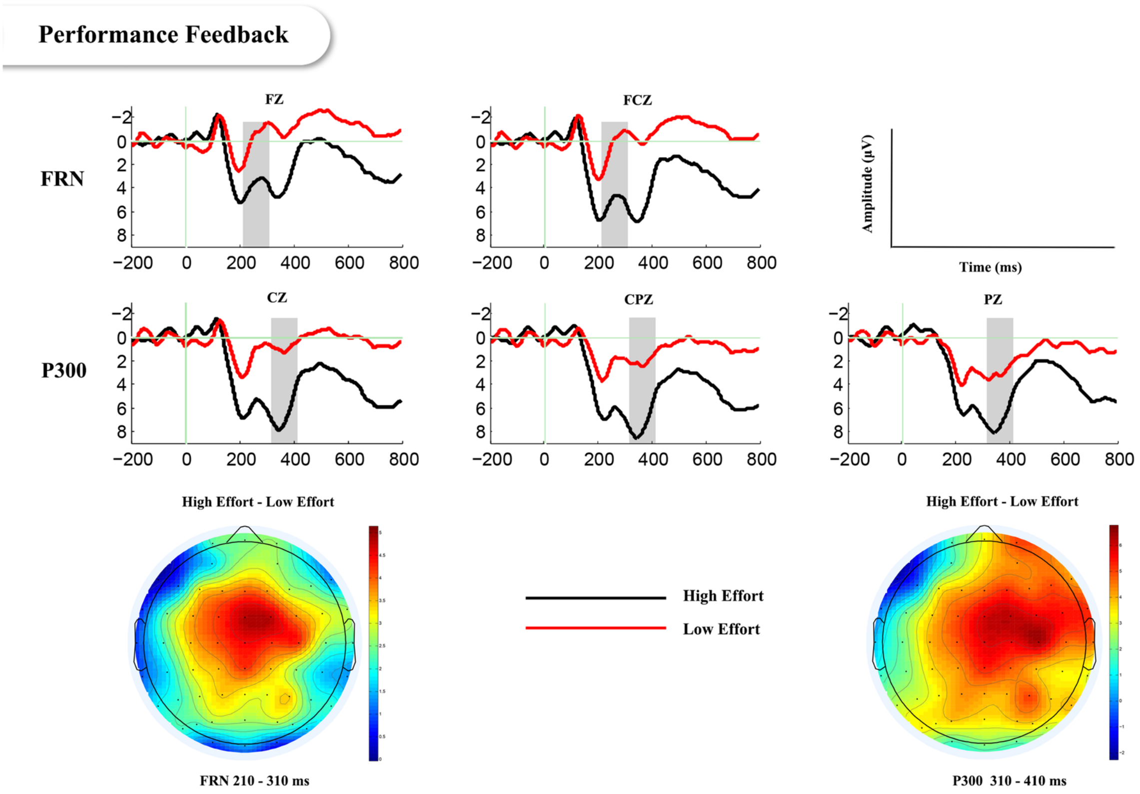

Fig. 3 Grand-averaged ERP waveforms during the evaluation stage of performance feedback. The 800 ms post-onset of performance feedback was segmented, during which participants were evaluating their performance feedback. Waveforms of the FRN-like component from two midline frontal electrodes (Fz, FCz) are shown in relation to effort (high effort versus low effort). Three midline parietal electrodes (Cz, CPz, Pz) are selected to show grand-averaged ERP waveforms of P300. Scalp topographic distribution of FRN and P300 (amplitude in the low effort condition subtracted by that in the high effort condition during the time window 210–310 and 310–410 ms, respectively) are provided. The *bar* for FRN ranges from +5 to 0 μV, while it ranges from +6 to −2 μV for P300

FRN/P300 complex

The evaluation of performance feedback is mainly reflected in amplitudes of the P300 and the FRN. It is worth mentioning that there were insufficient failing trials since accuracy was very high in both the high-effort and low-effort conditions. Thus, only ERPs in the winning trials entered into the ANOVA. As presented in Fig. 3, the mean P300 amplitude was 7.031 μV in the high-effort condition compared to 2.203 μV in the low-effort condition. Results from the ANOVA indicated significant main effects of effort ($F_{(1,\ 17)}=33.139$, $P<0.001$, $\eta^2 = 0.661$) and caudality ($F_{(2,\ 34)}=10.223$, $P=0.003$, $\eta^2 = 0.376$, $\varepsilon=0.601$). The paired contrast results showed that the difference between the central and the central-parietal electrodes as well as the difference between the central and the parietal electrodes were both significant ($P=0.001$ and 0.012, respectively), and the elicited P300 was least positive in the central area. However, no significant effect of laterality ($F_{(2,\ 34)}=1.463$, $P=0.246$, $\eta^2 = 0.079$) was observed. The P300 was larger in the high-effort condition than that in the low-effort one, illustrating potentially greater motivational significance subjectively assigned to outcomes in the high-effort tasks. There was a significant interaction effect of effort and caudality ($F_{(1,\ 17)}=7.095$, $P=0.008$, $\eta^2 = 0.294$, $\varepsilon=0.680$). No significant interaction effects of the other factors were found.

