Do you ever get tired of being wrong?

The unique impact of feedback on subjective experiences of effort-based decision-making

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Abstract

To achieve a goal, people have to keep track of how much effort they are putting in (effort monitoring) and how well they are performing (performance monitoring), which can be informed by endogenous signals, or exogenous signals providing explicit feedback about whether they have met their goal. Interventions to improve performance often focus on adjusting feedback to direct the individual on how to better invest their efforts, but is it possible that this feedback itself plays a role in shaping the experience of how effortful the task feels? Here, we examine this question directly by assessing the relationship between effort monitoring and performance monitoring. Participants ($N = 68$) performed a task in which their goal was to squeeze a handgrip to within a target force level (not lower or higher) for a minimum duration. On most trials, they were given no feedback as to whether they met their goal, and were largely unable to detect how they had performed. On a subset of trials, however, we provided participants with (false) feedback indicating that they had either succeeded or failed at meeting their goal (positive vs. negative feedback blocks, respectively). Sporadically, participants rated their experience of effort exertion, fatigue, and confidence in having met the target grip force on that trial. Despite being non-veridical to their actual performance, we found that the type of feedback participants received influenced their experience of effort. When receiving negative (vs. positive) feedback, participants fatigued faster and adjusted their grip strength more for higher target force levels. We also found that confidence gradually increased with increasing positive feedback and decreased with increasing negative feedback, again despite feedback being uniformly uninformative. These results suggest differential influences of feedback on experiences related to effort and further shed light on the relationship between experiences related to performance monitoring and effort monitoring.

Keywords: feedback; effort; fatigue; exertion; handgrip; confidence

To perform well and achieve their goals, people typically need to exert effort. However, increased effort does not always translate to better performance. For instance, when grabbing our morning cup of coffee and lifting it to our thirsty mouths, we need to finely calibrate our grip strength and muscle force – rather than simply gripping hard – or else we might end up with a broken mug or coffee all over our faces. In fact, and more generally, over the course of performing goal-relevant tasks well – especially in physically demanding settings – we continuously adjust and regulate our effort exertion in response to internal and external barriers to goal achievement (Bieleke & Wolff, 2020; Wolff et al., 2019). The experiences behind how we adjust our efforts have been studied in two largely parallel bodies of research – research on *effort monitoring*, which refers to how we assess and feel about our effort exertion, and research on *performance monitoring*, which refers to how we evaluate the extent to which we are meeting our goals through our effort exertion and how we incorporate performance feedback. These two lines of research have separately identified critical elements underlying people's experience of effort investment and how they choose whether to invest more or less effort towards their goal. Whether and how performance and performance monitoring interact – for instance, how perceptions of one's performance shape experiences of effort – is less well understood. Here, we seek to fill this gap.

Research on effort monitoring has characterized people's experiences of the cost of exerting effort over multiple timescales. Experiences of the *momentary* cost of effort investment (e.g., that experienced while lifting a set of weights) have been captured by measures of *perceived exertion*, which refers to the sensation of how hard one feels they are working on a task (Borg, 1982). This measure is thought to be tied to the physiological sensations arising from task workload and its associated effort exertion (e.g., respiration rate) (Chen, Fan, & Moe, 2002; de Morree and Marcora, 2015; Marcora, 2010). By contrast, experiences of the *cumulative* costs of effort investment have been captured by measures of *perceived fatigue*, which refers to the feeling of exhaustion from effort exertion (Boksem & Tops, 2008; Iodice et al., 2017; Massar et al., 2018; Müller & Apps, 2019; Müller et al., 2021). Fatigue fluctuates over extended time periods, and is generally thought to track increases in effort costs over the course of a task, reflecting the decreasing willingness to invest effort towards a goal over time (Massar et al., 2018; Müller & Apps, 2019; Müller et al., 2021). Experiences of perceived exertion and fatigue have been shown to be related during increasing physical exertion (e.g., Micklewright et al., 2017), but the two also diverge in important ways. For instance, at the point of exercise termination when effort investment is low, participants may rate experiencing high levels of fatigue and low levels of perceived exertion (Halperin & Emanuel, 2020; Micklewright et al., 2017). Conversely, low-difficulty tasks can induce low levels of momentary perceived exertion (Halperin & Emanuel, 2020) but still accumulate to high levels of fatigue when performed over long enough periods (Halperin & Emanuel, 2020; Milyavskaya et al., 2019).

