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Examining the role of route familiarity in modulating the effect of prediction error of perceived exertion on retrospective running pleasure

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A B S T R A C T

Pleasure is a central element of how physical exercise is experienced, and it depends on the perceived physical demands of the activity. Recent evidence suggests that the prediction error of perceived exertion (PEexert), defined as the discrepancy between anticipated and experienced effort, shapes pleasure experienced after exercise. Understanding how both individual and contextual factors influence this process is, therefore, critical. The present study examined whether repeated exposure to the same exercise route, thereby increasing route familiarity, reduces PEexert and modulates its association with retrospective running pleasure. Forty-seven participants completed four runs at a self-selected intensity along the same forest trail. Using this within-subjects design, familiarity was operationalized as repeated runs on the identical route. At each session, participants reported their prospective and retrospective ratings of perceived exertion (RPE) that created the PEexert index, confidence in prospective RPE, retrospective running pleasure, and pre- and post-run state-anxiety. Running speed and heart rate were measured. Tolerance to physical effort, physical activity level, and prior familiarity with the trail were also assessed. Linear mixed models showed that PEexert significantly decreased after the first run and stabilized in the next runs; indicating that repeated exposure to the same route reduced the discrepancy between anticipated and experienced exertion. In turn, more positive PEexert (runs feeling easier than expected) was associated with higher retrospective running pleasure and greater reductions in state-anxiety. Crucially, route familiarity reduced PEexert but did not change the strength of the PEexert-pleasure association. These findings suggest that growing familiarity with an exercise environment refines effort prediction without altering the core affective mechanism linking prediction error to the retrospective pleasure of running.

1. Introduction

Pleasure is a central evaluative component of how an exercise session is experienced and remembered, and it varies largely with the perceived physical demands of the activity (e.g., Hammer et al., 2022; Plante et al., 2018). Judgements about the intensity of the physical demands of the session are typically captured through ratings of perceived exertion (RPE), defined as the personal experience of how intense the effort or strain feels during physical activity (Haile et al., 2015; Robertson & Noble, 1997; but see Halperin & Emanuel, 2020 for conceptual discussion regarding its definition). Higher exertion ratings, evaluated after the exercise session, are generally associated with lower retrospective pleasure (operationalized here as an immediate post-run rating completed after each session), whereas lower ratings predict greater retrospective pleasure (Ekkekakis et al., 2011; Frazão et al., 2016; Hartman et al., 2019; Hutchinson et al., 2020; Marcotte-Chénard et al., 2025).

This negative exertion-pleasure pattern has been documented across exercise modalities and settings (Ekkekakis et al., 2005b, 2005c; Parfitt & Hughes, 2009; see also Limmeroth et al., 2022). Beyond this robust pattern, contextual factors, such as music (Delleli et al., 2023; Terry et al., 2020) and environmental or social settings (e.g., outdoor vs. indoor; group vs. solitary; Jones & Zenko, 2023; Rogerson et al., 2020) can modify affective responses at comparable exercise intensity, thereby

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influencing the strength of the exertion-pleasure association. One influential account of this intensity-affect relationship is the Dual-Mode Theory (Ekkekakis, 2003, 2005a) which proposes that affective responses during exercise, and their immediate post-exercise evaluation, reflect the relative contribution of cognitive appraisals (e.g., interpreting the physical exercise session as meaningful, beneficial, and in line with one's goals) and interoceptive cues linked to physiological strain, with bodily signals becoming increasingly dominant as intensity rises and thereby tending to shift affective experience and immediate post-exercise evaluations toward lower pleasure.

The aforementioned literature has primarily relied on momentary RPE (collected during exercise) or retrospective RPE (collected immediately after exercise; Foster et al., 2001; Haile et al., 2015). More recently, it has been suggested that incorporating prospective RPE (i.e., the anticipated intensity of a forthcoming exercise session, collected before the session; Haile et al., 2015) and examining its mismatch with experienced exertion may offer valuable insight into the exertion–retrospective pleasure relationship. What one expects to feel in an upcoming physical task might be influential on the post-run evaluation, since pre-exercise expectations shape one's affective responses and somatic sensations (Helfer et al., 2015). Accordingly, integrating prospective and retrospective RPE to test whether their mismatch (i.e., runs being harder or easier than anticipated) is associated with retrospective running pleasure can be insightful.

This idea draws on reward prediction error accounts, emphasizing the mismatch between what is anticipated and what is experienced. Specifically, a fundamental observation from the literature on reward processing is that the pleasure response is not solely determined by the intrinsic value of a reward but is strongly shaped by the discrepancy between what is anticipated and what is experienced, that is, a reward prediction error (Schultz, 2016). This reward-prediction perspective aligns with interoceptive accounts in which affect reflects precision-weighted prediction errors about bodily states (Barrett & Simmons, 2015; Seth, 2013; Seth & Friston, 2016). In this view, a mismatch between anticipated and experienced RPE can be seen as an interoceptive prediction error that shapes the retrospective hedonic evaluation (Garfinkel et al., 2015; Khalsa et al., 2018). Building on this framework, Brevers et al. (2024) demonstrated that this discrepancy, termed the prediction error of perceived exertion (PEexert; operationalized as prospective RPE minus retrospective RPE), modulates the retrospective pleasure ratings regarding an exercise session. When the experienced effort is lower than anticipated (positive PEexert), exercisers tend to report greater retrospective pleasure; when it is higher than anticipated (negative PEexert), retrospective pleasure decreases. Conceptually, positive PEexert can be interpreted as a bodily form of positive surprise, as the run feels easier than expected and may elicit relief or satisfaction that amplifies retrospective pleasure (Cheval et al., 2025). Conversely, negative PEexert may signal an aversive mismatch that dampens retrospective pleasure. Thus, PEexert provides a theoretically grounded way to capture the expectation–experience mismatch in perceived effort and its association with immediate post-exercise evaluative outcomes (i.e., retrospective pleasure).

Together, this perspective motivates the idea that retrospective pleasure is shaped not only by perceived exertion per se, but also by whether the session feels harder or easier than anticipated, that is, by the mismatch between prospective and retrospective exertion captured by PEexert (Brevers et al., 2024). So far, PEexert has been evaluated in free-running sessions where participants chose their running route, intensity, and duration; therefore, this emerging evidence requires replication in other settings, and the conditions under which PEexert exerts a stronger or weaker influence remain poorly understood. One contextual factor that may critically shape the influence of PEexert is *familiarity* with the exercise environment. Consistent with this view, research has shown that familiarity reduces uncertainty, strengthens predictive accuracy, and enhances affective responses across domains such as learning, decision-making, and memory (Collins et al., 2018; Macaluso et al., 2022; Rosburg et al., 2011). In exercise settings, repeated exposure to the same route or modality has also been linked to improved self-efficacy and competence (Rose & Parfitt, 2012; Vazou-Ekkekakis & Ekkekakis, 2009).

