**Investigating the effect of losses and gains on effortful engagement during an incentivised Go/NoGo task through anticipatory cortical oscillatory changes.**

**Short title:** Effects of incentives, motor set and value of effort on cortical oscillations

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**ABSTRACT**

Losses usually have greater subjective value (SV) than gains of equalnominal value but often cause a relative deterioration in effortfulperformance. Since losses and gains induce differing approach/avoidancebehavioural tendencies, we explored whether incentive type interactedwith approach/avoidance motor-sets. Alpha- and beta-band event-related desynchronization (ERD) of cortical oscillations was hypothesised to be weakest when participants expected a loss and prepared an inhibitory motor-set, and strongest when participants expected a gain and prepared an active motor-set. It was also hypothesised that effort would modulate reward and motor-set related cortical activation patterns.

Participants completed a cued Go/NoGo task while expecting a reward (+10p), avoiding a loss (-10p), or receiving no incentive (0p); and while expecting a NoGo cue with a probability of either .75 or .25. Premovement alpha- and beta-band EEG power was analysed using the ERD method, and the SV of effort was evaluated using a cognitive effort discounting task.

Gains incentivised faster RTs and stronger preparatory alpha band ERD compared to loss and no incentive conditions, while inhibitory motor-sets resulted in significantly weaker alpha-band ERD. However, there was no interaction between incentive and motor-sets. Participants were more willing to expend effort in losses compared to gain trials, although the SV of effort was not significantly associated with ERD patterns or RTs.

Results suggest that incentive and approach/avoidance motor tendencies modulate cortical activations prior to a speeded RT movement independently, and are not directly associated with the economic value of effort. The present results favour attentional explanations of the effect of incentive modality on effort.

**1 | INTRODUCTION**

Effort can be conceptualised as a decision-making factor, where individuals decide to expend effortful resources on the promise of an anticipated reward, monetary or otherwise (Inzlicht, Schmeichel, & Macrae, 2014; Kurzban, Duckworth, Kable, & Myers, 2013). It would therefore be expected that effortful resources are deployed proportional to the value of an offered incentive, as supported by the observation that larger rewards encourage improved effortful performance compared to smaller ones (James, Reuther, Angus, Clarke, & Hunt, 2019; Massar, Lim, Sasmita, & Chee, 2016; Soutschek, Kang, Ruff, Hare, & Tobler, 2018).

Losses are generally found to be more motivating (Baumeister, Bratslavsky, Finkenauer, & Vohs, 2001; Krebs & Woldorff, 2017; Rozin & Royzman, 2001; Wright & Rakow, 2017), as well as being more arousing, than gains (Low, Lang, Smith, & Bradley, 2008; Sokol-Hessner et al., 2009; Stancak et al., 2015) and causing greater activation in cortical and striatal areas (Gehring & Willoughby, 2002; Holroyd & Coles, 2002; Tom, Fox, Trepel, & Poldrack, 2007; Yeung, Botvinick, & Cohen, 2004). It would thus be expected that losses cause an increase in performance relative to gains. However, monetary losses often cause no change (Boksem & Tops, 2008; Seifert, Naumann, Hewig, Hagemann, & Bartussek, 2006), or even a deterioration in effortful performance relative to gains of equal nominal value (Carsten, Hoofs, Boehler, & Krebs, 2018; Fontanesi, Palminteri, & Lebreton, 2019; Paschke et al., 2015; Potts, 2011).

We have investigated the effect of incentive on cognitive effort using a neuroeconomic approach and showed that effortful engagement under high incentives was associated with the increased desynchronization of cortical oscillations in the alpha band over posterior parietal and frontal regions of the scalp, and in the beta band over bilateral sensorimotor areas (Byrne et al., 2020). Event-related desynchronization (ERD) in the alpha band has previously been associated with anticipatory attention (Corbetta, Patel, & Shulman, 2008; Coull, Walsh, Frith, & Nobre, 2003; Kastner & Ungerleider, 2000; Serences & Yantis, 2006), while sensorimotor beta-band ERD has been associated with the maintenance of a prepared motor response (Fox et al., 2016; Ishii et al., 2019; Pfurtscheller & Berghold, 1989; Tzagarakis, Ince, Leuthold, & Pellizzer, 2010; Tzagarakis, West, & Pellizzer, 2015). In our subsequent study, we showed symmetrical increases in the speeding of RTs and preparatory cortical activation under graded gains and losses, despite losses being more motivating than gains (Byrne et al., submitted). However, we were unable to establish the underlying cause behind the divergent effect of losses and gains on effortful performance.

The divergent effect of losses and gains on effortful performance has been hypothesised to be the result of attentional biases associated with loses. According to the attentional model of loss aversion, losses may cause a relative deterioration in effortful performance because they distract participants from the primary task goals (Yechiam & Hochman, 2013). Alternately, the contradictory effect of gains and losses on performance has been suggested to be due to approach and avoidance associations made with losses and gains; gains induce approach behaviours and losses induce avoidance behaviours (Buzzell, Beatty, Paquette, Roberts, & McDonald, 2017; Hoofs, Carsten, Boehler, & Krebs, 2019; Houtman & Notebaert, 2013; Pratto & John, 1991).

The present study investigated the approach/avoidance and attentional tendencies associated with losses and gains during effortful engagement. We asked whether preparatory approach/avoidance motor sets would interact with, or act independent of, the cortical effect of positive and negative incentives on cortical oscillatory responses during effortful engagement. The main effects and interactions of positive/negative incentives and preparatory approach/avoidance motor sets on behavioural performance and anticipatory ERD performance were investigated during a cued Go/NoGo task, where incentive was modulated on a trial-by-trial basis (Krebs, Boehler, & Woldorff, 2010; Novak & Foti, 2015; Zhang, Li, Wang, Liu, & Zheng, 2017). It is important to note that RTs and NoGo stopping rates may not provide a direct measure of effortful engagement, and may be confounded by factors such as mood, ability, and strategy (Locke & Latham, 1990). ERD measures were therefore implemented to shed further light on the cortical processes underlying effortful performance under differing reward and task conditions.