A parallel line of research has captured a complementary aspect of effort investment, related to how an individual monitors and evaluates how effective their efforts have been for achieving a given goal. One source of such monitoring is internal estimates of one's confidence in their performance on a task, which are thought to reflect a combination of one's current and past experience with that task (Boldt, Schiffer, & Yeung, 2019; Frömer et al., 2021; Rouault et al., 2019). The other main way in which a person monitors their performance is based on feedback from their environment (Kluger & DeNisi, 1996; Rouault et al., 2019). For instance, negative feedback typically indicates that one's efforts were inadequate for meeting a goal, lowering the person's judgment of their overall performance (Kluger & DeNisi, 1996; Krenn et al., 2013) and prompting them to invest more effort or a different form of effort to improve their performance (Ilgen & Davis, 2000; Ilies & Judge, 2005; Kluger & DeNisi, 1996; Krenn et al., 2013).

Thus, prior work has separately characterized how people estimate (a) how much effort they have put into a task (and the associated momentary and cumulative costs) and (b) how well they are doing on that task. Neuroscientific research has elaborated on this further, identifying dissociable systems responsible for tracking estimates associated with effort versus performance monitoring (Clairis & Pessiglione, 2022; Lopez-Gamundi et al., 2021; Ridderinkhoff et al., 2004; Ulsperger, Danielmeier, & Jocham, 2014; Vaccaro & Fleming, 2018), providing further evidence that these are estimated independently. Is it possible, though, that experiences of effort costs are partly shaped by estimates of one's performance? For instance, in addition to directing effort adjustments, could negative feedback also shape one's experience of those effort costs? The current study seeks to address this question, by examining how the investment and experience of effort is shaped by task demands, time on task, and performance feedback.

An obstacle to answering this question is that effort investment, effort experience, and performance are often correlated (i.e., higher levels of effort are typically associated with feelings of greater exertion and increased confidence that a person will achieve their goal and receive feedback accordingly). Here, we designed a novel experimental paradigm to explicitly disentangle these three variables from one another and, critically, from an individual's own estimates of their own performance. Specifically, we de-correlated performance (i.e., goal achievement) from the amount of effort invested, and from feedback. Participants performing our task (Figure 1) exerted physical effort (squeeze a dynamometer) to maintain a target level of force for a given trial. We decoupled effort monitoring and performance monitoring (i.e., greater effort output did not entail better performance) by requiring participants to invest a specified level of effort (no more and no less) and omitting online feedback about their current grip force intensity, which made it challenging for them to internally monitor their own performance. On a subset of trials, we gave participants feedback either about whether they achieved their goal on that trial (positive feedback blocks) or only when they failed to do so (negative feedback blocks). Unbeknownst to the participants, this feedback was non-veridical, and thus tied neither to their effort output nor their performance, enabling us to examine the *unique* influence of negative feedback on the experience of effort. We periodically probed participants for ratings of perceived exertion and fatigue (indices of effort costs) and ratings of their confidence in their performance on a preceding trial (index of internal performance monitoring, occurring only on feedback-absent trials).

Briefly, we found that our indices of effort cost differentiated in their sensitivity to effort invested in our task across short timescales (perceived exertion) versus longer timescales (fatigue). Critically, we found that negative feedback influenced the longer timescales of effort costs – participants reported experiencing greater fatigue over time when receiving negative feedback than when they were experiencing positive feedback. We further show that under conditions where effort, performance, and feedback are decoupled, participants adjust their estimates of confidence based on cumulative positive or negative feedback over time, despite maintaining similar levels of true performance over that time.

Results

To examine the selective influence of feedback on the experience of effort-based performance, we had participants (N = 68) perform a task that required varying degrees of physical effort exertion (dynamometer grip force) (Figure 1). On each trial, participants were instructed to maintain a target level of grip force, indicated by a horizontal band on the screen, for a fixed duration of time (at least 1.5 seconds out of 2 seconds per trial). They were not given online feedback about their performance, and therefore had to rely on external feedback to determine whether they had met their goal. Feedback was only given on a subset (one-third) of trials and, depending on the task block, either informed them when they had *succeeded* in meeting their goal (*positive feedback* blocks) or when they had *failed* to meet that goal (*negative feedback* blocks). Critically, and unknown to the participants, this feedback was *non*-veridical and its presentation was determined by a pseudorandom ordering (subject to some constraints aimed at maintaining believability; see Methods). To measure variability in experiences of effort costs and performance over the course of the session, we probed participants after a randomly selected quarter of the trials (i.e., on average, after every 8 trials) to indicate their level of fatigue, perceived exertion, and confidence in their performance.