The mean FRN amplitude was 4.211 μV in the high-effort condition compared to 0.112 μV in the low-effort condition. The ANOVA for the FRN revealed significant main effects of effort ($F_{(1,\ 17)}=42.594$, $P<0.001$, $\eta^2 = 0.715$) and caudality ($F_{(2,\ 34)}=15.813$, $P=0.001$, $\eta^2 = 0.482$), with a more positive FRN in the high-effort condition and in the frontal area. In contrast, the main effect of laterality ($F_{(2,\ 34)}=2.695$, $P=0.099$, $\eta^2 = 0.137$, $\varepsilon=0.752$) was not significant. In addition, only the interaction effects of effort and caudality ($F_{(1,\ 17)}=7.377$, $P=0.015$, $\eta^2 = 0.303$) as well as effort and laterality ($F_{(2,\ 34)}=4.248$, $P=0.023$, $\eta^2 = 0.200$) were significant. Successes elicited a less negative FRN in the high-effort condition than in the low-effort one, suggesting that a greater subjective value might be bestowed on the positive outcome in the high-effort tasks. Additional correlational analyses were carried out between magnitudes of the FRN and the P300. A positive correlation was shown between magnitudes of the FRN and P300 in both high-effort and low-effort conditions ($r = 0.733$, $P = 0.001$ in the high-effort condition and $r = 0.659$, $P = 0.003$ in the low-effort condition). At this moment, as it is impossible to disentangle the FRN from the P300, we decide to define it as the FRN-P300 complex.

Discussion

In the present study, we aimed to investigate to what extent performance feedback anticipation and evaluation would be modulated by the amount of exerted effort. Calculation tasks requiring varied mental efforts were adopted. Specifically, multiplication was defined as a high-effort task, while addition was deemed as a low-effort one. Electrophysiological results illustrated that effort indeed exerted significant effects on brain activities as the participants were anticipating and evaluating the corresponding performance feedback. During performance feedback anticipation, a more pronounced SPN was observed in the high-effort condition, which suggested that participants cared more about their task performance and paid more anticipatory attention toward performance feedback. During performance feedback evaluation, we observed a distinct modulation of exerted effort on the FRN/P300 complex. A less negative FRN-like component was elicited when positive feedback was presented in the high-effort condition compared with in the low-effort one, indicating that participants might place a greater subjective value on successes in the former case. In a similar manner, the amplitude of the P300 was prominently larger in the high-effort condition, further suggesting that there might be an inherent reward within exerted effort itself.

According to the behavioral data, the average reaction time of the multiplication tasks was significantly longer than that of additions. According to our design, participants were allowed to respond only after the assigned operation task had been displayed for 3 s. Thus, it is highly likely that some if not most of the addition tasks were already resolved before the prompt of "Response Allowed" was presented on the screen and that participants would choose the target result immediately after the prompt appeared. In this study, although the reported reaction time was not an accurate measurement of calculating time, this result still suggested that participants have to accomplish more complicated calculations when working on multiplications. Thus, we can conclude that multiplications are indeed more demanding and require greater effort.

As for the ERP results, despite numerous studies on outcome evaluation, few studies have explored the electrophysiological signature of outcome anticipation. During performance feedback anticipation, we observed distinct SPN patterns in both the high-effort and low-effort conditions. As the presentation of the task performance approached, the magnitude of the SPN increased steadily (Brunia et al. 2011; Pornpattananangkul and Nusslock 2015). Importantly, a more negative SPN was observed in the high-effort condition. According to previous studies, the SPN is well established to reflect anticipatory attention preceding feedback of one's actions (Böcker et al. 1994; Pornpattananangkul and Nusslock 2015). For the participants, feedback has significant informational value and is a motivational stimulus (Böcker et al. 1994; Donkers and van Boxtel 2005; Masaki et al. 2006). Existing studies have shown that the affective and motivational valence of an anticipated stimulus is a crucial factor for inducing an SPN (Brunia et al. 2012; Kotani et al. 2015). When it comes to effort, it has been demonstrated that exerted effort would increase the motivational significance of feedback information (Ma et al. 2014; Meng and Ma 2015). In the current study, according to average reaction time data, heightened effort was put into multiplications. Effort involvement might contribute to an enhanced motivational salience of the anticipated outcomes, and we expected participants to be more eager to know whether their effort worked in the high-effort condition. This might explain why a more negative SPN was observed when participants were anticipating performance feedback in the high-effort condition.