Importantly, however, the affective consequences of repetition are not unequivocal. On the one hand, novelty and variation can enhance pleasure through curiosity and engagement, with evidence that variable training can increase enjoyment and adherence compared with stable routines (Glaros & Janelle, 2001) and that novel exercise modalities can elicit more positive affective responses than familiar ones (Stevens et al., 2016). Moreover, repeated exposure to the same activity can also lead to hedonic adaptation, such that repeated actions become less pleasurable over time (Frederick & Loewenstein, 1999). On the other hand, from a predictive processing perspective, repeated exposure may additionally support learning and improved calibration of expected bodily demands, thereby reducing prediction errors across trials (de-Wit, Machilsen & Putzeys, 2010). Taken together, these perspectives imply that it is not self-evident whether running repeatedly on the same route will uniformly decrease PEexert and improve retrospective pleasure. Instead, route familiarity can be linked to both (i) changes in PEexert magnitude across sessions and (ii) whether the PEexert–retrospective pleasure association is attenuated, preserved, or modified with repetition.

Accordingly, the present study aimed to replicate the association between PEexert and retrospective running pleasure in a naturalistic setting and to test whether repeated exposure to the same outdoor route reduces PEexert and alters its association with retrospective pleasure. We hypothesized that increasing route familiarity would reduce uncertainty and improve the accuracy of prospective RPE, thereby decreasing PEexert magnitude across sessions (de-Wit et al., 2010). Given competing theoretical expectations regarding the affective consequences of repetition (novelty/engagement vs. hedonic adaptation), we examined whether retrospective pleasure and the strength of the PEexert-retrospective pleasure association remained stable or changed as familiarity increased. To minimize confounding in this ecological field design, analyses adjusted for baseline route familiarity, approach-avoidance tendencies toward effort (Cheval et al., 2024; Maltagliati et al., 2025), pre-run anxiety (Farris et al., 2017; Garfinkel et al., 2015; Khalsa et al., 2018), and objective intensity indicators (speed and heart rate; Achten & Jeukendrup, 2003; Barnes & Kilding, 2015; Impellizzeri et al., 2019).

From a complementary angle, we examined confidence in prospective RPE as an index of task familiarization, as repeated exposure may make RPE-guided self-regulation more stable and consistent (Crawford et al., 2018; O'Malley et al., 2023; Rose & Parfitt, 2012; Soriano-Maldonado et al., 2014), thereby increasing certainty in prospective exertion estimates and further reducing PEexert magnitude. We also explored whether PEexert was associated with changes in state anxiety from pre- to post-run, indexing short-term affect regulation beyond retrospective pleasure (Connor et al., 2023; Ensari et al., 2015; Harris et al., 2025; Knapen et al., 2009). More broadly, evaluative affect is proposed to reflect discrepancies between expectations and experienced outcomes, suggesting that unexpectedly manageable versus unexpectedly strenuous efforts, as indexed by PEexert, may trigger a cascade of affective adjustments from pleasure to calmness, reflecting recalibration of anticipated cost in the form of expected bodily demands and perceived coping ability.

Finally, because retrospective evaluations of exertion can be shaped by memory integration across segments (Jeunehomme & D'Argembeau, 2020, 2021; Kahneman et al., 1993), we compared global retrospective RPE with the mean of segment-based retrospective RPE to examine whether PEexert-related effects depend on how exertion is recalled.

Collectively, this study aimed to refine our understanding of the exertion–retrospective pleasure relationship by clarifying the conditions under which PEexert is associated with retrospective evaluative outcomes following exercise.

2. Methods

2.1. Transparency and openness

The methods and study design were preregistered on the Open Science Framework (OSF; https://doi.org/10.17605/OSF.IO/X5QJB. The deviations from the preregistration are reported in supplementary materials (Section 1). The Jamovi file containing all data and analyses, and outputs from the power simulations are publicly available on the OSF: https://osf.io/zubt4/.

2.2. Ethics

The study protocol was approved by the Ethics Committee of the UCLouvain Institute of Psychological Sciences (#2024–10).

2.3. Participants

A total of 47 participants (all > 18 years; 30 female, 17 male) completed the study. Participants received 10 euros as compensation. Initially, 56 participants were recruited, but 9 participants did not complete all four running sessions (2 due to injury, 5 participants ran 2 times, and 2 participants ran 3 times and dropped out) and were excluded from data analyses. 50 participants were needed according to sample size estimation (see also Section 2.9. Sample Size Estimation).

Participants were recruited through flyers (accessible on OSF: osf.io/zubt4), social media posts, and campus announcements at UCLouvain (Belgium), as well as through announcements in auditoriums/classrooms of UCLouvain. Interested candidates contacted the research team via email and received a link to an online screening tool (https://uclpsychology.co1.qualtrics.com/jfe/form/SV_8G3WHWG4uFHzI2O), which included an informed consent form. Contact information was provided for questions before agreeing or declining to participate.

The screening tool asked participants to complete the first seven questions of the French version of the Physical Activity Readiness Questionnaire (Warburton et al., 2022). Participants who answered "no" to all seven questions were eligible to participate. Those who answered "yes" to one or more questions were informed and excluded from the study.

Eligible participants completed the International Physical Activity Questionnaire (IPAQ; Craig et al., 2003) to determine physical activity level. No participants corresponded to category 1 of the IPAQ (i.e., low level of physical activity), 5 participants corresponded to category 2 (i.e., moderate), and 33 participants to category 3 (high). Six participants did not answer all the questions and were categorized as not valid, and 3 were outliers due to non-realistic responses. The online survey also assessed participants' "prior familiarity" with the running trail, which was later included as a predictor in analyses. Sixteen participants were already familiar with the trail, while thirty-one participants had no experience with the trail. (see Sections 2.8 and 2.9).

2.4. Design

The study employed a within-subject design with four running sessions (i.e., a four-level within-subject factor; see Section 2.9 Sample Size Estimation for the rationale for using four running sessions).