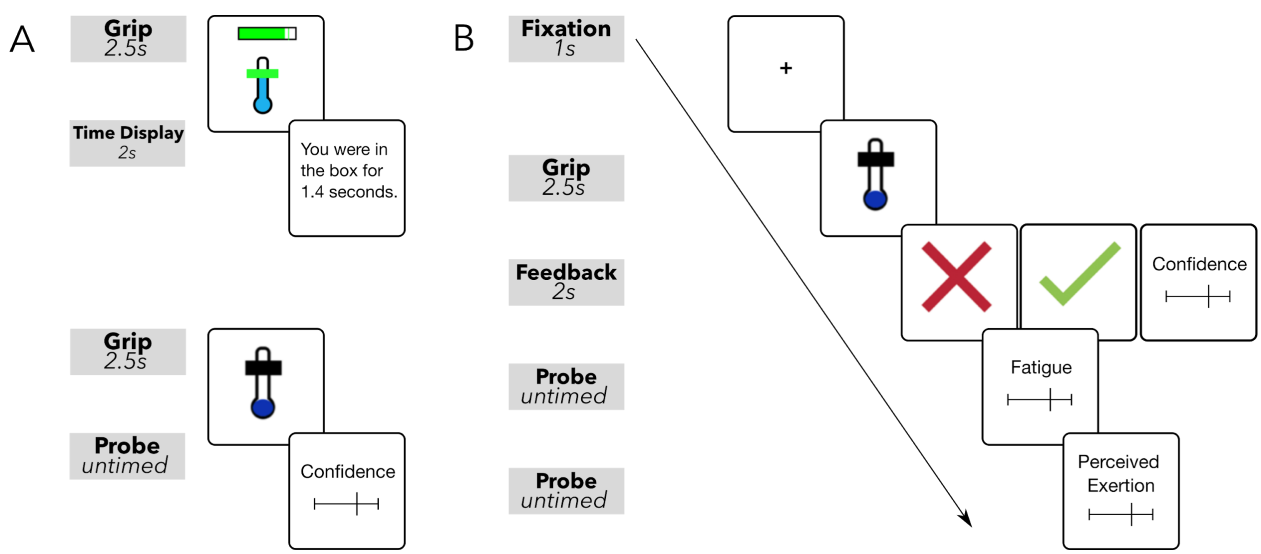

Figure 1. Handgrip Task Paradigm. A) After familiarizing themselves with the dynamometer, and prior to the main task, participants completed two practice rounds. In the first round, participants saw the duration their grip force was within the target range. In the second round, participants were not given any information about whether their grip force was within the range. They, afterwards, had to rate their confidence in meeting the target. **B)** In the main task, participants gripped the dynamometer to meet a target grip force without any information of their grip force during the trial or information about whether they met the target. The thermometer prompting participants to squeeze the dynamometer appeared for

2.5 seconds. Participants did not start gripping the dynamometer until a prompt appeared 0.5 seconds after the thermometer's appearance for them to start gripping. The prompt was that the blue circle at the bottom of the thermometer changed to light blue. In total, participants were expected to grip the dynamometer for 2 seconds out of the 2.5 seconds. Participants were then provided feedback, and were otherwise asked to rate how confident they were that they met the goal for that trial. For a quarter of the trials, participants rated their perceived exertion or fatigue at the end of the trial.

