Curiosity as an amplifier of reward-related feedback processing

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Abstract

Successful learning depends on various factors such as depth of processing, motivation, or curiosity about information. A strong drive to learn something or the expectation of receiving a reward can be crucial to enhance learning. However, the influence of curiosity on the processing of information-related feedback and its similarity with reward processing is not well understood. This study examined whether states of curiosity influence specific event-related-potentials (ERPs) associated with reward processing and whether these ERPs are related with later memory benefits. In an initial screening phase, participants indicated their curiosity and confidence about answers to various trivia questions. In a subsequent study phase, we targeted different time windows related to feedback processing during the presentation of trivia answers containing the Reward-Positivity (RewP; 250 - 350 ms), the P3 (250 - 500 ms), and the Late-Positive-Potential (LPP; 600 - 1000 ms). In a delayed surprise memory test, we found that participants recalled more high- than low-curiosity answers. The RewP, P3 and LPP showed greater positive mean amplitudes for high compared to low curiosity, reflecting increased feedback processing. In addition, we found that the RewP and the P3 showed more positive mean amplitudes for later recalled compared to later forgotten answers, but curiosity did not modulate this encoding-related finding. These findings support the view that curiosity can act as an amplifier of reward-related feedback processing and opens the investigation of further curiosity-related ERP studies.

Keywords: curiosity, event-related potentials, feedback processing, memory, reward

Introduction

Why did you start reading this paper? Maybe because you stumbled across it by accident, maybe because you have to, or because you are curious about its content. The state of curiosity is an intrinsic motivation that drives us to collect new information, and curiosity has been shown to enhance memory formation (Gruber & Ranganath, 2019; Kidd & Hayden, 2015; Galli et al., 2018; Loewenstein, 1994). For example, if someone asks you ”What is the longest river in the European Union?“, you might be curious and try to come up with the correct answer. In the last decade, initial research on curiosity has targeted the neural underpinnings of the *elicitation* of curiosity (Poh et al., 2022; Lau et al., 2020; Oosterwijk et al., 2020; Ligneul et al., 2018; Gruber et al., 2014; Kang et al., 2009), but the literature still lacks findings as to what specific processes take place during the *satisfaction* of curiosity (e.g., when you receive the answer "Danube").

Most concepts about curiosity have in common that the awareness of a knowledge gap leads to increased exploration for new information (Metcalfe et al., 2020; Gruber & Ranganath, 2019; Loewenstein, 1994; Berlyne, 1954). New information satisfies curiosity, reduces uncertainty, can improve predictions in the future, and can be described as an unconditioned reward stimulus (Kang et al., 2009). Therefore, curiosity reflects an intrinsically anticipated expectation of reward that intensifies the processing of upcoming information (Gruber & Ranganath, 2019; Marvin & Shohamy, 2016; Kidd & Hayden, 2015; Lowenstein, 1994). Investigating ERPs during the satisfaction of curiosity may possibly explain how curiosity influences the processing of feedback, what similarities regarding reward processing exist, and how curiosity satisfaction modulates memory formation.

There is evidence showing that the neural correlates of curiosity resemble those of reward anticipation (Oosterwijk et al. 2020; Lau et al. 2020; Gruber et al., 2014) and reward feedback processing (Ligneul et al., 2018; Jepma et al., 2012). For example, examining curiosity with ambiguous visual images, Jepma et al. (2012) showed that the resolution of the images was associated with increased activity of the striatum, which has been related to reward processing. However, it must be mentioned that is not clear whether reward and curiosity are really the same processes. For instance, investigating effects of intrinsic and extrinsic motivation on memory formation, Duan et al. (2020) found that curiosity-driven memory formation was associated with the ventral striatal reward network and the fronto-parietal attention system, whereas extrinsic-driven memory effects were correlated with deactivation in parietal midline regions. Consistent with the previous fMRI studies suggesting that curiosity anticipation is a form of reward anticipation we predicted that reward-related ERPs should also be modulated by states of curiosity.

As described above, the answer to a question can be seen as an unconditioned reward stimulus and the best-studied ERP components related to early reward processing are the Feedback-Related-Negativity (FRN) and the Reward Positivity (RewP; 250 ms – 350 ms; Proudfit et al., 2015). While the FRN is associated with the processing of gains and losses as well as reward prediction errors (Höltje & Mecklinger, 2020; Peterburs et al., 2016; Cohen & Ranganath, 2007), the RewP is assumed to reflect a better outcome than expected, an increase in dopaminergic signals, and reward processing at fronto-central sites (Glazer et al., 2018; Heydari & Holroyd, 2016; Proudfit et al., 2015; Sambrook & Goslin, 2015). In addition, the RewP seems to be correlated with neural activity in reward-mediating regions such as the ventral striatum, anterior cingulate cortex, and medial prefrontal cortex (Becker et al., 2014). We hypothesized that when curiosity is high, informational feedback should be perceived as more relevant, reflecting a greater reward, and should therefore result in a larger mean amplitude of the RewP.

After early reward processing reflected by the RewP, the P3 (P300/FB-P3; further: P3; 250 ms – 500 ms; Polich, 2007) could be also manipulated due to high and low curiosity levels. The P3 is usually found at central and parietal electrodes and assumed to reflect the allocation of neural resources based on reward effects, stimulus relevance, as well as context updating in working memory (Van Petten & Luka, 2012; San Martin, 2012; Polich, 2007). In addition, it displays attention-driven categorization and increased processing of feedback due to motivational salience. The P3 amplitude is larger if feedback is infrequent or the reward is greater than expected (Hajcak et al., 2006). For high curiosity, it is assumed that there should be a greater mean amplitude of the P3 during feedback presentation because of higher motivational relevance for the updating of the stimulus context, attention orientation, and a subjective greater reward than for low curiosity (Donaldson et al., 2016; Polich, 2007; Courchesne et al., 1975)

The Late-Positive-Potential (LPP; 600 ms – 1000 ms; Glazer et al., 2018) is a centro-parietal positive-going ERP component that has been associated with the processing of emotional stimuli as well as extended cognitive and attentional processing based on reward expectancy and magnitude (Hajcak & Foti, 2020; Glazer et al., 2018; Meadows et al., 2016; Gable et al., 2015; Weinberg et al., 2013; Schupp et al., 2000). Furthermore, the LPP appears to be manipulated by the significance of a stimulus, which is determined by the activation of motivational appetitive systems (Bradley, 2009). Based on these findings, we expect the mean amplitude of the LPP to be more positive for high than for low curiosity answers.