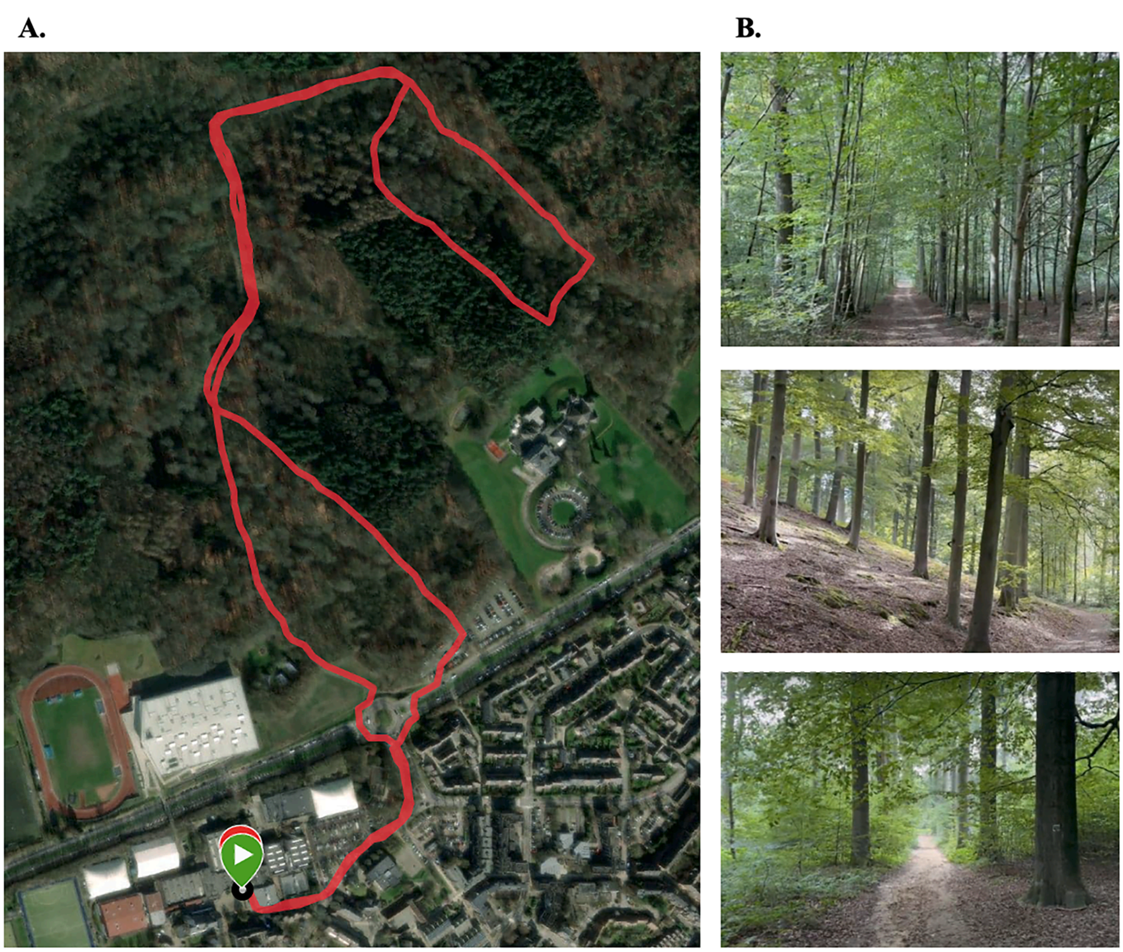

Fig. 1. Running trail. A. The route. B. Examples of trail sections. The trail was 3.5 km long and located at the "Bois de la Lauzelle" (Forest of Lauzelle); in the first and last 200 m of the trail were in the urban areas of the "Blockry" sports centre.

2.5. The running condition

The running trail is shown in Fig. 1. It was located in *Bois de Lauzelle* (a forest near the UCLouvain campus, Louvain-la-Neuve, Belgium) and covered 3.5 km. Guiding arrows were placed along the route in an ascending numerical order, and all participants were instructed to follow them to avoid deviations.

Similar to Brevers et al. (2024), all running sessions were undertaken individually and at a self-selected intensity. Allowing exercisers to self-select intensity, rather than imposing it, has been associated with higher enjoyment and more positive affective responses across exercise modalities (Ekkekakis et al., 2011; Oliveira et al., 2015; Vazou-Ekkekakis & Ekkekakis, 2009; see also Elsangedy et al., 2018, 2020). In addition, self-selected exercise is often characterized by low-to-moderate perceived exertion profiles that can support a more pleasant exercise experience (Elsangedy et al., 2020).

2.6. Measures

2.6.1. Route familiarity (via repeated running sessions)

Familiarity with the exercise route is operationalised as four repeated exposures to the same running trail. Hence, route familiarity was measured by the variable “running session” with four levels.

2.6.2. Prediction error of perceived exertion (PEexert)

Before and after each run, participants rated their perceived exertion (RPE). We used the French validation of Borg’s Category Ratio-10 RPE scale (Borg, 1998; Haddad et al., 2013), which ranges from 0 (“null” to 10 (“maximal”), with intermediate verbal labels (1=“very light”, 2=“light”, 3=“moderate”, 4=“somewhat hard”, 5=“hard”, 6=[no anchor], 7=“very hard”, 8=[no anchor], 9=[no anchor]).

As in Brevers et al. 2024, participants reported their *global* RPEs (overall perceived exertion for the whole run) for the entire running session (see Foster et al., 2001, for rationale). Prospective RPE was assessed immediately before each running session (“What intensity of exertion do you expect to feel during this session?”). Retrospective RPE was measured immediately after finishing each run (“What intensity of exertion did you feel during this session?”).

PEexert was calculated by subtracting retrospective RPE from prospective RPE. A positive PEexert score indicates that the experienced exertion was lower than expected (positive prediction error), whereas a negative score indicates that it was higher than expected (negative prediction error).

2.6.3. Retrospective running pleasure

Running pleasure was assessed using a single-item measure completed immediately after each run, adapted from the enjoyment item used by Stanley and Cumming (2010) and employed in prior work (Brevers et al., 2024). Participants rated the overall pleasure experienced during each session (“What intensity of pleasure did you feel during this session?”) on a 7-point Likert scale (0=“none at all,” 1=“very little,” 2=“slightly,” 3=“moderately,” 4=“quite a bit,” 5=“very much,” 6=“extreme”). This measure captures a retrospective evaluative judgement of the session (Ekkekakis, 2003; Hardy & Rejeski, 1989) and indexes the global hedonic evaluation of the run.

2.6.4. Confidence in prospective RPE

Confidence in prospective RPE was measured using a single item on a 10-point Likert scale (“How confident do you feel about your rating for the expected amount of effort?”; 0=not confident at all, 10=extremely confident).

2.6.5. Prior experience with the trail (Prior familiarity)

Because Bois de Lauzelle is a popular running area among the UCLouvain community, participants’ prior familiarity with the trail was used as a confounding factor in all analyses. This was assessed during pre-screening: participants were shown a map of the route and asked (yes/no) whether they had run this route before.

2.6.6. Average speed and average heart rate

The Formyfit running app (https://www.formyfit.com/) logged distance, average speed, and average heart rate (while respecting GDPR guidelines). The GPS function estimated distance and calculated speed. Heart rate was recorded using a Polar armband optical sensor paired via Bluetooth with the Formyfit smartphone app. Participants wore the armband on the mid–upper arm, tightened according to manufacturer recommendations to reduce motion artefacts. Before each run, a researcher ensured the sensor was activated, paired in the app, and that a stable heart-rate signal was displayed before starting the recording. The app logged heart rate continuously throughout the run. The heart-rate variable used in analyses was average heart rate (bpm) computed by the app across the entire recorded running bout (from the moment the participant pressed “start” to the moment they pressed “stop” at the end of the route). After each session, average heart rate and average speed were exported from the app and merged into the study dataset after a visual check by the research team.

2.6.7. Pre- and post-run anxiety states

Participants completed the state component of the State-Trait Anxiety Inventory (STAI-S; Spielberger et al., 1983) before and after each run. The STAI-S includes 20 items rated on a 4-point Likert scale (1=“not at all” to 4=“very much so”). Pre-run anxiety scores were included as a covariate in the main analyses. We also computed change scores (post-run minus pre-run anxiety) to examine the effect of PEexert on anxiety reduction.