Effort output (grip force) varies with both effort demands and time on task

Overall, our task was successful at inducing participants to (a) successfully achieve at least the minimum level of force needed for a given trial, while at the same time being both (b) largely unsuccessful at achieving the accuracy criterion for a given trial and (c) unable to discriminate between correct and incorrect performance. Participants increased their grip force as the height of the trial target increased (a proxy for effort demands), ($\beta = 0.048$, SE = 0.003, $t(67.1) = 14.76$, $p < 0.001$) (Table 1), and decreased their grip force over the course of the session ($\beta = -0.009$, SE = 0.003, $t(67) = -3.23$, $p = 0.002$). Participants were also generally biased to overshoot the target, applying, on average, more rather than less force than the target range (average overshoot as distance from target % of target range distance from target center (e.g., 100% would be 1 target range distance from center) = 276%, *SE* = 11.8%). As a result, participants only spent an average of 0.703 seconds in the target force window, achieving the accuracy criterion (minimum of 1.5 seconds) on only 39% of trials.

Table 1. Effects of effort demands and trial number on grip force.

Coefficient	Estimate	SE	t-value	df	p-value
(Intercept)	0.176	0.011	16.2	67	< 0.001
Effort Demands (z-scored)	**0.048**	**0.003**	**14.76**	**67.1**	**< 0.001**
Trial Number (z-scored)	**-0.009**	**0.003**	**-3.23**	**67**	**0.002**
Effort Demands:Trial Number	**-0.003**	**0.001**	**-3.43**	**69.4**	**0.001**

Note. We conducted linear mixed model analyses using the model "Grip Force ~ 1 + Difficulty * Trial Number + (1 + Difficulty * Trial Number|Subject)".

Critically, participants were largely unaware of how well (or how poorly) they were performing at the task. We found that participants' confidence ratings were unrelated to their true accuracy ($\beta = 0.01$, SE = 0.01, t(49.1) = 1.34, p = 0.19; Figure S1), suggesting that we were successful in creating the conditions under which they would be unable to determine the veridicality of feedback. This enabled us to examine subjective experiences of effort and feedback, independent of true performance.

Fatigue and perceived exertion are tied to dissociable aspects of effort output

Effort is associated with experiences of exertion and fatigue (Boksem & Tops, 2008; Hockey, 1997, 2011; Iodice et al., 2017; Marcora, 2009; Massar et al., 2018; Molden, 2013; Molden et al., 2016; Moree et al., 2012; Müller & Apps, 2019). We examined the degree to which these two experiences mapped onto the same or different aspects of effort output on our task, and observed a clear dissociation. Perceived exertion tracked the amount of grip force on a given trial ($\beta = 0.01$, $SE = 0.002$, $t(46.7) = 4.81$, $p < 0.001$) but did not systematically vary over the course of the experiment ($\beta = 0.003$, $SE = 0.002$, $t(55.4) = 1.31$, $p = 0.19$; Table 2B). By contrast, fatigue was not sensitive to grip force on a given trial ($\beta = -0.002$, $SE = 0.002$, $t(37.4) = -0.78$, $p = 0.44$), but significantly increased over the course of the experiment ($\beta = 0.019$, $SE = 0.003$, $t(63.4) = 6.01$, $p < 0.001$; Table 2A). Confirming this apparent dissociation, we found a significant cross-over interaction whereby grip force had a significantly stronger association with perceived exertion than fatigue ($\beta = 0.01$, $SE = 0.003$, $t(31.72) = 3.28$, $p = 0.003$), and time on task had a significantly stronger association with fatigue than with perceived exertion ($\beta = 0.013$, $SE = 0.003$, $t(66.7) = 4.43$, $p < 0.001$) (see Table S1**)**. Notably, this increase in fatigue was not a reflection of increased effort or poorer objective performance. Rather, participants exerted *less* effort over time (see above) while maintaining the same level of accuracy ($\beta = -0.025$, $SE <$ 0.015, $t(67) = -1.7$, $p = 0.09$). Neither fatigue nor perceived exertion were associated with the interaction between effort output and trial number (ps>0.40).