To generate states of high and low curiosity, we used the so-called trivia paradigm and adopted an identical experimental design as in a previous functional magnetic resonance imaging (fMRI) study from our lab (Gruber et al., 2014). In an initial screening phase, participants were presented with general knowledge questions, and were asked to indicate their curiosity and confidence about the potential answer. In the following study phase, participants were presented with a selected set of trivia questions from the screening phase and eleven seconds later with the associated answers. ERPs were computed time-locked to the onset of the answers. After a five-minute break, participants were asked to recall the answers in a surprise memory test.

Based on previous findings (e.g., Poh et al., 2022; Wade & Kidd, 2019; Marvin & Shohamy, 2016; Gruber et al, 2014; Kang et al., 2009), we predicted memory performance to be better for answers associated with high compared to low curiosity. Furthermore, we expected that feedback-related activity should differentiate between remembered and forgotten answers. To address this question, we used the memory test results to investigate subsequent memory effects (SMEs), for which ERPs recorded during the presentation of answers are sorted according to whether the answers are later remembered or forgotten (Höltje & Mecklinger, 2018; Cohen et al., 2015; Paller & Wagner, 2002). In general, subsequently remembered items should show a more positive ERP amplitude during encoding than those that have been forgotten (Kamp et al., 2017; Paller & Wagner, 2002; see Friedman & Johnson, 2000 or Fabiani & Donchin, 1995 for review). Accordingly, we predicted larger subsequent memory effects for answers processed in the state of high compared to low curiosity.

Materials & Methods

Participants

Thirty healthy young adults (13 female, 17 male, age range = 18-30 years, *M* = 21.03 years) participated in the experiment (sample size based on Gruber et al., 2014). One participant was left-handed and twenty-nine right-handed. All participants had normal or corrected-to-normal vision and were English native speakers. Eight participants had to be excluded due to either poor memory performance (in at least one condition fewer than eight memorized answers) or incomplete EEG or memory data. All participants were students at University California (UC) Davis and received money or course credits for their attendance. The UC Davis Institutional Review ethics committee approved the experiment.

Material

The questions and their matching answers for the screening and study phase were randomly drawn from a pool of 381 items (Murphy et al., 2021a), which in turn were acquired from online resources about general knowledge questions. In addition, care was taken to select from as many different subject areas as possible (i.e., sports, food, science, nature, TV/movies, music, history etc.). The stimuli were always presented centred in black on a grey background.

Procedure

The experiment was programmed with the Cogent 2000 Toolbox (Wellcome Laboratory of Neurobiology, University College London) and carried out in the Center for Neuroscience at UC Davis. The experiment is a version of the trivia paradigm (cf., Kang et al., 2009) and was divided into a screening, study, and test phase (for an almost identical task procedure see: Gruber et al., 2014; for an overview of the procedure, see Figure 1).

In the screening phase, randomly chosen questions were presented for six seconds and evaluated by participants according to their knowledge confidence and perceived level of curiosity. This intra-individual rating of the questions was necessary because curiosity levels for each trivia question and its respective answer differ between individuals. First, participants were asked to indicate how confident they were that they knew the answer to the trivia question (1-6; 1 = ‘‘I am confident that I do not know the answer’’ and 6 = ‘‘I am confident that I know the answer’’). As a second judgment, participants indicated their level of curiosity about the answer (1-6; 1 = ‘‘I am not interested at all in the answer’’ and 6 = ‘‘I am very much interested in the answer’’). Questions were presented until 56 items could be attributed to high (curiosity rating 4-6) and 56 to low curiosity (curiosity rating 1-3). However, if the participants had given a “6” for the confidence rating, the question was not included because it was assumed that participants already knew the answer. While participants were completing the screening phase, experimenters were attaching the EEG cap to the participant and were preparing all electrodes in order to record the EEG. The screening phase was followed by a short rest period (approx. 5 min) during which participants looked at a fixation cross.

In the study phase, 112 previously selected questions were presented again (3s) and after an anticipation period (11s), that is, the time between question presentation offset until answer presentation onset, the matching answers were displayed (1s). Six trials in each condition (~ 10%) were catch trials, during which a sequence of letters "xxxxx" were shown as answer, in order to keep participants' attention high. During the anticipation period a crosshair was presented before and after an emotionally neutral face (2s). Participants had to respond with "YES"

or "NO" as to whether this particular person would be knowledgeable about the trivia topic and could assist in answering the question. Behavioural and neural data related to face images were not investigated.

After a further five-minute rest period, during which participants looked at a fixation cross, a surprise memory test was carried out in the test phase. Participants were given a randomized list with all trivia questions from the study phase. They were encouraged to type in as many answers as possible within twenty minutes without guessing the answers. Participants also took part in a recognition memory test for all previously encoded face images, which are not part of this investigation. Each participant took part in each phase once and received the money or course credits after the test phase.