In addition to reflecting cognitive processes related to anticipatory attention, a few studies on SPN moved a step forward and suggested that SPN might reflect one's subjective expectancy toward a positive outcome (Fuentemilla et al. 2013; Meng and Ma 2015; Meng et al. 2016). For example, in a recent study, participants performed tasks either freely chosen by themselves or randomly assigned to them. Subjective expectancy toward successes was measured through a scale, and the SPN was examined across the two conditions. Interestingly, the successful rate was even slightly lower for the self-chosen tasks. Nevertheless, subjective expectancy toward the positive outcomes got enhanced when participants actively completed the self-chosen tasks and an enhanced SPN was observed (Meng and Ma 2015). In a recent study using a two-player stop watch game, which adopted a badminton tournament format, a more pronounced SPN was observed when the participants had a substantial lead. Although the objective expected value of winning was even smaller when the two players were performing equally well (nearly 50% to win versus 50% to lose), the subjective value of winning in the blowout condition was even higher in this case (Meng et al. 2016). In line with findings of these two studies, in another study using gambling tasks, anticipating improbable but desirable outcomes was reported to result in a more negative SPN (Fuentemilla et al. 2013). Taken together, findings of these pioneering studies suggested that the SPN might mirror subjective expectancy toward positive feedback but not the objective expected value. In this study, although participants stood a better chance to win in the low-effort condition, they might be better motivated to win in the high-effort condition, as multiplications are more demanding and greater effort have to be invested into these tasks. Thus, the current findings provided additional evidence for the argument that the SPN might mirror subjective expectancy.

As the amplitude of the SPN is also suggested to be sensitive to uncertainty and an enhanced SPN is generally elicited when participants are uncertain of their task performance (Catena et al. 2012), one may argue that the observed SPN pattern might be related with high uncertainty accompanied with the high-effort tasks. Indeed, compared with additions, the multiplication tasks were more demanding. Thus, although participants might have mastered the skills to calculate them, they might still be comparatively uncertain whether their answers were correct or not. In an fMRI study, when there was high uncertainty of rewards, sustained activation in the ventral striatum was observed during outcome anticipation (Dreher et al. 2006). The authors suggested that this finding indicated that uncertainty could enhance subjective anticipation of the outcome. Another study reported that the participants were more confident with tasks with predictable reward feedback, which gave rise to a significantly reduced SPN (Novak et al. 2016). As tasks that require greater effort are generally more demanding and involve greater uncertainty at the same time, it is difficult if not infeasible to isolate the effects of effort itself and the accompanied uncertainty. However, at least we can conclude that greater effort and greater accompanied uncertainty jointly contribute to enhanced anticipation of performance feedback. We expect that future studies with more ingenious experimental designs may isolate these effects and help resolve this issue. At this moment, we continue to examine the effect of exerted effort on temporal dynamics of performance evaluation. We believe that converging evidences from performance feedback anticipation and evaluation may help illuminate the positive effects of effort itself on one's psychological states.

During the performance evaluation stage, a distinct modulation of the exerted effort on the FRN/P300 complex was observed. Existing studies have shown that both the FRN and the P300 are sensitive to the valence of outcomes (San Martín 2012). For both the multiplication and addition tasks of the current study, the vast majority of which were successfully solved. Since a reliable measurement of ERP components requires a minimum number of valid trials (Luck 2005), only winning trials were analyzed for both the FRN and the P300. For the P300, a larger P300 was observed in response to the positive feedback in the high-effort condition. Beyond responding to the valence of rewards (Hajcak et al. 2005, 2007; Wu and Zhou 2009; Zhou et al. 2010), the P300 is also suggested to be involved in high-level motivational and affective salience evaluation (Yeung and Sanfey 2004; Nieuwenhuis et al. 2005; Leng and Zhou 2010). In line with pioneering studies (Schevernels et al. 2014, 2016), the current finding appeared to suggest that, with greater exerted effort, the task performance would be more motivationally salient to the participants, and that participants would be more concerned about their performance. Thus, we provided additional evidence for the argument that the P300 may encode the subjective value of outcomes (San Martín 2012; Ma et al. 2015).