The employment of decision-making approaches to evaluate the subjective value of effort is a comparatively novel development in the field of cognitive effort (Botvinick et al., 2009; Treadway et al., 2009; Kurniawan et al., 2010; Prévost et al., 2010), where it is proposed that the choice to engage in an effortful task results from the weighing of effort costs against the value of its outcomes (Westbrook and Braver, 2015; Kool et al., 2017; Shenhav et al., 2017). In discounting paradigms, participants are given the choice between a low-effort option for a small reward and a high-effort-option for a large reward. By measuring an individual’s preference for high-effort options over a range of reward levels, their effort-discounting rates can be plotted on a discounting curve. Measuring the subjective value of effort directly reflects a number of methodological and theoretical challenges to decision-making paradigms (Massar et al., 2016; Westbrook et al., 2013; Klein-Flügge et al., 2015; Warm et al., 1996). However, the effort value generated from discounting tasks has proved useful in predicting individuals’ need for cognition scores (Westbrook et al., 2013).

Our study sheds more light on how the subjective value of effort is mapped onto performance and cortical activation changes under differing incentives and task-conditions. The performance-based outcomes taken from the Go/NoGo task may not have been good measures of the subjective value of effort due to potential capacity limits, resulting in a ceiling effect (LeBouc et al., 2016). Similar to other studies (Massar et al., 2016; Westbrook et al., 2013), the subjective value of effort was evaluated using a decision-making experiment (COGED) offering trade-offs between the duration of the Go/NoGo task and the money that the participant would be willing to pay to avoid engaging in the task for a prolonged period of time. It was hypothesised that individual effort discounting rates, used as a proxy of their cognitive effort valuation, would manifest in shorter RTs when incentivised with a gain/loss, especially in Go-primed trials, and in stronger cortical activation changes sub-serving the execution of speeded RT movements.

Bolstering behavioural findings, amplitude changes of cortical oscillations, quantified using the ERD method, were chosen to probe the interaction between approach/avoidance movement tendencies and incentive because the Go/NoGo task elicits competing processes of motor activation and inhibition, and these competing processes can be tracked using the time courses of ERD or ERS. Specifically, ERD in the alpha and beta bands is found over sensorimotor areas during motor preparation (Chatrian et al., 1959; Cuevas, Cannon, Yoo, & Fox, 2014; Fox et al., 2016; Gastaut, 1952; Pfurtscheller & Aranibar, 1979; Pfurtscheller & Berghold, 1989), while ERS in the beta-band over right frontal areas of the scalp is strongly associated with motor inhibition (Buschman & Miller, 2007, 2009; Siegel, Donner, Oostenveld, Fries, & Engel, 2008). In contrast, phase-locked electrophysiological responses found during movement anticipation such as the motor readiness cortical potential (MRCP) do not lend themselves for measuring cortical activation and inhibition together (Shibasaki & Hallett, 2006).

The present study was motivated to analyse whether approach/avoidance motor tendencies, manipulated through Go/NoGo expectations, interacted with incentive valence during effortful engagement. Based on hypotheses that losses induce avoidance responses and gains induce approach responses (Guitart-Masip et al., 2011; Guitart-Masip et al., 2012; Richter et al., 2014; Hoofs, Böhler, & Krebs, 2019), it was postulated that approach/avoidance motor expectations and incentive valence would interact in such a way that gains would speed RTs in the Go-primed conditions, and losses would improve stopping rates in the NoGo-primed condition (Buzzell, Beatty, Paquette, Roberts, & McDonald, 2017; Hoofs, Carsten, Boehler, & Krebs, 2019; Houtman & Notebaert, 2013; Pratto & John, 1991). We further predicted that cortical activation in task-relevant regions of the scalp, objectivised using ERD/ERS measures, would show an interaction between approach/avoidance movement expectations and positive/negative anticipated incentives, and that ERD magnitude would account for changes in Go/NoGo performance.

It was hypothesised that frontal and posterior-parietal ERD in the alpha band, as well as bilateral sensorimotor ERD in the beta band, would be strongest when gains were anticipated and when Go-cues were likely to occur, and weakest when losses were anticipated and when NoGo cues were likely to occur. Interactions between approach/avoidance motor sets and incentive types were predicted to be revealed as losses sharpening the effect of inhibitory motor sets on ERD responses and gains sharpening the effect of approach motor sets on ERD responses. We further hypothesised that monetary losses would be more motivating than gains in the COGED task and improve the NoGo stopping rate. However, losses were predicted to slow RTs relative to gains and that individual SVs of effort would be associated with reward- and motor-set related cortical activation patterns.

**2 | METHODS**

**2.1 | Participants**

27 subjects (15 females) were recruited. However, 3 subjects were removed from subsequent anaylsis because of excessive muscle artefacts in the EEG data. The final sample included 24 subjects (14 females), aged 24.25 ± 6.24 (mean ± SD). The procedure used was approved by the Research Ethics Committee of the University of Liverpool, and all participants gave fully informed written consent at the start of the experiment, in accordance with the Declaration of Helsinki.

**2.2 | Procedure**

The participants were first required to complete a cued Go/NoGo task, which was a modified version of the sustained vigilance task used previously (Byrne et al., 2020; Massar et al. 2016) and the cued Go/NoGo task used by others (Filipovic et al., 2000; Randall & Smith, 2011). Participants were then required to complete the discounting task used previously, with gain and loss trials included (Byrne, et al., submitted; Maasar 2016; Westbrook 2014).

The Go/NoGo task consisted of four twenty-minute blocks, with 120 trials each. The reward and prime conditions were psuedo-randomly rearranged within each set of trials, meaning there was an equal number of trials for each incentive and reward trial within each block. In the gain condition, participants were offered a small monetary reward (+10p) whenever they reacted faster than their median RT in response to a Go cue, or successfully inhibited their response to a NoGo cue. In contrast, in the loss conditions, participants lost a small amount of money (-10p) whenever they reacted slower than their median RT in response to a Go’ cue, or if they failed to inhibit their response to a NoGo cue, and in the 0p condition participants were not offered a reward.

Additionally, participants were primed to expect a Go or NoGo cue. When participants were primed for a Go cue, they were told there was a 75% chance of the following target being a Go cue and a 25% chance of it being a NoGo cue; and when participants were primed for a NoGo cue, they were told that there was a 75% chance of the following target being a NoGo cue and a 25% chance of it being a Go cue.