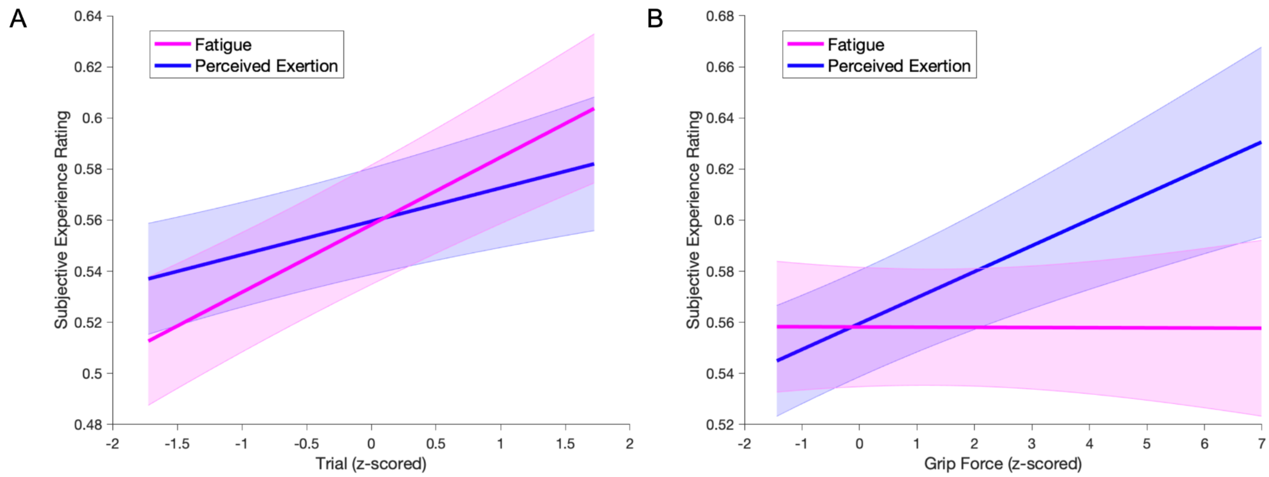

Figure 2. Effects of trial number and effort output on fatigue and perceived exertion. A) Experiences of fatigue (magenta) but not perceived exertion (blue) tracked the number of trials that had transpired by that point in the session. **B)** By contrast, perceived exertion but not fatigue tracked the amount of effort that a participant had put in on that trial. Lines show predicted values based on relevant mixed-effects regressions, and shaded errors reflect 95% confidence intervals. Trial and effort output (measured by grip force) were z-scored prior to analysis. See also Table S1.

Table 2. Effects of trial number and grip force on fatigue and perceived exertion

Coefficient	Estimate	SE	*t*-value	df	*p*-value
A. Fatigue					
Intercept	0.559	0.010	56.14	62.2	< 0.001
Trial Number (z-scored)	**0.019**	**0.003**	**6.01**	**63.4**	**< 0.001**
Grip Force (z-scored)	-0.002	0.002	-0.78	37.4	0.44
Perceived Exertion (z-scored)	**0.029**	**< 0.001**	**5.78**	**76.7**	**< 0.001**
Confidence (z-scored)	**-0.006**	**0.002**	**-2.73**	**75.5**	**0.01**
Trial Number:Grip Force	0.001	0.002	0.66	69.6	0.51
B. Perceived Exertion					
Intercept	0.56	0.01	75.7	54.7	< 0.001
Trial Number (z-scored)	0.003	0.002	1.31	55.4	0.19
Grip Force (z-scored)	**0.01**	**0.002**	**4.81**	**46.7**	**< 0.001**
Fatigue (z-scored)	**0.04**	**0.004**	**9.05**	**79.5**	**< 0.001**
Confidence (z-scored)	0.002	0.002	0.81	50.8	0.42
Trial Number:Grip Force	-0.003	0.002	-1.6	55.3	0.12

Note: We conducted linear mixed model analyses using the model: "Fatigue ~ 1 + Trial Number * Grip Force + Confidence + Perceived Exertion + (1 + Trial Number * Grip Force + Confidence + Perceived Exertion|Subject)" to analyze variables associated with fatigue. To analyze variables associated with perceived exertion, we used the model “Perceived Exertion ~ 1 + Trial Number * Grip Force + Confidence + Fatigue + (1 + Trial Number * Grip Force + Confidence + Fatigue|Subject)”.