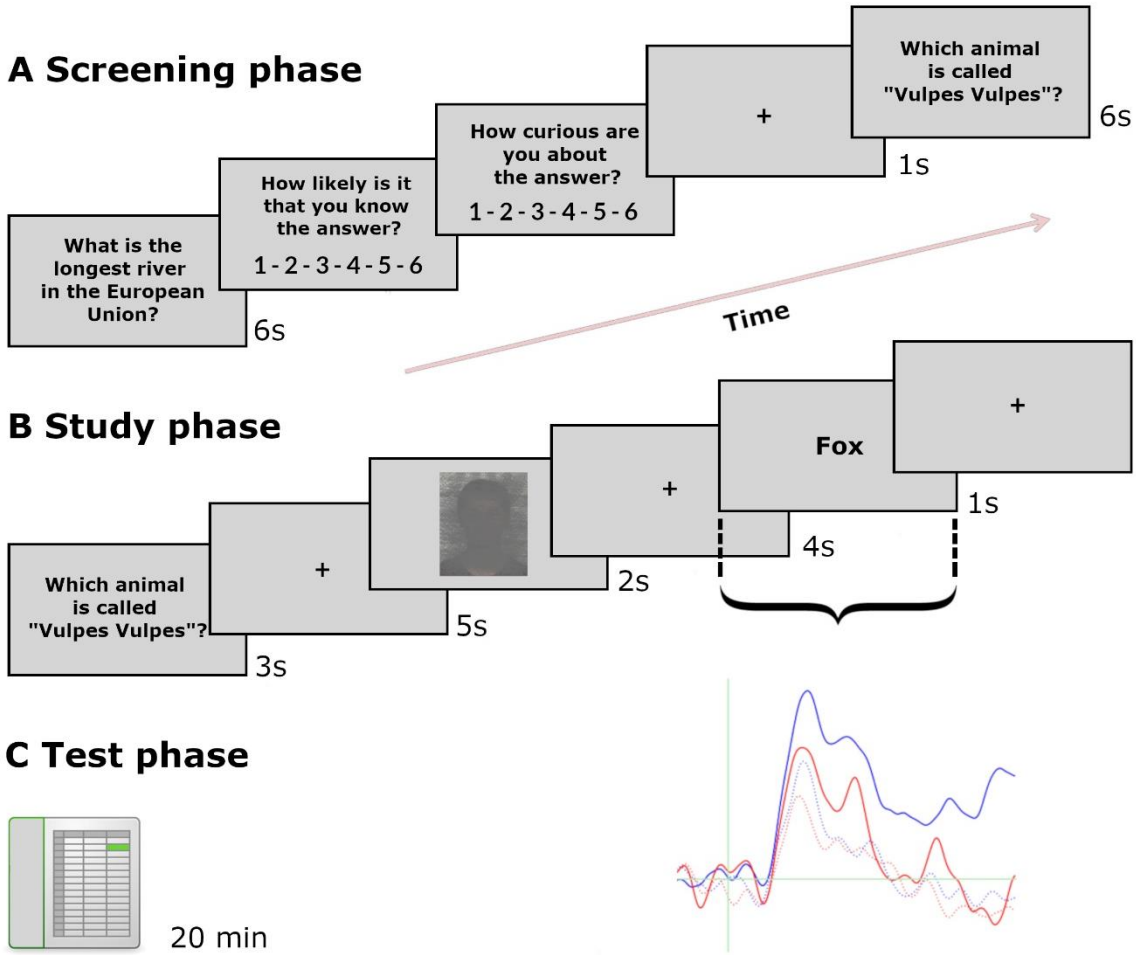

Figure 1. Experimental Procedure. (A) In the screening phase, trivia questions were presented and evaluated by participants according to their knowledge confidence and perceived level of curiosity without reading the corresponding answers. (B) In the following study phase, participants are presented with a subset of these questions again and eleven seconds later with their corresponding answers. Between questions and answers, faces were presented, which were not investigated in the present study. (C) At last, participants were asked to recall all answers in a surprise memory test. The EEG was recorded during the study phase and ERPs were computed time-looked to the onset of the answer.

EEG recording and processing

During the study phase, the EEG was recorded with the ActiveTwo EEG recording system (Biosemi, Neurospec) at 1024 Hz from 64 Ag/AgCl scalp electrodes, which were arranged according to an extended version of the international 10-20 electrode system (Jasper, 1958). The electrodes were offline re-referenced to the averaged mastoid electrodes. The vertical and horizontal electrooculogram was recorded from four electrodes placed above and below the left eye and at the canthi of the left and right eye.

The analysis of the EEG data was performed using MATLAB (MathWorks, Inc.) and the toolboxes EEGLAB (Delorme & Makeig, 2004) and ERPLAB (Lopez-Calderon & Luck, 2014). Electrodes were referenced to the average of the left and right mastoid electrodes. EEG data were down sampled to 500 Hz and bandpass filtered at 0.1-40 Hz using a second order Butterworth filter. The epochs started at -200 ms before stimulus presentation and ended at 1000 ms thereafter. In addition, data segments outside of the area of interest were discarded and an independent component analysis (ICA) was applied to correct for artifacts. Segments, which were still associated with ocular and noise artifacts, were rejected manually for each participant. Additionally, segments containing artifacts were removed based on the following criteria: The maximum voltage threshold was set between -150 µV and +150 µV, the maximal permissible difference of values at 150 µV during intervals of 200 ms, and the maximum allowed voltage difference between two time points was 30 µV. To exclude data with no signal, trials which did not exceed the limits -0.7 µV and +0.7 µV within a period of 200 ms were discarded. On average, 83.93% of trials were retained (M = 94, trial range = 40-110, high curiosity = 46.89, low curiosity = 47.11) and 16.07% rejected (M = 18, range = 2-72, high curiosity = 9.11, low curiosity = 8.89). These cleaned and pre-filtered data were pruned and merged using binary files (BINs; files containing group specifications) based on curiosity level and memory performance.

The RewP is typically measured at fronto-central sites and thus activity at electrodes FC1, FCz, and FC2 in the time range of 250 ms – 350 ms was investigated (Proudfit et al., 2015). The P3 is usually found at central and parietal electrodes, which is why activity at electrodes Cz, CPz, and Pz between 250 - 500 ms was analysed (Polich, 2007). The LPP is most pronounced at centro-parietal electrodes and hence activity at electrodes CP1, CPz, and CP2 in the time range of 600 - 1000 ms after stimulus onset was explored (Glazer et al., 2018; Gable et al., 2015). The time window of the LPP can also be broader, but our time window was limited to 1000 ms.

Statistical analyses

The statistical analyses were performed using the R Studio program (R Core Team, 2019). The significance level was set to $\alpha = .05$ and follow-up t-tests were one-tailed based on specific hypotheses. Behavioural and electrophysiological measures were analysed using repeated-measures ANOVAs and dependent t-tests. As measures of effect sizes, partial eta squared (η_p^2) is reported for ANOVA and Cohen's d (Rasch et al., 2021; Cohen, 1988) was calculated for dependent t-tests. In addition, the assumption of normal distribution was checked using the Shapiro-Wilk-Test and fulfilled for all calculations (Hanusz et al., 2016).