The effect of the different monetary incentives and primes on effortful performance and corresponding cortical responses were assessed using participants’ mean RTs and electrophysiologically using their changes in ERD in the 2s epoch preceding the presentation of the target stimulus. RTs and other measures of effortful performance have been used in previous studies as measures of effortful engagement (Aarts et al., 2008; Atkinson & Raynor, 1978; Bandura & Cervone, 1983; Eisenberger, 1992; Kukla, 1972; Locke & Latham, 1990; Wang et al., 2021; Luft et al., 2009), and have been associated with physiological measures of effortful engagement such as pupil diameter (Massar, Lim, Sasmita, & Chee, 2016). However, ERD measures, reflecting the involvement of task-relevant cortical regions, are required to shed further light on the gap between effortful engagement and effortful performance under differing incentives and task conditions.

The discounting task was the same as used previously (Byrne, et al., submitted), being a modified version of the discounting task used by other researchers (Massar et al., 2016; Westbrook et al., 2013), with monetary losses added. Discounting procedures allowed us to estimate the subjective value (SV), or the willingness to engage in effortful options, during different levels of effort in equivalent loss and gain modalities.

**2.3 | Go/NoGo Task**

Once the EEG net was applied, participants were taken into a dimly lit, sound-attenuated room and asked to complete the Go/NoGo task. The Go/NoGo task was a combination of the cued vigilance task used previously (Byrne et al, 2020), and the cued (S1-S2) Go/NoGo tasks used by other researchers (Filipovic et al., 2000; Randall & Smith, 2011).

During the baseline period, participants were presented with a white cross and not required to make a response. The participants were then presented with a cue stimulus which displayed the reward or punishment offered for that trial (-10p, 0p, +10p), as well as the probability of the target being a Go or a NoGo cue (75% Go, 75% NoGo), as indicated by the colour of the cue stimulus (blue, purple). After two seconds the participants were presented with the target stimulus (Go, NoGo). The inter-trial interval between the target stimulus and the baseline period was uniformly distributed and ranged from 3 to 7 seconds (see Figure. 1A).

Participants were instructed to respond as quickly as possible upon the occurrence of the Go stimulus and not make any response when presented with the NoGo stimulus. Participants were also informed of the probabilities of a Go/NoGo trial associated with each colour at the beginning of the experiment, which was kept consistent across each individual participant and counterbalanced across participants. The Go/NoGo target stimulus could be either a white circle or a white square, the associations with these targets was randomly assigned at the start of the experiment for each participant (e.g., a circle for Go and a square for NoGo). The participants were informed of this assignment before they began the task.

Participants completed a 15-trial practice run, with no rewards offered, allowing them to familiarise themselves with the rules of the task. Their median RT was calculated from this practice block and recalculated following each trial during the experimental blocks.

Participants were then required to complete four experimental blocks, lasting roughly twenty minutes, with 120 trials per block, and they completed 160 trials for each reward condition (-10p, 0p, +10p), with 80 Go primed trials and 80 NoGo primed trials. Participants were offered a maximum total gain/loss of £16 if they earned the reward or failed to avoid the loss on every trial. As the order of trials was pseudo-randomly rearranged at the start of each set of 5 trials, there was an equal number of trials for each condition and participants could not predict the next trial.

**2.4 | Discounting task**

Once the participants had completed the Go/NoGo task, they engaged in the discounting task (Massar et al., 2016; Westbrook et al., 2013), which was the same task as used previously (Byrne et al., submitted). The subjective cost of different levels of cognitive effort in both gain and loss conditions was evaluated by calculating the indifference point, defined as the average of the largest amount for which the participant chose the low-effort option and the smallest amount for which the participant chose the high-effort option. The indifference point represented the point that the subject perceived the high- and low-effort options as being subjectively equal, or changed their response from their initial choice. The area under the curve (AuC) in the participants SVs across effort levels was computed (Myerson, Green, & Warusawitharana, 2001), a measure which has been found to correlate with need for cognition scores (Westbrook et al., 2013), and has been used to compare effort and delay discounting rates (Massar et al., 2015).

In this task, participants chose between two monetary gains (up to £12), or two monetary losses (up to £12), and each choice was between one lower monetary offer and one higher monetary offer (Figure. 1). The monetary choices were tied to two effort-based outcomes, with one low-effort outcome (completing the Go/NoGo task again for 1 minute with no additional rewards) and one high-effort outcome (completing the Go/NoGo task again for 5, 10, 15, 20, 25, or 30 minutes with no additional rewards). In gain choices, the lower-monetary incentive was always tied to the low-effort outcome and the higher-monetary incentive was always tied to the high-effort outcome. In loss choices, the higher monetary loss was always tied to the low-effort outcome and the lower monetary loss was always tied to the high-effort option.

After each choice, the monetary reward/loss for each pair of offers was adjusted following a staircase titration method (i.e., in gain conditions, the low-effort option was increased if the high-effort option was chosen and decreased if the low-effort option was chosen), and the amount of money being added to, or taken away from, the choices was halved each time the participants made a choice. Once the participant had completed the task, one trial was randomly selected, and the participant was required to complete the Go/NoGo for the chosen amount of time and would receive the monetary gain/loss tied to that choice. The participants were made aware of the time they would have to complete the Go/NoGo task again, and its associated monetary outcome once the discounting task was completed.

The indifference point has been used in previous studies as a measure of individual effort-discounting rates based on participant’s willingness to engage in an effortful task for longer periods of time (Massar et al., 2016; Westbrook et al., 2013). Indifference point values have been shown to correlate with the need for cognition score (Westbrook 2013). Providing further support for the validity of COGED indifferent point measures, the discounting curve taken from COGED tasks commonly matches the sigmoidal shape associated with effort discounting (Massar et al., 2016; Klein-Flügge et al., 2015). However, while it is clear that prolonged engagement with tasks requiring sustained vigilance is perceived as effortful (Warm et al., 1996), the choices made to engage in effortful tasks for prolonged periods of time may employ different cognitive processes to the choice to maintain engagement during ongoing effortful engagement.

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To control for temporal discounting, participants were informed that they would be required to remain in the laboratory for the full 30 minutes in total, including the time spent completing the Go/NoGo task; ensuring that the participants made decisions during the discounting task based upon the effort required, rather than the time taken to complete the task. While the effect of boredom associated with remaining in the lab was not directly investigated, all participants discounted higher levels of effort (30 mins) more than lower levels of effort (5 mins), suggesting that they were all reluctant to complete the task for longer periods of time.