Fatigue increases more rapidly when receiving negative relative to positive feedback

Experiences of fatigue on our task were thus largely unrelated to the objective effort that participants were putting into the task, suggesting that other sources of information in the task influenced fatigue. We tested whether performance feedback served as one such source of information. In particular, we tested whether participants experienced the task as more fatiguing when they were getting negative rather than positive feedback. We found that this was in fact the case. Experiences of fatigue increased more over time when receiving negative rather than positive feedback ($\beta = 0.018$, $SE = 0.007$, $t(59.7) = 2.62$, $p = 0.01$) (Table 3A; Figure 3A). These steeper increases in fatigue were not accounted for by changes in perceived exertion, which did not vary over time as a function of feedback type ($\beta = -0.002$, $SE = 0.006$, $t(63.1) = -0.41$, $p = 0.62$; Table S2), nor were they accounted for by changes in grip force (which also did not vary over time as a function of feedback type; Table S3) or by the interaction of feedback and grip force (Table S2).

By contrast to fatigue, perceived exertion was not influenced by the type of feedback the participant was receiving. The relationship between perceived exertion and grip force remained the same whether the participant was receiving positive or negative feedback (Table 3B; Figure 3B).

Table 3. Feedback interaction effects on fatigue and perceived exertion

Coefficient	Estimate	SE	*t*-value	df	*p*-value
A. Fatigue					
Intercept	0.555	0.011	50.12	61.7	$p < 0.001$
Trial Number (z-scored)	**0.022**	**0.006**	**4.02**	**56.4**	$\boldsymbol{p < 0.001}$
Grip Force (z-scored)	-0.002	0.002	-1.06	35.4	0.30
Negative - Positive Feedback	**0.018**	**0.008**	**2.11**	**51.2**	**0.04**
Perceived Exertion (z-scored)	**0.024**	**0.005**	**4.82**	**77.9**	$\boldsymbol{p < 0.001}$
Confidence (z-scored)	-0.002	0.002	-1.00	164.0	0.32
Trial Number:Grip Force	0.000	0.002	0.13	70.0	0.90
Trial Number:Negative Feedback	**0.018**	**0.007**	**2.62**	**59.7**	**0.01**
B. Perceived Exertion					
Intercept	0.561	0.008	73.03	53.7	$p < 0.001$
Trial Number (z-scored)	0.003	0.002	1.48	47.3	0.15
Grip Force (z-scored)	**0.012**	**0.003**	**3.79**	**37.1**	$\boldsymbol{p < 0.001}$
Negative - Positive Feedback	0.001	0.004	0.31	121.6	0.76
Fatigue (z-scored)	**0.039**	**0.004**	**8.95**	**77.8**	$\boldsymbol{p < 0.001}$

Confidence (z-scored)	0.002	0.002	0.88	50.5	0.38
Trial Number:Grip Force	-0.002	0.002	-1.26	46.0	0.22
Grip Force:Negative Feedback	-0.001	0.003	-0.37	50.0	0.71

Note. We conducted linear mixed model analyses using the model "Fatigue ~ 1 + Negative - Positive Feedback * Trial Number + Grip Force + Trial Number * Grip Force + Confidence + (1 + Negative - Positive Feedback * Trial Number + Grip Force + Trial Number * Grip Force + Confidence|Subject)" to analyze feedback effects associated with fatigue. To analyze feedback effects associated with perceived exertion, we used the model "Perceived Exertion ~ 1 + Negative Feedback * Grip Force + Trial Number + Trial Number * Grip Force + Confidence + (1 + Negative - Positive Feedback * Grip Force + Trial Number + Trial Number * Grip Force + Confidence|Subject)".