Results

Behavioural results

Analysis of memory performance showed a significant mean difference between high curiosity (M = 55.5%, SD = 16.2%) and low curiosity answers (M = 38.6%, SD = 16.8%; $t(21) = 7.37$, $p < .001$, $d = 1.57$), which replicates the previously found curiosity-related memory benefit (Kang et al., 2009; Gruber et al, 2014) (see Figure 2). The overall memory performance was M = 45.13% (lowest = 18.00%; highest = 76.00%) and the curiosity benefit was M = 16.82% (high curiosity answers – how curiosity answers).

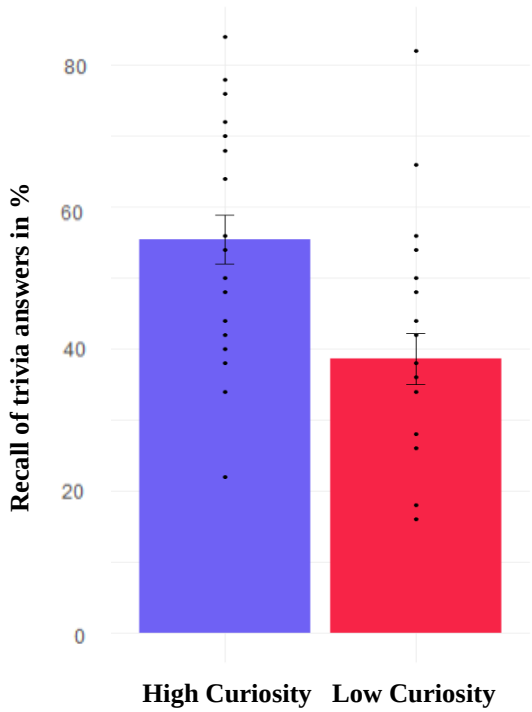

Figure 2. Curiosity-related memory benefit. Better memory performance for trivia answers in the high- compared to the low-curiosity condition. Error bards indicate the standard error of the mean. The points correspond to the performance of individual participants.

Electrophysiological results

Reward Positivity (250 – 350 ms)

To investigate reward-related feedback processing during the presentation of trivia answers, the RewP was analysed in a 2 (curiosity: high, low) × 2 (memory: remembered, forgotten) × 3 (electrodes: FC1, FCz, FC2) ANOVA. This analysis yielded a significant main effect for curiosity, $F(1, 21) = 6.29$ $p = .020$, $\eta_p^2 = .23$, and for memory, $F(1, 21) = 6.43$, $p = .019$, $\eta_p^2 = .23$, but not for electrodes, $F(1.77, 37.13) = 1.56$, $p = .225$, $\eta_p^2 = .07$ (Figure 3). Notably, 2-way interactions between curiosity and memory, curiosity and electrodes, memory and electrodes, as well as the 3-way interaction between curiosity, memory, and electrodes were not significant (all p-values > .229). The RewP amplitude was more positive for high-curiosity (M = 3.26, SD = 3.54) compared to low-curiosity answers (M = 2.07, SD = 3.56; t (21) = 2.508, p = .010, d = 0.54) as well as for remembered answers (M = 3.41 SD = 3.51) compared to forgotten answers (M = 1.91, SD = 3.78; $t(21) = 2.54$, p = .009, d = 0.54). It can be assumed that the greater RewP amplitude for high-curiosity answers indicates increased reward-related processing of the answers in comparison to low curiosity. Furthermore, a greater amplitude of the RewP was predictive for

better memory, but we did not find that increased reward processing benefitted later memory, that is, there was no interaction between curiosity and memory for the RewP.