**2.5 | EEG recordings**

The EEG net was aligned with reference to two preauricular points and the nasion landmark. Data was then recorded continuously using a 129-channel Geodesics EGI system (Electrical Geodesics, Inc., Eugene, Oregon, USA) with a sponge-based HydroCel Sensor Net. Electrode-to-skin impedances were kept below 50 kΩ and kept at equal levels across all electrodes, a recording band-pass filter was set at 0.001-200 Hz with a sampling rate of 1000 Hz, and the Cz electrode was used as a reference electrode.

**2.6 | EEG data preprocessing**

EEG data was pre-processed using BESA v 7.0 (MEGIS GmbH, Germany), and re-referenced using a common average reference method (Lehmann, 1984), restoring the signal at electrode Cz. A principle component analysis method (Berg and Scherg 1994) was used to remove eye-blinks and electrocardiographic artefacts and data was visually inspected for muscle artefacts; all trials containing artefacts were excluded from subsequent analysis.

The average number of trials accepted for EEG analysis in each Go primed condition was: 65.5 ± 10.19 (mean ± SD) in the -10p condition; 65.67 ± 10.11 (mean ± SD) in the 0p condition; 65.58 ± 8.79 (mean ± SD) in the +10p condition, and in each NoGo primed condition was: 67.25 ± 8.14 (mean ± SD) in the -10p condition; 66.63 ± 10.51 (mean ± SD) in the 0p condition; 67.25 ± 8.14 (mean ± SD) in the +10p condition. The mean number of accepted trials did not differ across reward conditions (p > .05); however, significantly more NoGo cued trials were accepted than Go cued trials (p = .034), possibly due to greater muscle activity as a result of motor preparation in Go cued trials.

**2.7 | Event-related desynchronization analysis**

To compute the ERD curves, EEG signals were down sampled to 256 Hz. Power spectra was computed in Matlab R2020a (The Mathworks, Inc., USA) using Welch’s power spectral estimate method. The power spectral densities were computed from non-overlapping 1-second segments (256 points), which were smoothed using a Hanning window, and were estimated in the range 1-80 Hz with a frequency resolution of 1 Hz. ERD curves were evaluated from 2 s before, and 5 s after the onset of the cue stimulus in both the alpha (8-12 Hz) and beta (16-24 Hz) bands using the classical ERD transformation (Pfurtscheller & Aranibar, 1979). Absolute band power was calculated from 1 s time epochs shifted in 100 ms across the 7 s time window. The baseline used in the ERD calculation was the epoch ranging from -1.5 s to -0.5 s before the onset of the cue stimulus, and the time-epoch ranging from 2 to 3 s after the onset of the cue stimulus was chosen for statistical analysis.

**2.8 | Statistical analysis**

The main effects and interactions between reward and primes on median RTs and NoGo stopping rates were assed using 2×3 repeated measures ANOVAs with three levels of reward (-10p, 0p, +10p), and two-levels of prime (75% Go, 75% NoGo). To test the assumption of normality used in the ANOVA a Shapiro-Wilk test of normality was used. The test was chosen above that of Kolmogorov-Smirnov because it was more appropriate for the small sample size used (Guo, 2012; Zimmerman, 2003). NoGo stopping rates were defined as the percentage number of trials where participants successfully inhibited their response to NoGo cues in each reward/prime condition.

Similarly, ERD changes due to reward and primes were investigated in both the alpha (8-12 Hz) and beta (16-24 Hz) frequency bands across all 129 electrodes using 2×3 repeated measures ANOVAs. However, to correct for false positive errors due to repeated significance tests, p values were calculated for each electrode using a permutation analysis (Maris & Oostenveld, 2007), implemented in the *Statcond.m* program in the EEGLab 2019 package (Makeig, Debener, Onton, & Delorme, 2004). Then, to ensure that only electrodes with a significantly large ERD or ERS were included in subsequent analysis, univariate T-tests with significance thresholds of p = .01 were used to test whether ERD values over each electrode were significantly different from 0. Electrode clusters showing significant effects in both the permutation analysis and the t-tests were selected for further investigation in the 2×3 repeated measures ANOVAs using SPSS v.22 (IBM Inc., USA), and a Greenhouse-Geisser epsilon correction was used to tackle violations of sphericity in the data.

The AuC (Myerson et al., 2001) in the indifference points across effort-levels in the discounting task was computed for every participant. The AuC has previously been found to be correlated with need for cognition scores (Westbrook et al., 2013), and was used as an estimate as individual SVs of effort in terms of monetary gains and losses separately (Byrne, et al., submitted).

Pearson’s correlation coefficients between individual RTs, changes in ERD, and the AuC of SVs in the discounting task were computed to test for possible associations between behavioural data and ERD.

**3 | RESULTS**

**3.1 | Go/NoGo Task**

Distribution of RT data was tested for normality using a Shapiro-Wilk test, finding that the data did not significantly deviate from Gaussian distribution (W = .93, p = .082). Median RTs were therefore evaluated further using parametric statistical tests. Differences between median RTs were compared across the two prime conditions (Go, NoGo) and three reward conditions (-10p, 0p, +10p) using a 2×3 repeated measures ANOVA. A significant main effect of prime was found (F(1,23) = 21.48, p <.001, = .48), with RTs in Go primed trials being significantly faster than those in NoGo primed trials (Figure 2A). A statistically significant main effect of reward was also found (F(2,46 = 17.02, p < .001, = .43). Further analysis of the data revealed this main effect to be due to RTs in the +10p condition being significantly faster than in both the 0p condition (p < .001), and in the -10p condition (p = .004). RTs in the -10p condition were also significantly faster than those in the 0p condition (p = .005). However, no statistically significant interaction was found between prime and reward conditions (p > .05), suggesting that prime and reward effects acted independently.

NoGo stopping rates were defined as the percentage of trials where participants successfully inhibited their response to NoGo cues in each reward/prime condition. The percentage stopping rates in NoGo trials were analysed using a 2×3 repeated measures ANOVA , and a significant main effect of prime was found (F(1,23) = 45.36, p < .001, = .664), with percentage stopping rates in NoGo primed trials being much higher than those in Go primed trials (Figure 2B). A statistically significant main effect of reward was also found (F(2, 46) = 3.86, p = .043, = .14), and further analysis showed that this effect resulted from the NoGo stopping rate being lower in the +10p reward condition than in the 0p reward condition, meaning participants made more incorrect responses to NoGo cues in gain compared to no incentive conditions.