2.6.8. Tendencies to approach and avoid physical effort

The Physical Effort Scale (PES; Cheval et al., 2024) was used to assess individual differences in effort valuation. This 8-item scale (1=“completely disagree” to 5=“completely agree”) has two 4-item subscales: approach (e.g., “I usually like activities that require physical effort”) and avoidance (e.g., “I tend to avoid situations in which I have to exert physical effort”). Average scores were computed for each dimension, and a relative approach score was obtained by subtracting avoidance from approach (Cheval et al., 2024). The sub-scales of the questionnaire showed good internal consistency (Approach: $\alpha = 0.86$, $M = 4.51$, $SD = 0.53$; Avoidance: $\alpha = 0.89$, $M = 1.40$, $SD = 0.51$). Relative approach scores ranged from -0.25 to 4 ($M = 4.50$, $SD = 0.95$).

2.6.9. Retrospective RPE across segments of the trail

In addition to the global retrospective RPE, participants rated perceived exertion for the beginning, middle, and end of the trail (1/3, 2/3, and 3/3 segments) after the run. A map divided into three segments (see supplementary materials, Figure S1) was provided to aid recall. We computed the mean of the three segment scores and examined its correspondence with the global retrospective RPE score.

2.6.10. Weather

Weather conditions (1= sunny, 2= cloudy, 3= light rain, 4= moderate rain) were recorded and analyzed in exploratory models. In total, 74 sessions were undertaken under sunny conditions, 73 under cloudy conditions, 23 under light rain, and 18 under moderate rain.

2.7. Procedure

A flowchart of the procedure is shown in Fig. 2. The study was conducted between October 7, 2024, and March 25, 2025. Participants scheduled their sessions within two weeks using an online booking system. Ideally, runs were spaced 2–3 days apart, but due to scheduling conflicts, some participants ($N = 14$) completed the study over a four-week period. All the runs were individual.

Participants received reminder emails before each run with

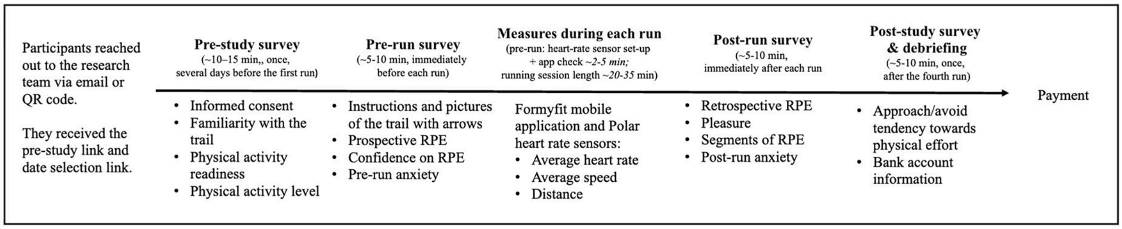

Fig. 2. Flowchart of the procedure.

instructions and were asked to download the Formyfit app. At the meeting point near the running trail, participants were welcomed by a researcher. During the first session, participants were shown the route map (Fig. 1) and instructed on how to start the Formyfit app. The heart rate monitor was synchronized with the app, and participants were offered an armband to carry their smartphones.

Before each run, participants completed ratings of prospective RPE, confidence in prospective RPE, and the state-anxiety. After the run, under the supervision of the researcher, they completed retrospective RPE (single-item and segment-based), retrospective pleasure ratings, and state-anxiety. The research team reported the weather conditions manually and was present to answer any questions.

After the fourth session, participants completed the PES questionnaire, provided bank account details for the 10-euro compensation, and were debriefed about the aim of the study.

2.8. Data analysis

2.8.1. Analytical approach

Linear Mixed Models (LMM) were used to test the main hypotheses. Analyses were conducted with the *GAMLj3* module in Jamovi (Version 2.6; The jamovi project, 2025), which relies on the *lme4* package (Bates et al., 2015) in R. Significance testing used the *lmerTest* package (Kuznetsova et al., 2017), applying Satterthwaite's approximation to estimate degrees of freedom and p-values. In all LMMs, participants were included as a random effect (1|participant).

We evaluated whether the data supported more complex random-effects structures by testing random slopes for PEexert at the participant level. Random-intercept and random-slope specifications were compared using information criteria (AIC) under maximum likelihood estimation, and variance components were inspected for potential instability/singularity. As random-slope models did not improve fit and/or produced unstable variance estimates, we retained parsimonious random-intercept LMM (model comparisons are reported in supplementary materials, Table S1).

We inspected standardized residual diagnostics for each final LMM (Q-Q plots, residual histograms, and residuals-versus-fitted plots; see supplementary materials, Figure S2). For all LMMs, we report 95 % confidence intervals based on bootstrap resampling to provide inference that is less sensitive to distributional assumptions. Because the pleasure rating is bounded and discrete, departures from strict normality in residual diagnostics can be expected; bootstrap CIs therefore offer a consistent robustness-oriented approach across all models.

The final mixed-effects models reported in the main text correspond to our a priori planned analytic strategy and include a limited set of theoretically motivated covariates (including indicators of running intensity) to reduce confounding in this ecological field design. To address potential concerns regarding model complexity relative to sample size, we additionally conducted sensitivity analyses in which the primary models were re-estimated without covariates. These no-covariate models allow evaluating whether conclusions regarding the effects of PEexert and its interactions depend on covariate adjustment. Full outputs for the sensitivity models are reported in the supplementary materials (Section 3), together with bootstrap confidence intervals.

2.8.2. Confirmatory analyses

Impact of running sessions and confidence in prospective RPE on PEexert. PEexert was the dependent variable, with fixed effects of running session, prior familiarity with the trail, confidence in prospective RPE, average speed, average heart rate, physical effort approach/avoidance tendencies, pre-run anxiety, and the interaction (running session × confidence_RPE with the trail): *PEexert ∼ 1 + running_session + familiarity_trail + confidence_RPE + speed_average + heart_rate_average + approach_over_avoid + pre_run_anxiety + running_session:confidence_RPE + (1|participants)*. See supplementary materials (Section 3.1) for LMM without covariates.

Impact of running sessions and PEexert on running pleasure. Retrospective running pleasure was the dependent variable, with fixed effects of running session, prior familiarity with the trail, PEexert, average speed, average heart rate, approach/avoidance, pre-run anxiety, and the interaction running session × PEexert: *running_pleasure ∼ 1 + running_session + familiarity_trail + PEexert + speed_average + heart_rate_average + approach_over_avoid + pre_run_anxiety + running_session:PEexert + (1|participants)*. See supplementary materials (Section 3.2) for LMMs without covariates. Note that, in line with previous research (Brevers et al., 2024), LLM with PEexert as a fixed effect with random slope did not result in a significant increase in model fit (see supplementary materials, Section 2).