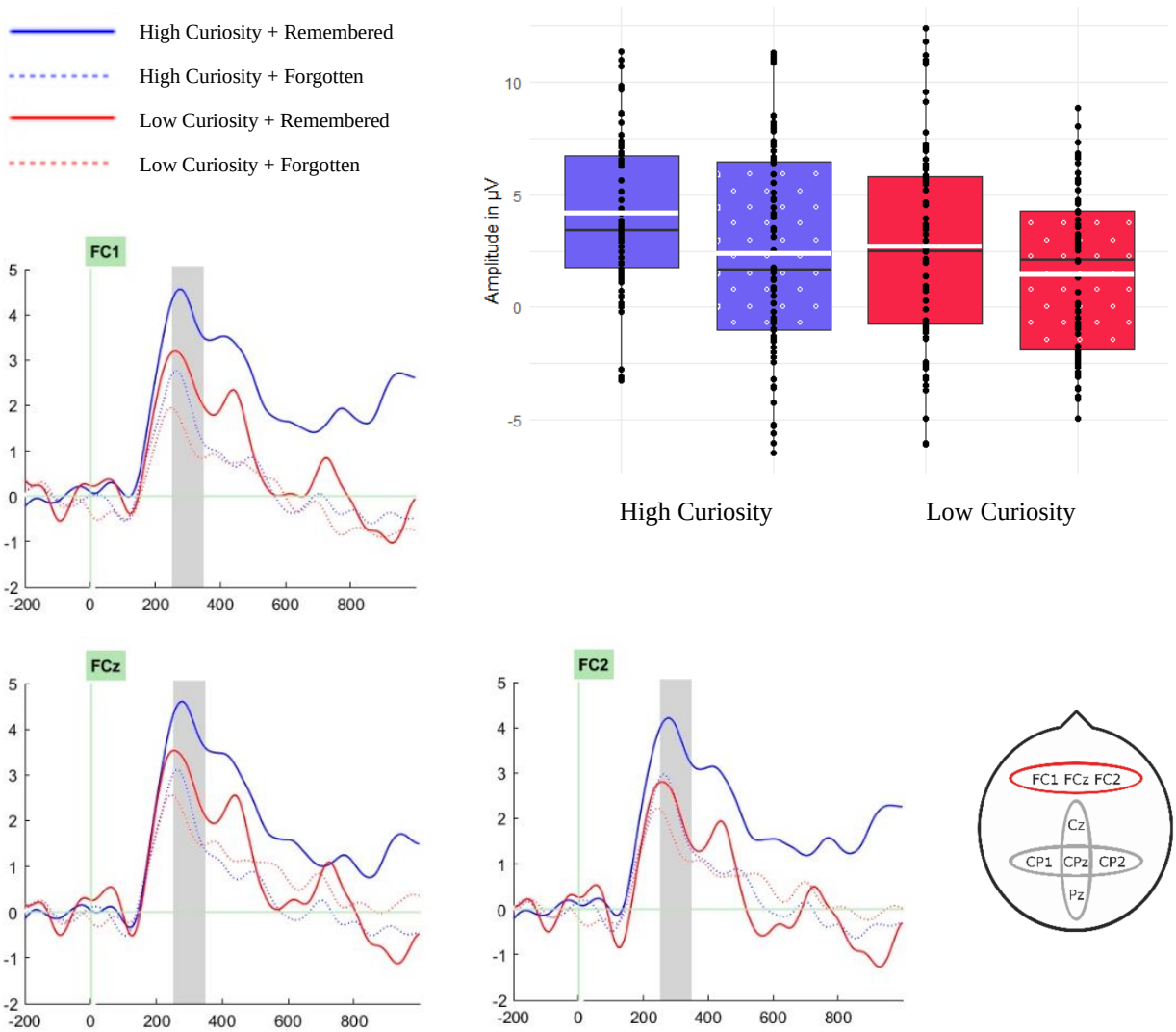

Figure 3: Curiosity and memory independently modulate the Reward Positivity (RewP) component during answer presentation at fronto-central electrode sites. Box plots are bounded by the first and third quartiles and the black line represents the median whereas the white line displays the mean. The points correspond to the measures for individual participants. ERPs were time-locked to the onset of the answers in the study phase at electrode sites FC1, FCz, and FC2 in the grey time window of 250 – 350 ms.

P3 (250 – 500 ms)

For examining the allocation of neural resources based on reward effects, stimulus relevance, and context updating in working memory, the P3 was analysed in a 2 (curiosity: high, low) × 2 (memory: remembered, forgotten) × 3 (electrodes: Cz, CPz, Pz) ANOVA. Similarly to the findings of the RewP, this analysis yielded a significant main effect for curiosity, $F(1, 21) = 4.70$, $p = .042$, $\eta_p^2 = .18$, as well as for memory, $F(1, 21) = 6.70$, $p = .017$, $\eta_p^2 = .24$, but not for electrodes, $F(1.21, 25.38) = 2.41$, $p = .128$, $\eta_p^2 = .10$, and any interactions involving curiosity (all *p*-values > .332, Figure 4). The amplitude was more positive for high-curiosity ($M = 2.83$, $SD = 3.99$) compared to low-curiosity answers ($M = 1.76$, $SD = 3.31$; $t(21) = 2.17$, $p = .021$, $d = 0.46$). However, the interaction between memory and electrodes, $F(1.99, 41.88) = 3.28$, $p = .048$, $\eta_p^2 = .14$ was significant. Follow-up post-hoc *t*-tests

revealed that the memory effect was largest at Cz ($t(21) = 3.30$, $p = .002$, $d = 0.70$) and smaller at CPz ($t(21) = 1.97$, $p = .031$, $d = 0.42$) and Pz ($t(21) = 1.78$, $p = .045$, $d = 0.38$), which could suggest that the memory effect varies depending on the electrode site, but this variability could also be due to electrode selection . Most relevantly, the greater P3 amplitude for high curiosity suggests increased stimulus relevance as well as more pronounced context updating in working memory. In addition, as with the RewP, a greater amplitude of the P3 was predictive for better memory.