Finally, the percentage Go-success rates were analysed using a 2×3 repeated measures ANOVA. This analysis revealed statistically significant main effects of both the prime (F(1,23) = 101.02, p < .001,  = .82) and reward (F(2,46) = 36.26, p < .001, = .62) and a statistically significant interaction between reward and prime (F(2,46) = 16.18, p < .001, = .41) (Figure 2C). The main effect of prime was due to Go-success rates being significantly higher in Go-primed trials compared to NoGo-primed trials, and the main effect of reward was due to Go-success rates being significantly better in no-incentive trials compared to gain (p < .001) or loss (p < .001) trials, and in gain compared to loss trials (p = .002). The interaction between reward and Go/NoGo prime was found to be due to the statistically significant difference between Go- and NoGo-primed trials in gain and loss, but not in no incentive conditions.

**3.2 | Discounting task**

A 6×2 ANOVA was conducted to compare the main effects of effort level (5, 10, 15, 20, 25, 30 minutes) and gain/loss condition (gains, losses) on the participant indifference points. The discounting curve shown from the choice task is shown in figure 3. A significant main effect of effort level was found (F(5,120) = 28.27, p = .001, = .55), with a significant linear trend (p < .001). There was a significant difference between all effort levels (p < .05), meaning that participants were more likely to choose the low-reward option in high effort trials. A significant main effect of gain/loss conditions was also found, with indifference points in loss trials having a significantly larger AuC than gain trials (F(1,24) = 6.28, p = .044, = .16), indicating that monetary losses were significantly more motivating than equivalent gains.

The associations between the subjective value of effort, evaluated as AuC of the discounting curve, in gain and loss conditions and ERD/ RT changes under gain and loss trials were evaluated using bivariate correlations. Specifically, individual subjective values of effort for loss- and gain-conditions in the discounting task were compared with ERD in gain and loss trials in the Go/NoGo task. To compare individual sensitivities to gain and loss conditions in both subjective value of effort and ERD and RTs, a difference variable was computed representing the AuC of individual discounting rates in gain conditions subtracted from the AuC of individual discounting rates in loss conditions. Similarly, difference variables were created for ERD and RTs, defined as the ERD or RT values found in gain trials subtracted from values found in loss trials. However, no statistically significant correlations were found (p > .05) between gain/loss AuC findings and ERD or RT changes in gain and loss trials.

**3.3 | ERD patterns across trials**

The time courses and topographic maps of alpha, beta, and theta ERD/ERD for Go- and NoGo-primed trials are shown in Figures. 4A-C and 5A-C, respectively. Activity during the presentation of the cue stimulus (0.5 s after cue onset) were featured by a prominent alpha ERD (Figures. 4A and 5A) over occipital electrodes, which is thought to represent the attentional and visual processing of the stimulus cue. During period of motor preparation (2-2.5 s after cue onset), both alpha and beta-band ERD was found over motor and sensorimotor areas. ERD in the beta band (Figures. 4B and 5B) was comparatively weaker in this period and distributed mainly over contralateral regions compared to ERD in the alpha band, which occurred over more posterior electrodes when compared to beta-band ERD. During the period of response execution or suppression (3.3 s after cue onset), ERD was observed bilaterally in both frequency bands, which occurred over more posterior regions in the alpha-band than in the beta-band. ERD patterns in both the alpha and beta bands showed a similar pattern in both Go- and NoGo-primed trials, with weaker ERD shown in NoGo-primed trials.

Finally, in the theta band (Figure. 4C and 5C), ERD/ERS during the cue interval (0.5s after cue onset) was confounded by phase-locked evoked responses, causing a large ERS over the entire scalp. The following periods were featured by a theta ERS over central and precentral midline electrodes which grew stronger as the participants anticipated the target stimulus.

**3.4 | Alpha-band ERD**

The grand average topographic maps showing alpha-band for all trials as well as the electrodes found to be significantly different from 0 are shown in Figure. 6A. Topographic maps showing ERD for Go primed trials in each of the three reward conditions are shown in Figure. 6B, and topographic maps showing ERD for NoGo primed trials are shown in Figure. 6C. ERD can be seen over contralateral sensorimotor areas in all conditions, becoming bilateral in Go primed trials and both gain and loss trials (+10p, -10p), and spreading to frontal electrodes when participants were incentivised with a gain or loss.

To investigate the effects of reward and prime on ERD values, 2×3 repeated measures ANOVAs were computed to assess using prime (75% Go, 75% No-Go) and reward (-10p, 0p, +10p) as factors. ERD values were only analysed over electrode clusters which passed the combined statistical and amplitude thresholds (Figure6A), ensuring that only electrodes showing a robust ERD across conditions were assessed.

The 2×3 repeated measures ANOVA revealed two clusters showing a main effect of reward; one in central-frontal regions of the scalp (C1) and one over the ipsilateral posterior parietal region (C2). The locations of these electrode clusters are shown in Figure 6D. The statistically significant main effect of reward in the frontal cluster of electrodes (F(2,46) = 6.43, p = .003,  = .22) was the result of the ERD in the +10p reward conditions being stronger than that in both the 0p (p = .002) and -10p (p = .02) conditions, with a significant quadratic trend (p = .002). In contrast, significant main effects of both reward (F(2,46) = 5.16, p = .01, = .18) and prime (F(1,23) = 6.23, p = .02, = .21) were found over the posterior parietal cluster of electrodes (C2). The main effect of reward was due to the ERD in +10p reward trials being significantly stronger than in 0p reward trials (p = .01), with a significant quadratic trend found (p = .01), and the main effect of prime was the result of ERD being stronger in Go primed conditions compared to NoGo primed conditions. Bar charts showing the ERD differences in these clusters is shown in Figure 6E.

The 2×3 repeated measures ANOVA found two clusters of electrodes to have significant main effects of prime; one over the contralateral posterior parietal cortex, moving anteriorly to sensorimotor areas, and one over the ipsilateral posterior parietal cortex (Figure. 6F). A statistically significant main effects of and prime was found over the contralateral cluster (C3) of electrodes (F(1,23) = 14.74, p = .001, = .39), and this was due to the ERD in Go primed trials being stronger than in NoGo primed trials. Similarly, a significant main effects of prime (F(1,23) = 12.14, p = .002, = .35) were found in the ipsilateral cluster of electrodes (C4), with this being due to ERD in the Go primed condition being stronger than in the NoGo primed condition. No significant interaction between reward or prime were found in any of the electrode clusters selected for further analysis. Bar charts showing ERD values across conditions can be seen in Figure 6G.