Impact of running sessions and PEexert on state-anxiety change. State-anxiety change was the dependent variable, with fixed effects of running session, PEexert, average speed, average heart rate, prior familarity with the trail, approach/avoidance, and interactions (running session × PEexert, PEexert × approach/avoidance): *anxiety_change ∼ 1 + running_session + PEexert + speed_average + heart_rate_average + familiarity_trail + approach_over_avoid + running_session:PEexert + PEexert:approach_over_avoid + (1|participants)*. See supplementary materials (Section 3.3) for LMM without covariates.

2.8.3. Exploratory analyses

Models adjusted with weather. As an exploratory robustness check, we re-estimated the primary LMMs after adding weather conditions as an additional fixed-effect covariate. Weather was coded as a categorical variable (sunny, cloudy, light rain, moderate rain) and entered in otherwise identical model specifications for each outcome: PEexert, running pleasure, and state-anxiety change.

Examination of segment-based retrospective RPE. A repeated-measures ANOVA was used as a manipulation check to test whether retrospective RPE increased across the three trail segments ($1/3 < 2/3 < 3/3$). We then used a Bayesian paired-sample *t*-test to examine the correspondence between the mean segment RPE and the single-item global retrospective RPE, quantifying evidence for the null hypothesis. The Bayesian *t*-test was performed with the default Cauchy prior width ($r = 0.707$) using the Bayes Factor package (Morey & Rouder, 2011) in Jamovi.

2.9. Sample size estimation

The sample size was estimated using the *smir* R package, based on data from Brevers et al. (2024). Following recent recommendations to base power analyses on the smallest meaningful effect size (Bates et al., 2015), we simulated 1000 datasets assuming a raw slope of 0.09 units in running pleasure per one-unit change in PEexert (https://osf.io/rch2t). Using the lower bound of the 80 % confidence interval for PEexert effects [0.09 to 0.20], results indicated that with α = 0.05 and power = 0.80 (95 % CI [.78 to 0.83]), 50 participants across 200 observations were sufficient. Accordingly, we required 50 participants with four running sessions to detect the main PEexert–pleasure effect (i.e., a conceptual replication of Brevers et al., 2024; see supplementary materials, Section 2, for a direct replication).

4. Results

4.1. Data overview

As preregistered, route familiarity constituted a core within-subject manipulation, requiring that all participants complete the same running route across sessions. Despite clear instructions and guiding arrows, eight participants deviated from the route during their first run. These participants were asked to repeat the session on the correct route, resulting in five total runs. To ensure that all participants had exactly four exposures to the identical route, we excluded the initial incorrect run and retained the four correct runs for these participants. This procedure preserved the integrity of the route-familiarity manipulation and ensured a balanced repeated-measures design across the sample. Accordingly, the final analyses included 47 participants who each completed four runs on the same trail. Importantly, we also conducted sensitivity analyses excluding these eight participants entirely. These analyses yielded the same pattern of significant results as the main analyses, indicating that the handling of incorrect routes did not affect the substantive conclusions. Full outputs of these sensitivity analyses are reported in supplementary materials (Tables S6-S8).

4.2. Confirmatory analyses

4.2.1. Impact of running sessions and confidence in prospective RPE on PEexert

PEexert significantly reduced across sessions, $F = 4.37$, $p = .006$, indicating that the route familiarity allowed for smaller PEexert. This decrease was significant between run 1 and subsequent runs (all *ps* < 0.03; Table 1; Fig. 3A). We also observed a main effect of confidence in prospective RPE ($t = -2.13$, $p = .03$; Table 1). Importantly, Fig. 3B indicates that high confidence in prospective RPE is associated with negative PEexert and low confidence with positive PEexert, while moderate confidence is associated with a smaller magnitude of PEexert (closer to zero). No other significant main or interaction effects were observed; all *ps* > 0.35.

4.2.2. Impact of running sessions and PEexert on running pleasure

PEexert significantly predicted retrospective running pleasure ($t = 2.19$, $p = .03$; Table 2; Fig. 3C), such that more positive discrepancies (i.e., runs feeling easier than expected) were associated with greater pleasure. No other significant main or interaction effects were observed (all *ps* > 0.26). Importantly, including confidence in prospective RPE as an additional predictor did not alter these results.

4.2.3. Impact of running sessions and PEexert on anxiety change

A significant effect of PEexert on anxiety change was found ($F = 7.61$, $p = .006$; Table 3, Fig. 3D). Participants who had more positive PEexert had a larger decrease in anxiety and vice versa. No other significant main or interaction effect was observed (all *ps* > 0.15).

4.3. Exploratory analyses

4.3.1. Models adjusted with weather

Across outcomes (PEexert, running pleasure, and state-anxiety change), the models indicated no main effect of weather, and the inclusion of weather did not change the statistical conclusions of the primary effects of interest. Full model outputs are reported in the supplementary materials (Tables S9-S11).

Table 1
Results of the LMM examining the impact of route familiarity (running sessions) and confidence in prospective RPE on PEexert .

Model Component Variable	Estimate (SE)	Bootstrapped 95 % CI
Intercept	−0.20* (0.09)	−0.37, −0.02
heart_rate_average	−0.003 (0.005)	−0.01, 0.008
speed_average	0.003 (0.04)	−0.10, 0.97
pre_run_anxiety	0.002 (0.01)	−0.01, 0.02
approach_over_avoid	0.100 (0.09)	−0.07, 0.30
familiarity_trail (not familiar - familiar)	−0.15 (0.18)	−0.50, 0.24
runnning_session 2 - 1	0.58* (0.21)	.15, 1.03
runnning_session 3 - 1	0.45* (0.21)	.02, 0.84
runnning_session 4 - 1	0.73*** (0.21)	.35, 1.16
confidence_RPE	−0.12* (0.05)	−0.24, 0.09
runnning_session 2 - 1 ✻ confidence_RPE	−0.14 (0.16)	−0.48, 0.12
runnning_session 3 - 1 ✻ confidence_RPE	0.08 (0.14)	−0.21, 0.34
runnning_session 4 - 1 ✻ confidence_RPE	−0.08 (0.15)	−0.40, 0.19
Variance components		
Within-participant variance	987	
Intercept variance	0.10	
Additional information		
ICC	.09	
−2 log likelihood (FIML)	570.89	
Number of estimated parameters	13	
Conditional R^2	.17	
Marginal R^2 (Pseudo R^2)	.09	
AIC	557.82	

Note. Total number of running sessions = 188, number of participants = 47. Values in parentheses are standard errors. t statistics were computed as the ratio of each regression coefficient divided by its standard error. ICC = intraclass correlation coefficient; AIC = Akaike information criterion, FIML = full-information maximum likelihood estimation. * p < .05. *** p < .001.

4.3.2. Examination of segment-based retrospective RPE

The repeated-measures ANOVA showed that the three segments of the running trail (1/3, 2/3, 3/3; beginning, middle, ending) and the global retrospective RPE were significantly different from each other ($F(3, 561) = 313.64$, $p < .001$; Fig. 4). Hence, retrospective RPE exhibited a non-linear pattern throughout the run. Pairwise comparisons (Holm correction) showed that each segment and global RPE were significantly different than from one another (*ps* < 0.001). Perceived exertion increased across each segment. The Bayesian paired-sample *t*-test provided moderate evidence that the mean of the RPE segments and the global retrospective RPE are not significantly different ($B_{10} = 0.18$).