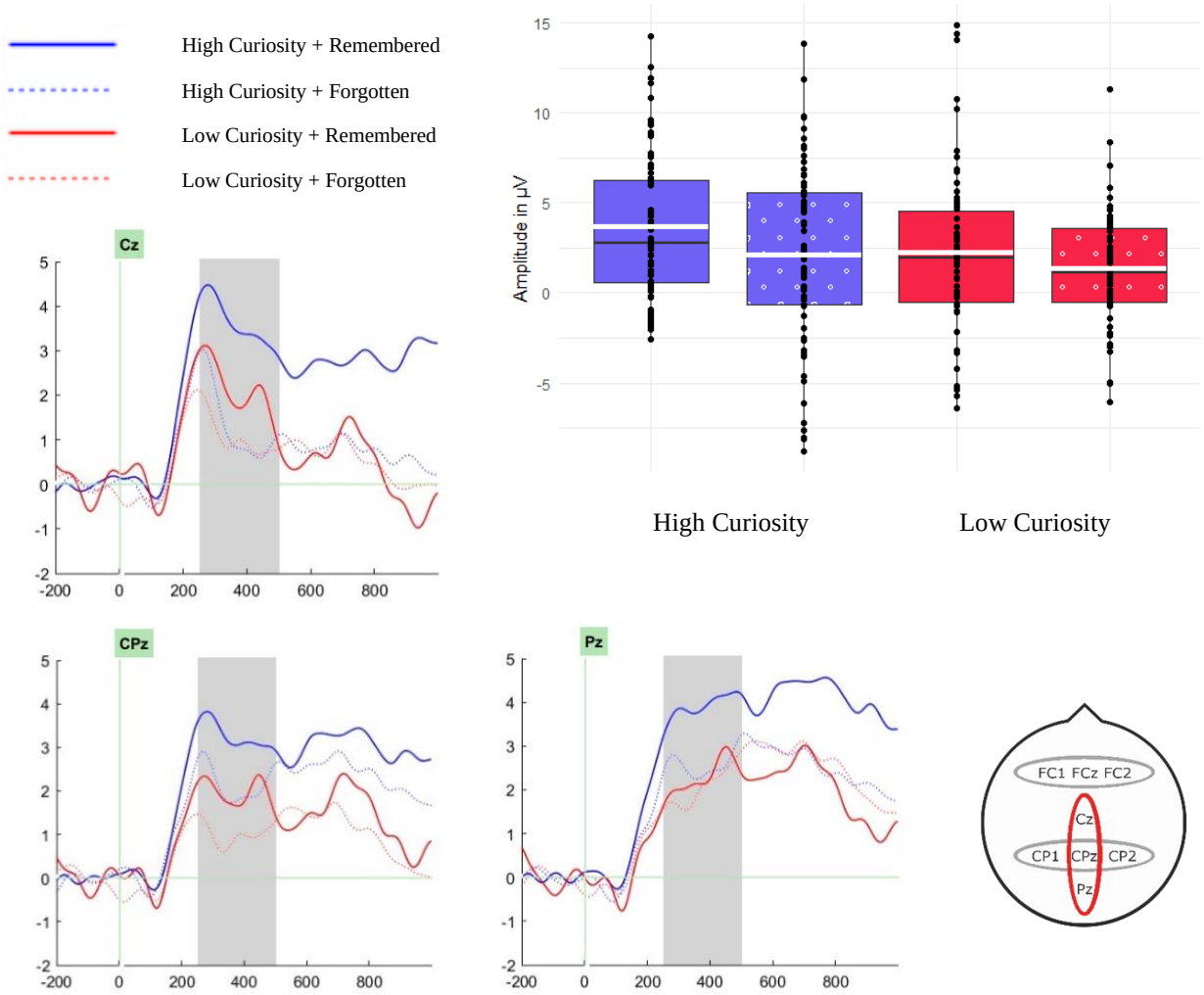

Figure 4. Curiosity and memory independently modulate the P3 component during answer presentation at central and parietal electrode sites. Box plots are bounded by the first and third quartiles and the black line represents the median whereas the white line indicates the mean. The points correspond to the measures for individual participants. ERPs were time-locked to the onset of the answers in the study phase at electrode sites Cz, CPz, and Pz in the grey time window of 250 - 500 ms.

Late-positive-potential (600 – 1000 ms)

The analysis of extended cognitive and attentional processing based on reward expectancy and magnitude was implemented in a 2 (curiosity: high, low) × 2 (memory: remembered, forgotten) × 3 (electrodes: CP1, CPz, CP2) ANOVA on the LPP. This analysis yielded a significant main effect for curiosity, $F(1, 21) = 5.16$, $p = .034$, $\eta_p^2 = .20$, but not for memory, $F(1, 21) = 0.83$, $p = .374$, $\eta_p^2 = .04$, and not for electrodes, $F(1.98, 41.63) = 0.12$, $p = .884$, $\eta_p 2 < .01$ (Figure 5). The amplitude was more positive for high-curiosity ($M = 2.66$, $SD = 5.40$) compared to low-curiosity answers ($M = 1.32$, $SD = 4.61$; $t(21) = 2.27$, $p = .017$, $d = 0.48$). Notably, there were no 2-way interactions between curiosity and memory, curiosity and electrodes, memory and electrodes, and no 3-way

interaction between curiosity, memory, and electrodes (all *p*-values > .118). The greater LPP amplitude for high compared to low-curiosity answers is assumed to indicate extended cognitive and attentional processing based on reward expectancy and magnitude.