To analyse the correlations between behavioural and ERD results, difference variables were created by subtracting individual NoGo primed RTs and ERD values from Go primed RTs and ERD values, as well as subtracting individual ERD and RT values in the 0p and the -10p conditions from those in the +10p condition. However, no significant correlations were found, between ERD and RT difference variables, or between ERD difference variables and individual AuC rates in the COGED task.

**3.5 | Beta-band ERD**

The grand average topographic map for all trials and the distribution of electrodes showing an ERD significantly different from zero are shown in Figure 7A. Activity in the beta-band was charecterised by a consistent ERD over contralateral sensorimotor regions, an effect which became stronger and more bilateral in Go primed trials and when participants were offered a +10p reward. Grand average topographic maps in each of the three reward conditions are shown for Go primed trials in Figure 7B and for No-Go primed trials in Figure. 7C.

Three clusters of electrodes showing a significant main effect of reward or prime were found in the left (contralateral) and right (ipsilateral) sensorimotor region of the scalp. Consistent with previous research (Salmelin & Hari, 1994; Stancak & Pfurtscheller, 1996), these clusters were marginally more anterior than the cluster of electrodes selected in the alpha band (Figures 6B-C).

The significant main effect of reward found in the ipsilateral sensorimotor cluster of electrodes (C1;shown in Figure. 7D) (F(2,46) = 11.73, p <.001, = .34) was found to be the result of ERD in the 0p reward condition being significantly weaker than in both the +10p condition (p <.001) and the -10p condition (p = .01), but no difference was found between the +10p and -10p conditions (p > .05). A significant main effect of prime was also found in this cluster of electrodes (F(1,23) = 4.65, p = .042, = .17), with ERD being stronger in Go primed compared to NoGo primed trials. A bar chart to show the ERD across conditions for this cluster can be seen in Figure 7E.

Two clusters were found in the permutation analysis with significant main effects of prime. The locations of these clusters are shown in Figure. 7F. The first cluster (C2), was found over contralateral sensorimotor regions, and the main effect of prime (F(1,23) = 17.30, p < .001, = .43) was due to ERD in Go primed trials being stronger than in NoGo primed trials. The second cluster (C3) was found over ipsilateral sensorimotor area, where the main effect of prime (F(1,23) = 17.08, p < .001, = .43) was the result of a stronger ERD in Go primed compared to NoGo primed trials. No significant interactions were found between reward and prime in any of the electrode clusters selected for further analysis. Bar charts of ERD values across conditions in these two clusters can be seen in Figure 7G.

To test the relationship between ERD changes in the beta band and RT changes, difference variables were created by subtracting Go primed from NoGo primed ERD and RTs, as well as by subtracting mean ERD and RTs in the +10p and -10p conditions from those in the 0p condition.

Two significant correlations were found between RTs and ERD difference variables in the right-central cluster of electrodes (C1). First, a significant negative correlation was found (r = -.41, p = .046) between the prime difference variables (NoGo primed trials subtracted from Go primed trials; see Figure. 7H) calculated between individual RTs and ERD values. The correlation indicates that participants who showed faster RTs in Go- compared to NoGo-primed trials also showed stronger ERD in Go compared to NoGo-primed trials. Second, a significant negative correlation (r = -.65, p = .001) was found between the RT and ERD difference variables calculated between the +10/-10 p conditions and the 0p condition (+10/-10 p subtracted from 0 p) (Figure 7I-H) in this cluster. The second correlation shows that participants who displayed shortening of RTs to positive/negative incentives compared to no incentive conditions also showed stronger ERD in gain/loss trials compared to no incentive trials.

Two statistically significant negative correlations were also found in the left-central cluster of electrodes (C2). One correlation was found between the difference variables calculated between the Go and NoGo primed conditions for RTs and ERD changes (r = -.59, p = .002; see Figure 7J), showing that participants who displayed faster RTs in Go-primed compared to NoGo-primed conditions also showed stronger ERD in Go-primed relative to NoGo-primed trials. The other correlation was found between the difference variables calculated between the +10/- 10 p conditions and the 0 p condition (+10/-10 p subtracted from 0 p) (r = -.53, p = .003; see Figure 7J). This correlation indicates that participants who responded more quickly to the Go cue in positive/negative relative to no incentive conditions also showed stronger beta-band ERD in these conditions compared to during no incentive trials.

**3.6 | Interaction between frequency and reward/motor-prime**

To analyse if alpha and beta bands were differently involved in effects of reward, prime or their interaction, three-way ANOVAs involving factors of frequency bands (alpha vs. beta), reward (+10p, 0p, -10p) and motor cue (Go vs. NoGo) were carried out in clusters of electrodes showing statistically significant effects of reward or primes in both frequency bands. These analyses revealed that an electrode located in ipsilateral central region of the scalp overlying the sensorimotor cortex (electrode 83, Figures 8A- B) manifested a statistically significant interaction between frequency bands and Go/NoGo primes (F(1,23)= 10.451, p = .004, = .312); this interaction was caused by a significantly larger ERD in NoGo than Go trials in the alpha band (p = .002) but not in beta band (p > .05).

Another electrode, also located in ipsilateral central region of the scalp (electrode 103, Figure 8 C and D), showed a statistically significant interaction between frequency bands and reward (F(2,46) = 4.54, p = .016, = .165). This interaction was related to the presence of a statistically significant effect of reward in the alpha band (F(2,46) = 3.80, p = .032, = .142) but not in the beta-band (P > 0.05).

**4 | DISCUSSION**

It was hypothesised that losses would be associated with the weakest alpha- and beta-band ERD prior to a speeded RT response when expecting a low probability of movement (NoGo cued), and that gains would be associated with the strongest ERD when expecting a high probability of movement (Go cued). While the results confirmed the presence of a stronger alpha-band ERD in frontal and posterior-parietal scalp regions in gain compared to loss trials and in Go-cued compared to NoGo-cued trials, the effect of incentives and motor sets did not significantly interact. Further, although sensorimotor beta-band ERD was weaker in NoGo-primed conditions and no incentive trials, no difference was found between gain and loss conditions. The SV of effort, evaluated using a COGED method, was larger in loss than gain conditions but did not significantly correlate with ERD changes.