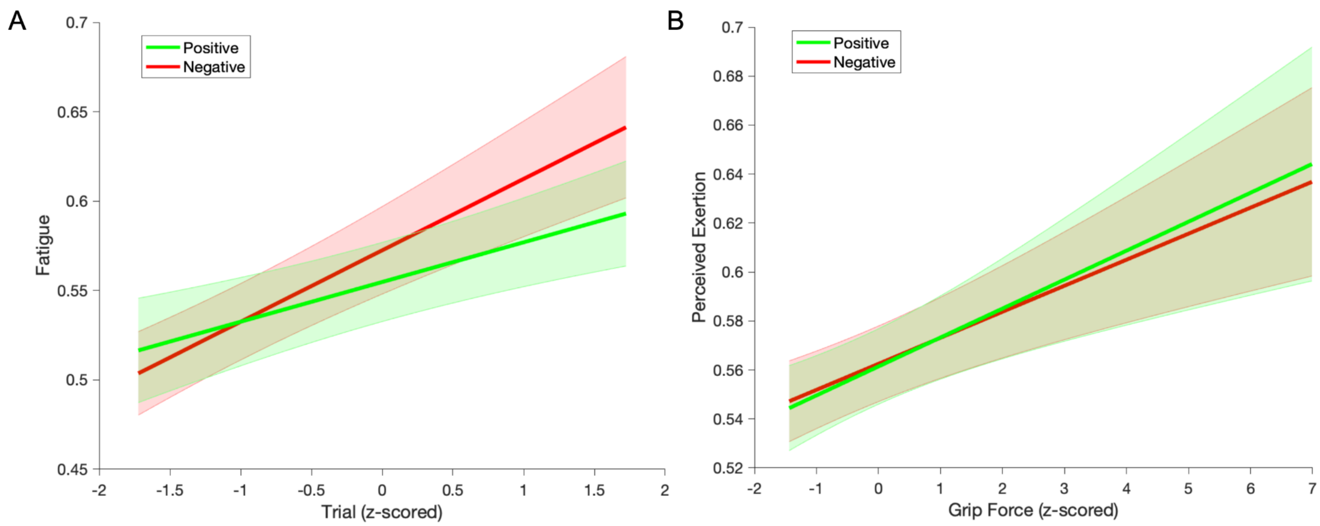

Figure 3. Feedback interaction effects with time and effort output on subjective experiences of effort. The predicted values of fatigue and perceived exertion associated with feedback's interaction effects with time and grip force are shown. **A)** Fatigue increased over time (z-scored) with greater increases in the negative feedback condition. **B)** There was no significant influence of feedback condition on the relationship between grip force (z-scored) and perceived exertion. Lines show predicted values based on relevant mixed-effects regressions, and shaded errors reflect 95% confidence interval for predicted values.

Negative feedback increases the sensitivity of effort output to task difficulty

We noted earlier that participants increased their effort output (grip force) as the target difficulty level increased, and they decreased their effort output over the course of the session (Table 1). We found that the former was modulated by feedback condition, such that a participant's grip force was more sensitive to the demands of given trial (i.e., increased more) when they were in the negative feedback compared to the positive feedback block ($\beta = 0.005$, $SE = 0.002$, $t(56.2) = 2.63$, $p = 0.01$; Figure 4B; Table S3). Negative feedback did not influence the rate at which grip force decreased over time (β = 0.001, *SE* = 0.008, *t*(67) = 0.12, *p* = 0.9; Figure 4A; Table S3), nor did we find a main effect of negative feedback on grip force (β = 0.008, *SE* = 0.007, *t*(66.3) = 1.24, *p* = 0.22; Table S3).