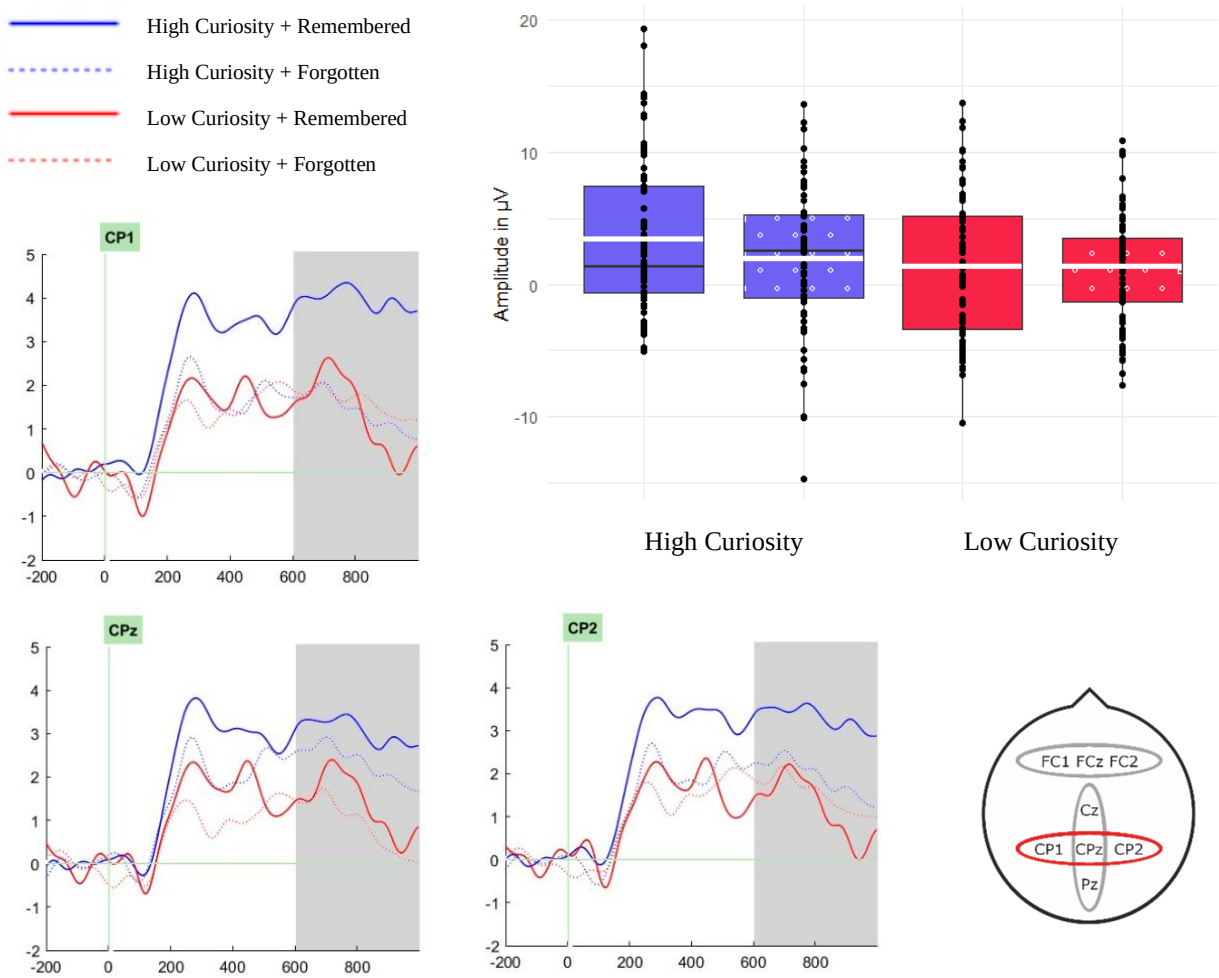

Figure 5. Only curiosity (but not memory) modulates the Late-Positive-Potential (LPP) during answer presentation at centro-parietal electrode sites. Box plots are bounded by the first and third quartiles and the black line represents the median whereas the white line displays the mean. The points correspond to the measures of individual participants. ERPs were time-locked to the onset of the answers in the study phase at electrode sites CP1, CPz, and CP2 in the grey time window of 600 - 1000 ms.

Discussion

The present paper addressed the question of whether states of high curiosity amplify reward-related feedback processing. In particular, we asked whether curiosity influences specific ERP components that are sensitive to feedback and updating processes during the feedback-related satisfaction of curiosity. To answer this question, we choose ERPs associated with reward and feedback processing, namely, the RewP, P3, and LPP. In an initial screening phase of the trivia paradigm, participants were presented with general knowledge questions and were asked to indicate their level of curiosity and confidence of knowledge about the respective answer. In a subsequent study phase the influence of curiosity levels on feedback processing was examined via the RewP, P3, and LPP. At the end of the experiment, there was a surprise memory test about the answers. Behaviourally, we found better memory performance for high-curiosity answers in contrast to low-curiosity answers. In the same study setup,

Gruber et al. (2014) found similarly large differences between high and low curiosity memory performance. In general, the reported memory benefit for high curiosity is in line with the findings of several other studies (Poh et al., 2022; Fandakova & Gruber, 2021; Lau et al., 2020; Galli et al., 2018; Stare et al., 2018; Marvin & Shohamy, 2016; Gruber et al, 2014; Kang et al., 2009). ERP analysis aimed at assessing differences in the online processing of high- compared to low-curiosity answers and processes predictive of successful memory formation. We found that the amplitudes of the RewP, P3, and LPP elicited during trivia answer presentation (i.e., during the satisfaction of curiosity) were more positive in the high- than in the low-curiosity condition. Furthermore, the RewP and P3 (but not the LPP) showed greater positive amplitudes for later remembered compared to later forgotten answers. No interaction between curiosity levels and subsequent memory were found for the three ERP components. These results suggest that curiosity acts like an amplifier for reward-related feedback processing.

Firstly, we assumed that information – here the answer to a trivia question – represents a rewarding stimulus that reduces uncertainty and closes a knowledge gap (Loewenstein, 1994). Several behavioural and neuroimaging studies support the view that states of high curiosity and extrinsically motivated reward depend on similar mechanisms and activate overlapping brain areas (FitzGibbon et al., 2020; Marvin & Shohamy, 2016; Gruber et al., 2014; Kang et al., 2009; Bromberg-Martin & Hikosaka, 2009). Moreover, the RewP is seen as an indicator of reward processing (Höltje & Mecklinger, 2018; Anderson et al., 2017; Heydari & Holroyd, 2016; Sambrook & Goslin, 2015; Baker & Holroyd, 2011; Holroyd et al., 2008) and differences of the RewP amplitude based on curiosity states can be seen as a neurophysiological correlate of reward processing.

Moreover, the Prediction, Appraisal, Curiosity, and Exploration (PACE) framework (Gruber & Ranganath, 2019) suggests that higher expectation of reward and curiosity are accompanied by increased dopaminergic activity, which leads to facilitated hippocampus-based memory formation (Gruber & Ranganath, 2019; Smith et al., 2005; Wittmann et al., 2005; Schultz, 2002; Holroyd & Coles, 2002). Even though the present work does not allow to draw any direct conclusions about dopaminergic circuit activity, the identical experimental paradigm as in our previous fMRI study on curiosity (Gruber et al., 2014) permits to assume an increase in dopaminergic activity. Furthermore, the RewP can be an indication of dopaminergic signals itself (Baker & Holroyd, 2011). The origin of the dopaminergic activity echoed by the RewP has been localized in the basal ganglia and other reward-related brain areas and positive reward seems to be associated with increased medial prefrontal cortex (mPFC) activity (Becker et al., 2014). In addition, van Lieshout et al. (2018) found increased mPFC activity during curiosity satisfaction and Murphy et al. (2021b) investigated functional connectivity between the hippocampus and mPFC during answer presentation, which predicted the curiosity-related memory benefit. In summary, the increased positivity of the RewP in the high-curiosity condition indicates, that the answers were perceived as more rewarding, which in turn seems to have strengthened reward-related processing.

Secondly, larger P3 and LPP amplitudes in the high-curiosity condition may reflect increased allocation of neural resources and attention. A more positive amplitude of the P3 for high- compared to low-curiosity answers suggests that there was an enhanced allocation of neural resources based on reward processes and feedback relevance (San Martin, 2012; Debener et al., 2005; Friedman et al., 2001; Courchesne et al., 1975). The modulation of the LPP also suggests that feedback relevance might have been greater during states of high curiosity due to the activation of appetitive motivational systems through curiosity (Hajcak & Foti, 2020). The increased activity of the dopaminergic system as well as greater allocation of neural resources can lead to more attention to upcoming expected rewards (Anderson et al., 2016; Hickey et al., 2010). First evidence for this was provided by fMRI studies that showed increased activity at high curiosity in frontal and parietal brain areas associated with attentional and

cognitive control (Lieshout et al., 2018; Jepma et al., 2012). The greater positivity in the high-curiosity condition of the P3 (Van Petten & Luka, 2012; San Martin, 2012) and the LPP (Weinberg et al., 2013; Schupp et al., 2000) can also be regarded as a marker of an increase in attention allocation, based on reward processes and feedback relevance.