RTs were shorter in gain compared to loss trials, and alpha-band ERD was stronger over fronto- and posterior-parietal regions of the scalp in gain trials compared to loss and no incentive trials. In contrast, beta-band ERD over bilateral sensorimotor areas was sensitive to the presence of an incentive, but no difference was found between gain and loss conditions. Amplitude changes in cortical oscillations have previously been linked to value-based decision-making (Balconi, Finocchiaro, & Canavesio, 2014; Balconi & Mazza, 2009), and alpha oscillations have been shown to be subject to reward-learning in biofeedback paradigms (Byun & Hitchcock, 2012; Chatterjee, Aggarwal, Ramos, Acharya, & Thakor, 2007; Othmer, Othmer, & Kaiser, 1999; Sakamak, Tavakoli, Wiebe, & Adams, 2020). However, the beta-band ERD explored here likely refers to the state of motor preparation in the sensorimotor cortex (Kilner, Friston, & Frith, 2007; Miall, 2003; Palmer, Zapparoli, & Kilner, 2016; Filipović et al., 2001; Alegre et al., 2004; Liebrand et al., 2017 *Liebrand et al., 2017*), while fronto- and posterior-parietal alpha-band ERD may reflect the anticipatory attention in the fronto-parietal network required to quickly detect the upcoming target stimulus (Corbetta, Patel, & Shulman, 2008; Coull, Walsh, Frith, & Nobre, 2003; Kastner & Ungerleider, 2000; Serences & Yantis, 2006; Capotosto, Babiloni, Romani, & Corbetta 2009). Further, the patterns of NoGo stopping rates and Go-success rates across incentive conditions match the behavioural approach/avoidance effects of gains and losses on Go and NoGo behaviour found previously (Guitart-Masip et al., 2011; Guitart-Masip et al., 2012; Richter et al., 2014; Hoofs, Böhler, & Krebs, 2019), although the improved Go-success rates in no incentive conditions suggests that gain and loss incentive cues may have distracted the participants from the primary task goals.

The patterns of ERD and RTs shown in response to gains and losses are consistent with our previous results comparing cortical oscillatory changes with reward (Byrne et al., submitted), although a previously unobserved preference for gains was revealed for RTs and alpha-band ERD. However, our previous research used a simple RT task, while in the present experiment participants were required to correctly identify a probabilistic Go/NoGo cue. Changes in anticipatory attention in loss compared to gain conditions as indicated by alpha band ERD may not have affected RTs found previously as no stimulus detection was required, meaning the attentional biases associated with gains and losses may be more pronounced in tasks requiring stimulus detection. The present results therefore suggest that anticipatory attention increased preferentially in response to gains over losses, aiding fast stimulus detection, while the motor preparation primarily employed in simple RT tasks increased with incentives, but was insensitive to their valence. The significant correlations between RT and beta-band ERD differences found across incentive and no incentive conditions support the idea that motor preparation drove the speeding of RTs under the presence of incentive but was insensitive to its valence. The results shown presently expand on the divergent effect of losses and gains on effortful performance (Carsten, Hoofs, Boehler, & Krebs, 2018; Fontanesi, Palminteri, & Lebreton, 2019; Paschke et al., 2015; Potts, 2011). The present results showed that gains contributed to overall faster RTs through increased attentional engagement, while motor preparation contributed to faster responses motivated by the presence of an incentive, but did not account for differences found between gain and loss conditions.

While the patterns of the effects of reward and primes were similar in alpha- and beta-bands across the clusters of electrodes, the electrodes overlying the ipsilateral sensorimotor cortical area manifested stronger effects of reward and prime in the alpha- than beta-band. This finding may be related to an overall larger amplitude of band-power changes in the alpha- than beta band in ipsilateral sensorimotor cortex seen during voluntary movements (Niedermeyer, 2005; Pfurtscheller, Stancak, & Edlinger, 1997; Stancak & Pfurtscheller, 1996; Cuevas, Cannon, Yoo, & Fox, 2014; Fox et al., 2016).

Approach/avoidance motor sets were found to modulate similar patterns of ERD to monetary incentives. Alpha-band ERD over fronto- and posterior-parietal areas and beta-band ERD over sensorimotor areas were stronger when participants expected an approach (75% Go-cued trials) compared to an inhibitive response (75% NoGo-cued trials). Previous research investigating ERD changes during movement execution and inhibition has showed no difference in alpha-band ERD (Filipović, Jahanshahi, & Rothwell, 2001; Alegre et al., 2004), but a stronger beta-band ERD during the execution of Go compared to NoGo responses (Alegre et al., 2004). Expanding on these results, Liebrand, Pein, Tzvi, and Krämer (2017) showed significantly weaker anticipatory posterior alpha-band ERD, but stronger sensorimotor beta-band ERD, when participants expected the occurrence of a Go cue seconds later, compared to trials with equiprobable subsequent Go and NoGo cues. While the present findings of stronger alpha-band ERD during Go-primed trials seem at odds with those found by Liebrand, Pein, Tzvi, and Krämer (2017), these differences can be reconciled by considering cue probability. Liebrand, Pein, Tzvi, and Krämer (2017) compared Go cues occurring with a 100% probability to equiprobable Go/NoGo trials, while the present study used Go/NoGo-primed conditions with equal probabilities of .75 of the occurrences of a subsequent Go/NoGo cue. The differences in Go/NoGo cue probabilities in Liebrand et al. (2017) and the present study may explain the differing results found rather than these being the result of Go/NoGo cue expectations. The 100% Go condition used by the researchers required no stimulus detection, which may have slowed RTs rather than approach/avoidance tendencies associated with Go/NoGo expectations. Taken with previous findings, the present results suggest that anticipatory alpha-band ERD is sensitive to attention or overall task engagement, while beta-band ERD is reflective of preparatory approach motor responses. The significant correlations found presently between differences in RTs and beta-band ERD across participants supports the hypothesis that sensorimotor beta-band ERD accounts for motor-approach behaviours, while alpha-band ERD reflects attention or task-engagement.