Consistent with findings on the P300, effort's modulation on an FRN-like component was also observed. Although most studies adopted a difference wave approach and compared magnitudes of the d-FRN across different conditions, some researchers separately calculated the FRNs elicited by positive and negative outcomes and suggested that the observed FRN pattern is mainly the result of a positive deflection toward positive outcomes (Foti et al. 2011; Wardle et al. 2013; Weinberg et al. 2014; Ma et al. 2015). Several groups of researchers further suggested this component to be "an underlying positive-going deflection", and named it as RewP (Proudfit 2015; Threadgill and Gable 2016). In line with these findings, if exerted effort influences subsequent performance evaluation, then modulation of exerted effort on the FRN elicited by positive feedback should be observed. Indeed, a less negative FRN toward positive feedback was observed in the high-effort condition.

During the feedback period, the magnitudes of the elicited FRNs were found to reflect subjective evaluation of outcome valence (for a recent review, see San Martín 2012). For example, in a recent study, an unfair offer proposed out of good intentions was subjectively evaluated as more positive than the same offer proposed with bad intentions, resulting in a more pronounced FRN in the latter case (Ma et al. 2015). In the current study, after participants overcame difficulties and won a victory, they might be able to experience a real sense of achievement, elevating the motivational salience of positive feedback. Thus, the finding of a less pronounced FRN when positive feedback was provided in the high-effort condition suggested that accomplishments are cherished more when tasks are more demanding and when more effort has been invested into these tasks.

In line with previous studies, the significant positive correlation between the FRN and the P300 in both the high- and the low-effort conditions might reveal the FRN and P300 as a complex (Kraus and Horowitz-kraus 2014). In our study, the FRN was suggested to reflect one's subjective evaluation of the positive outcome, which would be more positive in magnitude when participants experienced the success after hard working. Since the outcome in the high-effort condition was generally considered to be more motivationally relevant, preferential attention would be allocated, as reflected by a more pronounced P300. Therefore, the FRN/P300 complex in the current study may index a process of motivational significance evaluation.

The current study makes considerable contributions to existing neuroscientific investigations of exerted effort. Previous studies have investigated the role of cognitive effort during several cognitive stages, such as task preparation (Schevernels et al. 2014, 2016), task participation (Hernandez Lallement et al. 2014; Ma et al. 2014) and learning progress (Brouwer et al. 2012, 2014). Specifically, most of these pioneering studies focused on the effect of exerted effort on the cognitive processing of associated rewards (Ma et al. 2014; Schevernels et al. 2016), and it was consistently reported that the more effort invested into the task, the greater subjective value would be assigned to the subsequent monetary reward (Ma et al. 2014). Extending and complementing existing studies, this study is among the first attempts to probe the positive impact of effort itself across two other equally important while relatively neglected cognitive stages (performance feedback anticipation and performance feedback evaluation).

While preliminary electrophysiological evidence suggests that effort may provide its own reward, it is worth noting that high-effort tasks adopted in this study are inherently more demanding than low-effort ones. Thus, although more effort was invested into the high-effort tasks, participants did not voluntarily do so. Still, the current findings suggested that enhanced anticipatory attention was paid to performance feedback, and a strengthened subjective expectancy was formed toward positive feedback. In addition, once participants won a victory, successes might be treasured to a greater extent. In our daily life, there are situations where individuals voluntarily exert more effort in certain activities. Under these circumstances, we expect that the positive impact of effort will be even greater. However, our predictions remain to be examined in future studies. Besides, in our study, we failed to use any questionnaires or self-report measures to assess the subjective data. Well-designed scales should be adopted in future studies in order to prove and enhance conclusions of the current study.

Conclusion

To examine the inherent reward of effort, EEGs were recorded while participants performed calculation tasks that required a varied amount of effort. A more pronounced SPN was observed during the performance feedback anticipation stage of the high-effort condition, illustrating enhanced anticipatory attention and strengthened subjective expectancy toward performance feedback. In addition, for the more demanding tasks, a more pronounced FRN/P300 complex was elicited upon positive feedback presentation, suggesting that successes might be assigned with additional subjective value when more effort had been invested. To conclude, these results suggested that effort may carry its own reward, and that endeavors may reinforce subjective expectation and evaluation of task performance.

Acknowledgements Lei Wang was supported by the National Natural Science Foundation of China [Grant No. 71471163]. Liang Meng was funded by “Chen Guang” project supported by Shanghai Municipal Education Commission and Shanghai Education Development Foundation [Grant No. 16CG36], and a project from the Planning Fund of Shanghai International Studies University [Grant No. 20161140012].

Compliance with ethical standards

Conflict of interest The authors declare that they have no conflict of interest.

Ethical approval All procedures performed in studies involving human participants were in accordance with the ethical standards of the institutional research committee and with the 1964 Helsinki declaration and its later amendments or comparable ethical standards.

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