Thirdly, the more positive amplitudes for answers of high curiosity could also be interpreted with the Tip-of-the-Tongue (TOT) phenomenon. It is defined as the concurrent feeling of not being able to name something but to be confident to recall it with more time (Schwartz, 2006). The TOT state acts as a signal that enhances the processing of subsequent feedback if the response cannot be retrieved (Metcalfe et al., 2020; Bloom et al., 2018; Metcalfe et al., 2017). According to Bloom et al. (2018), the TOT state occurs as a predictor temporally before the state of high curiosity, creating similar manipulations of ERP amplitudes. Bloom et al. (2018) found an enhanced late positivity during feedback presentation at centro-parietal electrode sites, when participants reported to be in a TOT state, similar but not identical to our P3 effect. In addition, we tend to assume that the TOT phenomenon only describes the highest level of curiosity (rating = 6) and cannot be transposed to medium or low levels of curiosity. Therefore, TOT states temporally before the states of high curiosity could have manipulated the ERPs during feedback presentation.

In addition, the modulation of LPP (comparable with the P600 between 600 ms – 1000 ms; Kuperberg et al., 2020; DeLong et al., 2014) by curiosity can potentially be interpreted as increased integration effort of the answers. Late positive potentials have proven to be relevant EEG markers for the processing and integration of new information into context (Aurnhammer et al., 2021; Brouwer et al., 2017; Kos et al., 2012; Kuperberg, 2007; Friederici, 1995). Accordingly, a more positive amplitude may reflect larger semantic prediction errors related to the answers due to higher expectation for certain words (DeLong et al., 2014; Kutas et al., 2011). In the present study, all answers were plausible – except the catch trials – and participants' expectations varied in relation to curiosity. A high semantic expectation reduces the possible prediction space and thus elevates the integration effort after semantic prediction errors. First evidence for this interpretation was provided by Murphy et al. (2021b), suggesting that increased hippocampus – default mode network connectivity in a trivia paradigm might reflect memory integration during the satisfaction of curiosity. In the present study, the LPP amplitude was more positive for high-curiosity answers, which might reflect an increased integration effort due to higher expectations and constraints based on high curiosity. Since neither the contextual prior knowledge nor expectancy errors were collected in this study, this idea could be addressed in future research.

Subsequent Memory Effects

An SME was found for the amplitudes of the RewP and P3 without an interaction with curiosity. On the one hand, the difference in the amplitudes between remembered and forgotten words implies that the processes reflected by the RewP/P3 contribute to successful memory formation. On the other hand, the lack of an interaction does not allow for a direct connection between the curiosity modulation of the RewP/P3 and the behavioural curiosity-related memory benefits. However, an SME could have been influenced by previous occurring processes, such as increased hippocampal activity or dopaminergic activity. It is important to note that Gruber et al. (2014) also did not find any significant interaction between curiosity-related brain activity and memory during answer presentation in the dopaminergic regions and the hippocampus. Critically, activation of dopaminergic areas and the hippocampus during curiosity elicitation but not satisfaction seems to support the curiosity-related memory benefit. However, during curiosity satisfaction, it seems that integration processes between hippocampus and large scale

cortical networks (e.g., with the default mode network, Murphy et al., 2021b) might contribute to the curiosity-related memory benefit. It is also conceivable that high curiosity levels might have enhanced the distinctiveness of events in a given processing context and the more distinctive items were more efficiently encoded and gave rise to an SME in the P3 time window (Otten & Donchin, 2000). As with the RewP, the lack of an interaction does not allow for a direct connection between the curiosity modulation of the P3 and better memory performance. Nevertheless, the SME for the P3 implies that the reflected processes (e.g., distinctiveness-based encoding) contribute to successful memory formation. The absence of the SME for the LPP can have several reasons. On the one hand, it is possible that SMEs were simply too small to modulate the investigated ERP components significantly. On the other hand, SME effects for the LPP with onset latencies beyond 600 ms have typically been reported when intentional and elaborative encoding strategies emphasizing associative processing of multiple study features are required (Kamp & Zimmer, 2015; Cheng & Rugg, 2010). These processing characteristics were presumably not initiated by the presentation of the answers to the trivia questions. Taken together, the SMEs in this work turned out to be greater at the beginning of the feedback processing (RewP, P3) and to vanish when it comes to later time windows (LPP).

Conclusion

In the present work, we specifically targeted the RewP, P3, and LPP because of their relation with reward processing and found meaningful connections between these ERPs and curiosity. The findings show increased positive amplitudes for all examined ERPs for high compared to low curiosity, suggesting increased feedback processing based on reward and expectancy. The SMEs for the RewP and P3 indicate that these reward-related processes contribute to successful memory encoding. According to this first investigation of ERPs during curiosity satisfaction, our findings support the view that curiosity acts as an amplifier of reward-related feedback processing, opening up the investigation of curiosity-related ERPs for future research. Moreover, the present study has shown that not only the state of curiosity but also its satisfaction is an important object of research to better understand the processes underlying curiosity. Furthermore, understanding which processes are normally influenced by the satisfaction of curiosity could help to detect clinical conditions that are accompanied by a lack of motivation and dopaminergic circuit activity. In addition, ERPs are a valuable tool to explore effects of curiosity due to their high temporal resolution. They allow to track the time course of curiosity-related feedback processing while it unfolds. In summary, our findings suggest a state of high curiosity can help to discover and more efficiently process new knowledge into existing semantic networks due to amplified feedback processing.

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Author contributions

C.R. and M.J.G. designed research, J.C.-D. and M.J.G. performed research, T.R. analysed the data, K.C.J.E. and J.C.-D. helped with data analysis, A.M. and M.J.G. supervised the project. T.R. drafted the paper, T.R., A.M., K.C.J.E. and M.J.G. wrote the paper, and all other authors gave comments on the paper.

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