5. Discussion

The present study examined whether repeated exposure to the same running route reduces prediction errors of perceived exertion (PEexert) and how such changes shape affective responses to exercise. Using a within-subject design with four self-paced runs on an identical trail, we tested how familiarity alters exertion predictions, running pleasure, and state-anxiety.

5.1. Route familiarity and confidence modulate exertion predictions

Confirming our hypothesis, PEexert significantly decreased after the first run. This reduction was especially pronounced between the first and second runs, then tended to plateau from the second to the fourth session. This pattern suggests a rapid early calibration phase followed by stabilization once participants had built a reliable internal model of the route's physical demands. In predictive processing terms, the first exposure likely involved higher uncertainty regarding anticipated

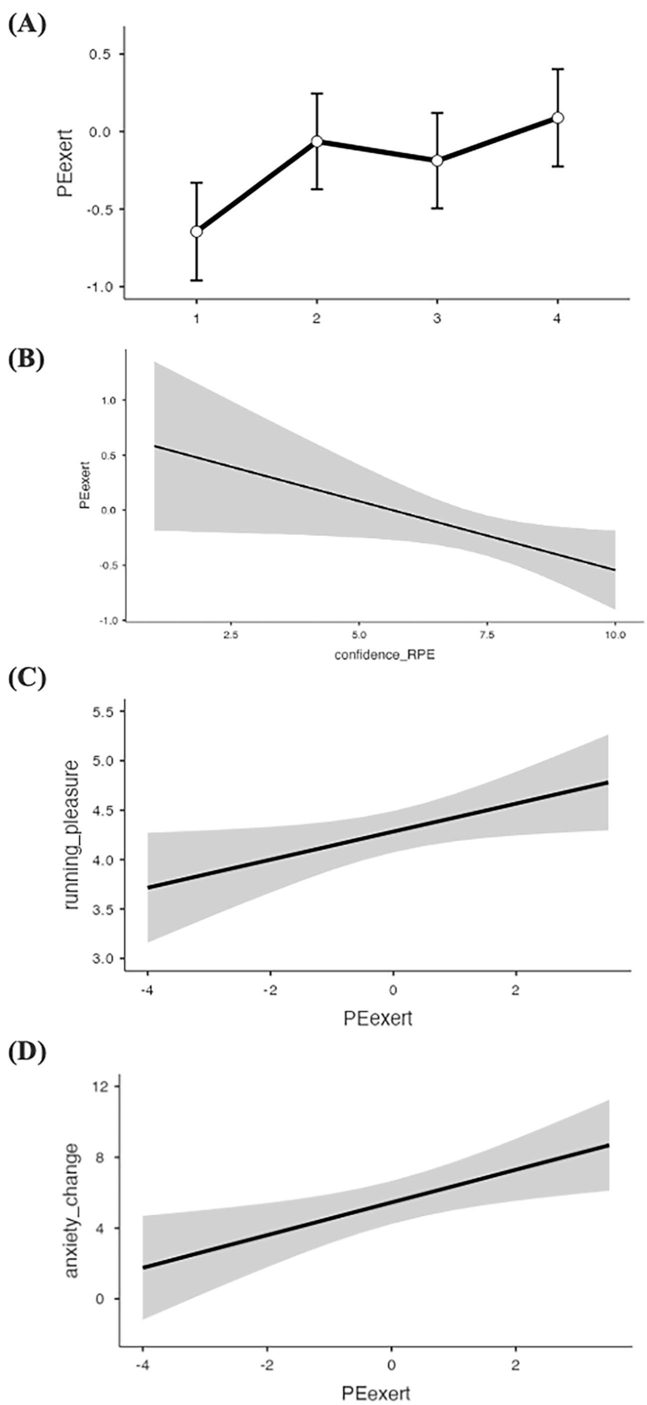

Fig. 3. A. The main effect of running session on PEexert. B. The main effect of confidence on prospective RPE on PEexert. C. The main effect of PEexert on retrospective running pleasure. D. The main effect of PEexert on anxiety change. Note. PEexert = prediction error of ratings of exertion. Semitransparent gray areas indicate the 80 % confidence interval of the fixed effect.

bodily costs, resulting in larger discrepancies between expected and experienced exertion (Auksztulewicz & Friston, 2016; Seth & Friston, 2016). With repetition, participants were able to update these anticipatory models, reducing uncertainty and improving the alignment between prospective and retrospective RPE. This pattern is consistent with learning mechanisms in hierarchical predictive coding accounts, in which initial high-error trials drive model updating and subsequent reductions in prediction error magnitude (Barrett & Simmons, 2015; Clark, 2013; Friston, 2010; Wit et al., 2010).

Table 2
Results of the LMM examining the impact of running sessions and PEexert on retrospective running pleasure.

Model Component Variable	Estimate (SE)	Bootstrapped 95 % CI
Intercept	4.28*** (0.10)	4.07, 4.48
running_session 2–1	0.001 (0.17)	−0.33, 0.33
running_session 3–1	−0.07 (0.17)	−0.40, 0.26
running_session 4–1	−0.08 (0.17)	−0.38, 0.25
PEexert	.14* (0.06)	.02, 0.28
familiarity_trail (not familiar - familiar)	−0.23 (0.20)	−0.63, 0.16
speed_average	.04 (0.04)	−0.04, 0.14
heart_rate_average	.002 (0.005)	−0.007, 0.01
pre_run_anxiety	.003 (0.01)	−0.02, 0.02
approach_over_avoid	.09 (0.108)	−0.13, 0.31
running_session 2–1*PEexert	.04 (0.16)	−0.24, 0.40
running_session 3–1*PEexert	−0.12 (0.18)	−0.45, 0.23
running_session 4–1*PEexert	0.04 (0.17)	−0.22, 41
Variance components		
Within-participant variance	0.65	
Intercept variance	0.26	
Additional information		
ICC	.29	
−2 log likelihood (FIML)	−1021.77	
Number of estimated parameters	13	
Conditional R^2	0.33	
Marginal R^2 (Pseudo R^2)	0.07	
AIC	510.84	

Note. Total number of running sessions = 188, number of participants = 47. Values in parentheses are standard errors. t statistics were computed as the ratio of each regression coefficient divided by its standard error. ICC = intraclass correlation coefficient; AIC = Akaike information criterion, FIML = full-information maximum likelihood estimation. * $p < .05$. *** $p < .001$.

Table 3
Results of the LMM examining the impact of running sessions and PEexert on state-anxiety.