It has been posited that losses are associated with avoidance responses and gains with approach responses, and that the loss-avoidance response is stronger than the gain-approach response (Elliot, 2006; Phaf, Mohr, Rotteveel, & Wicherts, 2014; Solarz, 1960). It would therefore be expected that approach/avoidance motor sets would interact with losses and gains during effortful engagement; where losses sharpen the inhibitive effect of avoidance motor sets, while gains sharpen the activating effects of approach motor sets. However, while we found overlapping patterns of activation between incentive and approach/avoidance motor sets, no significant interactions were found between these variables. Early studies investigating the interaction between incentive valence and approach/avoidance behavioural tendencies found that gains and losses enhance Go/NoGo performance in trials compatible to the valence of the offered incentive (i.e., Go-gain/NoGo-loss) (Guitart-Masip et al., 2011; Guitart-Masip et al., 2012; Richter et al., 2014; Hoofs, Böhler, & Krebs, 2019). A key methodological difference between previous studies investigating the interaction between approach/avoidance tendencies and incentive valence is whether the valence cue was presented seconds before the Go/NoGo target stimulus (Guitart-Masip et al., 2011; Guitart-Masip et al., 2012; Richter et al., 2014; Schevernels et al., 2016) or concurrent with the Go/NoGo stimulus (Boehler et al., 2012; Freeman et al., 2014), with the latter finding significant interactions between incentive valence and approach/avoidance tendencies. Task designs presenting incentive and target stimuli concurrently thereby tap into reactive control mechanisms, while those presenting incentive stimuli prior to the target stimulus tap into proactive control mechanisms (Krebs & Woldorff, 2017). Our data falls in line with the studies failing to show clear evidence of such incentive/action interactions (Boehler et al., 2012; Verbruggen & McLaren, 2018; Schevernels et al., 2016), suggesting that incentive valence modulates immediate approach/avoidance responses in reactive control mechanisms, but attentional biases associated with incentive valence modulate sustained proactive control mechanisms.

An important methodological difference which may partially account for the inconsistent interactions between approach/avoidance tendencies and incentive valence is whether the incentive is presented concurrent with the cue or the target stimulus. A more pronounced interaction between incentive valence and approach/avoidance responses occurs when target stimuli (Go/NoGo cues) are directly associated with incentives compared to when incentives are presented seconds before (Hoofs, Böhler, & Krebs, 2019). The placement of incentive valence concurrent with target or cue stimuli may therefore trigger different control mechanisms. The cued-incentive trials used trigger proactive control mechanisms (Braver, 2012; Krebs & Woldorff, 2017), while incentives presented concurrently with target stimuli trigger immediate control mechanisms, which are highly sensitive to approach/avoidance tendencies (Bargh et al., 1996; Chen & Bargh, 1999; Kozlik et al., 2015). The ERD modulations found in response to positive/negative incentives likely reflect changes in proactive control, which are sensitive to attentional biases made with losses and gains, whereas the reactive control associated directly with incentive presentation is likely to be more reactive to approach/avoidance associations.

Finally, while a sustained increase in power in the theta frequency range was found over frontal midline areas of the scalp throughout the Go/NoGo task, theta-band power did not significantly change across reward or task conditions. Frontal-midline theta-band power enhancements have repeatedly been associated with broad working memory and cognitive control processes, (Gevins et al., 1997; Jensen & Tesche, 2002; Klimesch et al., 2005; Onton et al., 2005). Synchronisation in the theta band is hypothesised to reflect sustained effortful engagement in the face of growing mental fatigue (Umemoto et al., 2019), suggesting that the incentive and task cues used presently caused phasic rather than sustained modulations in effortful engagement and task-relevant cortical activation.

During the discounting task, participants were more willing to engage in higher effort options when incentivised with losses compared to gains. However, individual SVs of effort did not significantly correlate with either the speeding of RTs or increases in anticipatory ERD under gain and loss conditions; similar findings were also shown in our previous experiments (Byrne et al., 2020; Byrne et al., submitted). The discounting task results show the increased SV often associated with monetary losses (Baumeister, Bratslavsky, Finkenauer, & Vohs, 2001; Krebs & Woldorff, 2017; Rozin & Royzman, 2001; Wright & Rakow, 2017). These results also suggest that the valuation of losses and gains regarding participants’ willingness to engage in effortful behaviour does not directly inform the implementation of effortful resources during ongoing effortful engagement, or that the willingness to engage in effortful task employs different valuation processes to those employed by incentive during ongoing effortful engagement.

A probable cause of these divergent results is that the discounting task required participants to choose between two discrete options, while the Go/NoGo task required participants to make the continuous decision to deploy effortful resources over a period of seconds. The discounting and Go/NoGo tasks may therefore recruit different decision-making processes or may be affected by different confounding variables. For example, the decisions made during the discounting task may be confounded by the salience of the incentives offered (Yechiam & Hochman, 2013), while ongoing effortful engagement may be confounded by attentional or approach/avoidance associations made with gains and losses (Buzzell, Beatty, Paquette, Roberts, & McDonald, 2017; Hoofs, Carsten, Boehler, & Krebs, 2019; Houtman & Notebaert, 2013; Pratto & John, 1991; Yechiam & Hochman, 2013).

Previous studies have shown that perceived effort is significantly associated with the electrophysiological movement-related cortical potential (MRCP) preceding effortful movement (Slobounov et al., 2004; de Morree et al., 2012; Lampropoulou & Nowicky, 2012). The MRCP has been localised to sensorimotor areas (Deecke & Kornhuber, 2003; Ikeda & Shibasaki, 2003; Hiroshi Shibasaki & Mark Hallett, 2006; Toma et al., 2002), and is considered to be a direct indicator of central motor command in active muscle groups (Bötzel et al., 1997). Taken with previous findings, the present results suggest that while participants are able to accurately monitor effortful engagement, the SV of effort does not directly inform effortful engagement, meaning the lack of associations found may not result from an inability of the participants to accurately monitor effortful engagement.

In conclusion, gains/losses and approach/avoidance motor sets act independently during the preparation of a Go/NoGo motor response. Further, neural activation reflecting anticipatory attention is stronger when participants are incentivised with a gain compared to a loss, while activation reflecting motor-approach behaviours increases symmetrically when participants are incentivised with losses and gains. Gains, therefore, likely motivate increased effortful performance relative to losses during proactive control by modulating increased attentional engagement during proactive control rather than motor preparation, and this effect acts independent of approach/avoidance motor tendencies. Finally, the value of effort is not significantly associated with behavioural or cortical oscillatory changes during effortful behaviour. Thus, willingness to engage in effortful tasks may not directly contribute to ongoing effortful engagement under reward or instantaneous states of motor readiness preceding movement.

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