Model Component Variable	Estimate (SE)	Bootstrapped 95 % CI
Intercept	5.45*** (0.60)	4.34, 6.77
running_session (2–1)	−0.07 (0.89)	−1.86, 1.67
running_session (3–1)	−0.49 (0.87)	−2.12, 1.52
running_session (4–1)	−0.36 (0.90)	−2.06, 1.37
familiarity_trail1 (not familiar - familiar)	−0.29 (1.20)	−2.83, 1.72
PEexert	0.93* (0.33)	0.33, 1.66
speed_average	−0.35 (0.25)	−0.83, 0.14
heart_rate_average	−0.03 (0.02)	−0.09, 0.02
approach_over_avoid	−0.53 (0.59)	−1.58, 0.62
running_session1*PEexert (2–1* PEexert)	−0.80 (0.86)	−2.53, 1.12
running_session2*PEexert (3–1*	0.55 (0.94)	−1.18, 2.49
PEexert)	−0.06 (0.89)	−1.82, 1.76
running_session3*PEexert (4–1*	−0.08 (0.40)	−0.77, 73
PEexert)		
PEexert*approach_over_avoid		
Variance components		
Within-participant variance	16.3	
Intercept variance	11.2	
Additional information		
ICC	0.41	
−2 log likelihood (FIML)	1090.62	
Number of estimated parameters	13	
Conditional R^2	0.45	
Marginal R^2 (Pseudo R^2)	0.07	
AIC	1125.08	

Note. Total number of running sessions = 188, number of participants = 47. Values in parentheses are standard errors. t statistics were computed as the ratio of each regression coefficient divided by its standard error. ICC = intraclass correlation coefficient; AIC = Akaike information criterion, FIML = full-information maximum likelihood estimation. * $p < .05$. *** $p < .001$.

A complementary goal of this paper was to investigate whether some personal traits and states influence the exertional prediction errors, such as pre-run anxiety, approach over avoidance tendencies towards

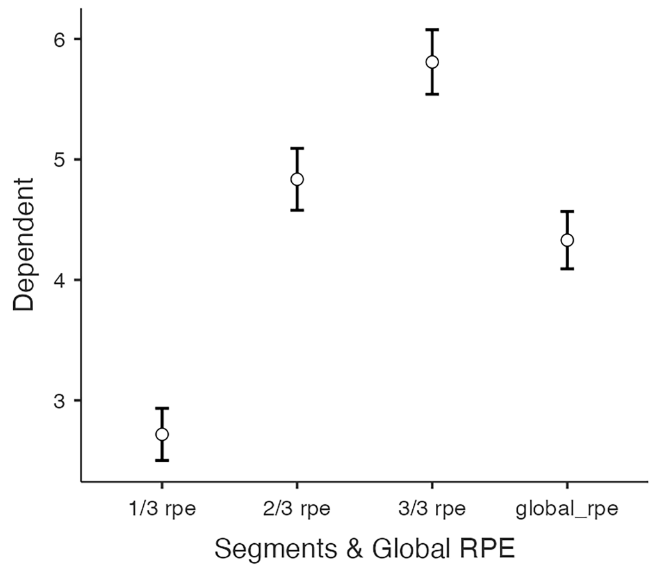

Fig. 4. Means and 95% confidence intervals for the three segments of the retrospective RPE and the global retrospective RPE.

physical effort, and confidence in prospective RPE. We observed a non-linear descriptive pattern whereby higher confidence was associated with more negative PEexert (i.e., the session felt harder than expected), lower confidence with more positive PEexert (i.e., the session felt easier than expected), and confidence ratings closer to the midpoint of the scale with smaller absolute PEexert values (i.e., little or no mismatch between prospective and retrospective RPE). This pattern suggests that confidence does not simply track predictive accuracy linearly but may reflect how firmly pre-exercise expectations are specified (see supplementary materials, Section 4.1, for a more detailed discussion of these complementary findings).

5.2. PEexert robustly shapes pleasure, without moderation by session

A second central hypothesis concerned the affective consequences of PEexert. Consistent with our predictions and with prior findings (Brevers et al., 2024), runs that felt easier than expected were rated as more pleasant. This association remained robust after controlling for pre-run anxiety, effort-related approach-avoidance tendencies, and objective intensity indicators such as heart rate and running speed. At a theoretical level, this finding aligns with reward prediction error frameworks (Schultz, 2016) and interoceptive predictive coding models (Seth & Friston, 2016), which emphasize that affective valuation depends on deviations from expectation rather than on absolute bodily states. Consistent with this framework, positive PEexert may amplify retrospective pleasure, whereas negative PEexert may reduce it. These findings can also be interpreted in light of the Dual-Mode Theory (Ekkekakis, 2003, 2005a), which posits that affective responses to exercise reflect the shifting balance between cognitive appraisals and interoceptive cues linked to physiological strain as intensity increases. Within this framework, the prediction-error mechanism examined in the present study can be conceptualized as primarily grounded in interoceptive processing, operationalized here as a mismatch between expected exertion and exertion retrospectively reported for the whole run. Accordingly, when prospective exertion exceeds retrospectively reported exertion, negative exertional prediction errors are associated with lower retrospective pleasure, whereas lower-than-anticipated (i.e., positive) prediction errors are associated with higher retrospective pleasure.

Contrary to our hypothesis, route familiarity did not attenuate the PEexert-pleasure relationship. Although PEexert decreased after the initial run and then plateaued, the strength of its association with pleasure remained stable. From a predictive processing perspective, repeated exposure may reduce exertional prediction error magnitude through improved calibration and reduced uncertainty (Auksztulewicz & Friston, 2016; Friston, 2010), while leaving intact the affective relevance of residual mismatches (Seth & Friston, 2016). In other words, increased familiarity may enhance the precision of anticipatory models of bodily demand (Barrett & Simmons, 2015), thereby reducing large discrepancies without altering the core mechanism by which deviations from expectation shape retrospective valuation (Schultz, 2016). This invariance is theoretically informative and has practically implications: even when exercise becomes more predictable, PEexert still operates as an affective feedback signal, meaning that sessions that feel easier than expected remain more pleasant, whereas sessions that feel harder than expected remain less pleasant, albeit typically with smaller discrepancies as familiarity grows. Consistent with this interpretation, robustness analyses indicated that the absence of moderation was observed across alternative model specifications, suggesting that it is unlikely to reflect a model-dependent artifact.

Beyond predictive calibration mechanisms, contextual features of the exercise protocol may also help explain this invariance. One factor that may contribute to this invariance is the self-selected nature of the exercise intensity. Self-selected intensity is consistently associated with more stable and positive affective responses across exercise sessions compared to imposed intensities (Ekkekakis et al., 2011; Elsangedy et al., 2018; Oliveira et al., 2015). In this context, increased familiarity with the route may have enabled participants to more accurately anticipate bodily demands and pace accordingly, thereby maintaining a pleasant affective state. Rather than eliminating prediction errors, familiarity may have facilitated more precise effort regulation, allowing hedonic evaluations to remain stable despite a reduction in PEexert magnitude. This interpretation is consistent with prior work showing that experience with an exercise task supports affective stability through improved intensity self-regulation (Rose & Parfitt, 2012).

Taken together, present findings suggests that the affective meaning of prediction errors is intrinsic to interoceptive inference: easier-than-expected exertion feels pleasant and harder-than-expected exertion feels unpleasant, regardless of familiarity. Similar invariance has been observed in other prediction error-based affective responses, such as relief or frustration, which remain tightly coupled to expectation deviations even as overall surprise diminishes (Joffily & Coricelli, 2013). From a functional standpoint, maintaining a stable affective response to prediction errors may be adaptive. Even in predictable environments, affective feedback continues to signal whether bodily demands align with expectations, thereby guiding effort regulation and future behavior. This interpretation resonates with inhibitory learning models emphasizing continued updating rather than extinction of predictive associations (Brevers & Philippot, 2023; Craske et al., 2014; Vervliet & Craske, 2020).

5.3. Beyond pleasure: PEexert and emotional restoration

Beyond retrospective pleasure, we examined changes in state anxiety as a secondary and exploratory outcome indexing short-term affect regulation. Unlike retrospective pleasure, which reflects a global evaluative judgment of the exercise session (Ekkekakis, 2003; Hardy & Rejeski, 1989), state anxiety captures a transient affective state that may be modulated by both physiological activation and cognitive appraisal processes (Spielberger, 1983). Acute exercise is well documented to reduce state anxiety across contexts (Ensari et al., 2015), suggesting that anxiety may function as a regulatory affective state rather than a purely evaluative outcome.

From this perspective, anxiety reduction was not conceptualized as a direct evaluative outcome of the run, but rather as a regulatory consequence potentially shaped by exertional prediction errors. More positive PEexert was linked to larger reductions in state anxiety, consistent with models in which affect operates as a feedback signal informing adaptive regulation (Cacioppo & Berntson, 1999; Carver & Scheier, 1990; Inzlicht et al., 2018; note that an exploratory complementary analysis examining whether retrospective pleasure may partly account for this association is provided in the supplementary materials, Section 4.2.). Applied to physical exertion, this framework implies that an unexpectedly manageable bodily demand may be accompanied by a shift toward calmer affective states, whereas unexpectedly strenuous effort may co-occur with less pronounced anxiety reduction.

5.4. Limitations and future directions

A first limitation of the present study concerns the inability to draw causal conclusions regarding the effect of RPE-based prediction error on effective outcomes. One component of PEexert (i.e., retrospective RPE), retrospective pleasure, and post-run anxiety were all assessed at the same post-exercise time point, immediately after the running session. As a result, the observed associations may partly reflect shared variance among subjective evaluations of the PEexert and affective outcomes rather than a directional effect of PEexert on pleasure or anxiety. This limitation is particularly relevant for anxiety outcomes, as physical exercise itself is well established to reduce state anxiety (Ensari et al., 2015), independently of prediction-related processes. Accordingly, all associations involving PEexert and affective outcomes should be interpreted at a correlational level. Future research should adopt experimental and longitudinal designs that more clearly separate prediction, experience, and evaluation. For instance, PEexert could be used to predict subsequent pleasure anticipation or affective responses in later exercise sessions, allowing stronger tests of whether exertion-based prediction errors play a causal role in shaping affective experiences.

Second, the number of repeated sessions was limited to four, which constrained our ability to model more complex or non-linear learning trajectories. Nonetheless, this design was sufficient to capture a rapid early reduction in PEexert followed by relative stabilization, consistent with fast calibration dynamics described in predictive processing accounts (Clark, 2013; Friston, 2010). With only four repetitions, linear mixed-effects models provided a parsimonious summary of the dominant pattern, whereas more flexible temporal models would have been underpowered (Singer & Willett, 2003). Future studies using longer repeated-running protocols are needed to characterize the precise temporal form of exertion calibration and to test whether sustained reductions in prediction error relate to longer-term engagement or adherence.

Third, retrospective pleasure was assessed using a single item. This measure captured a global evaluative judgement of the session after completion rather than the momentary affective experience unfolding during the run (Ekkekakis et al., 2003). Accordingly, our findings were interpreted as relating to retrospective, not to in-task, pleasure. Nevertheless, single-item retrospective evaluations are also vulnerable to memory biases, including peak-end effects, whereby recall is disproportionately influenced by the most intense moment and the ending of the experience (Kahneman et al., 1993; Zenko et al., 2016). Future work should therefore combine temporally resolved affect measures (e.g., repeated in-task valence ratings) with post-exercise evaluations, to dissociate experienced affect from retrospective appraisal and to test whether PEexert relates similarly to both components (Ekkekakis & Petruzzello, 2002).

Since both pleasure and anxiety reduction may represent distinct stages within the same predictive updating process (e.g., pleasure mediating anxiety change; Harris et al., 2025), future work should adopt temporally resolved assessments to model their dynamic interplay. Combining such measures with path-analytic frameworks adapted to within-subject data (Montoya & Hayes, 2017) could allow for a more direct examination of mediation processes over time.

Fourth, the sample consisted predominantly of physically active individuals, and a subset was already familiar with the running environment (campus-based route). Although we statistically adjusted for prior trail familiarity, this restricted range in activity level and contextual experience may limit generalizability to less active or exercise-avoidant populations. It may also partly explain why certain hypothesized moderators (e.g., approach–avoidance tendencies toward physical effort) did not emerge as significant, as such effects may be more detectable in samples with greater variability in exercise engagement and effort-related attitudes (Herbert et al., 2007; O'Malley et al., 2023; Soriano-Maldonado et al., 2014). Future research should test the robustness of the PEexert–affect associations in more diverse samples, including individuals with elevated anxiety symptoms, to better evaluate generalizability and the scope of anxiety-related effects.

Finally, the segment-based analysis remains exploratory as it was not designed to test prediction error mechanisms per se (for a discussion on these findings; see Supplementary Materials, Section 4.3.). Nevertheless, the findings point to a fruitful direction: examining how the temporal segmentation of experience, both in anticipation and in memory, interacts with the affective meaning of exertion. Incorporating segment-level prospective predictions could help clarify whether affective learning during exercise operates continuously or through discrete, segment-like updates (Jeunehomme & D'Argembeau, 2020, 2021).

5.7. Conclusion

Repeated exposure to the same running route reduced prediction errors of perceived exertion (PEexert). More positive PEexert was associated with greater retrospective pleasure and larger reductions in state-anxiety, while route familiarity did not modify the strength of PEexert–affect associations. By integrating reward prediction error principles with predictive coding in a naturalistic running context, this study highlights PEexert as an ecologically valid marker linking anticipatory exertion to retrospective affective evaluation.

Data availability

Data and analyses are available in Open Science Framework (OSF): https://osf.io/zubt4/files

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CRediT authorship contribution statement

İrem Tuğçe Öz: Writing – review & editing, Writing – original draft, Visualization, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Bas de Geus:** Writing – review & editing, Supervision, Resources, Project administration. **Bénédicte Thonon:** Writing – review & editing, Methodology, Investigation, Formal analysis, Data curation. **Damien Brevers:** Writing – review & editing, Writing – original draft, Supervision, Methodology, Investigation, Formal analysis, Data curation, Conceptualization.

Declaration of competing interest

The authors report that there are no competing interests to declare.

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Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.peh.2026.100422.

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