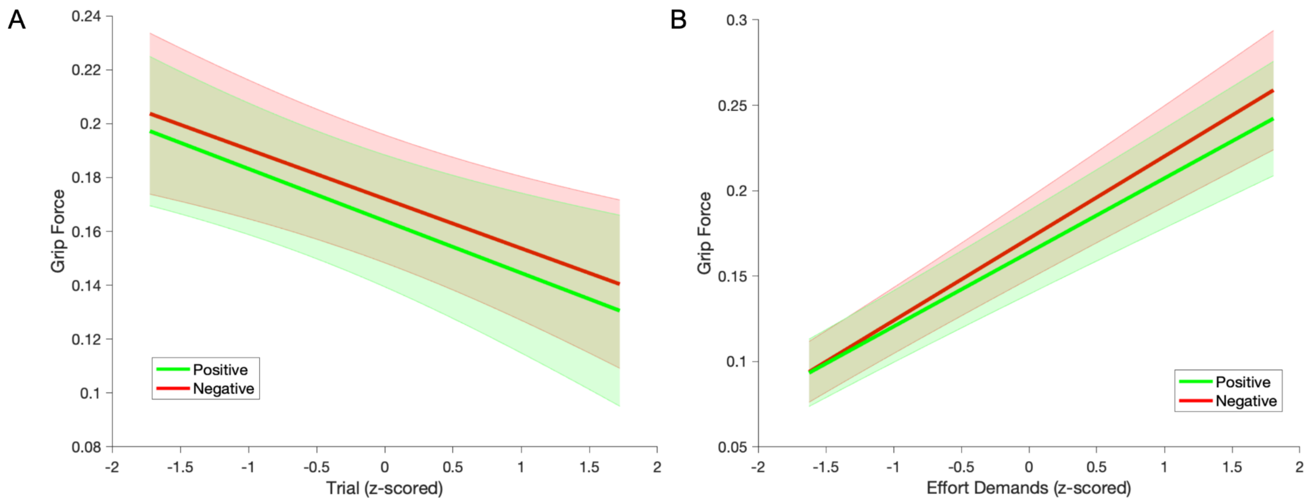

Figure 4. Feedback interaction effects with time and effort demands on effort output.
The predicted grip force associated with feedback's interaction effects with time and effort demands are shown. A) Grip force decreased over time (z-scored), but feedback did not show a significant influence on the rate of this decline. B) Grip force increased as effort demands (z-scored) increased, with greater increases in the negative feedback condition. Lines show predicted values based on relevant mixed-effects regressions, and shaded errors reflect 95% confidence interval for predicted values.

Confidence reflects cumulative feedback, despite both being decoupled from performance

Previous work has consistently shown that participants can closely monitor their performance on a task, and that their experiences of confidence in their performance are generally well-calibrated to how they are actually doing (Eva et al., 2012; Fleming & Daw, 2016; though see Kelemen et al., 2000, Song et al., 2011, and Fleming & Lau, 2014 for discussion of variability in confidence calibration). These studies typically examine confidence under conditions where performance can be assessed from internal monitoring, that is, tasks that are relatively easy or well-trained and where feedback is thus largely redundant with those experiences (Holroyd & Coles, 2002) . In other words, participants in these studies are often aware of how likely it is that they were correct (see e.g., Rouault, Dayan, & Fleming, 2019). However, internal performance monitoring is not the only cue to confidence (Boldt, Schiffer, & Yeung, 2019; Fassold, Locke, & Landy, 2023; Locke, Landy, & Mamassian, 2022); external feedback can play a role in further calibrating confidence, independent of participants' internal awareness of their performance (Kluger & DeNisi, 1996; Rouault et al., 2019). Our task was uniquely suited to test how feedback impacts confidence independently of performance, since feedback was non-veridical, and people were not able to accurately assess their performance. This is in stark contrast to previous research on confidence monitoring, where feedback is either performance-contingent or absent.

Participants in our task were sporadically probed to report how confident they were that they met (vs. failed to meet) the goal on the most recent trial (in addition to reporting levels of fatigue and exertion). These confidence probes were given in lieu of feedback on those trials. As noted earlier, these ratings confirmed that participants were unsuccessful at internally monitoring their true performance. We tested whether confidence may have nonetheless tracked the (non-veridical) feedback participants were receiving over the course of the task. Importantly, the way feedback was structured in our task, with a random subset of trials indicating either success (positive feedback blocks) or failure (negative feedback blocks), this feedback should not have been taken to be informative about overall performance on that block (i.e., in either block, the feedback-absent trials could have been inferred to be equally likely to be successes as failures). In spite of this, we found that participants were substantially less confident in their performance when they were receiving negative feedback relative to when they were receiving positive feedback ($\beta = -0.03$, $SE = 0.01$, $t(83.5) = -3.58$, $p < 0.001$; Table 4).

Confidence also varied over the course of a given block, as feedback accumulated (Figure 5; Table 4), and the direction of this relationship depended heavily on the type of feedback participants were receiving. Over the course of positive feedback blocks, participants grew more confident each time they received feedback ($\beta = 0.002$, $SE = 0.001$, $t(62.7) = 4.12$, $p < 0.001$); conversely, over the course of negative feedback blocks, we found the opposite: confidence instead *decreased* with cumulative feedback ($\beta = -0.004$, $SE = 0.001$, $t(65.9) = -5.09$, $p < 0.001$). This was despite the fact that trial difficulty and performance were equivalent across the two conditions, and remained equivalent across trials within a condition. While there was a numerical trend for confidence to decrease more with cumulative negative feedback than it increased with cumulative positive feedback, a z-test for equality of regression coefficients did not reveal significant differences between the absolute value of the slopes ($z = -0.14$, $p = 0.89$). The effects of cumulative feedback on confidence were not explained by variability in effort exertion, accuracy, fatigue, or perceived exertion (see Table S4).

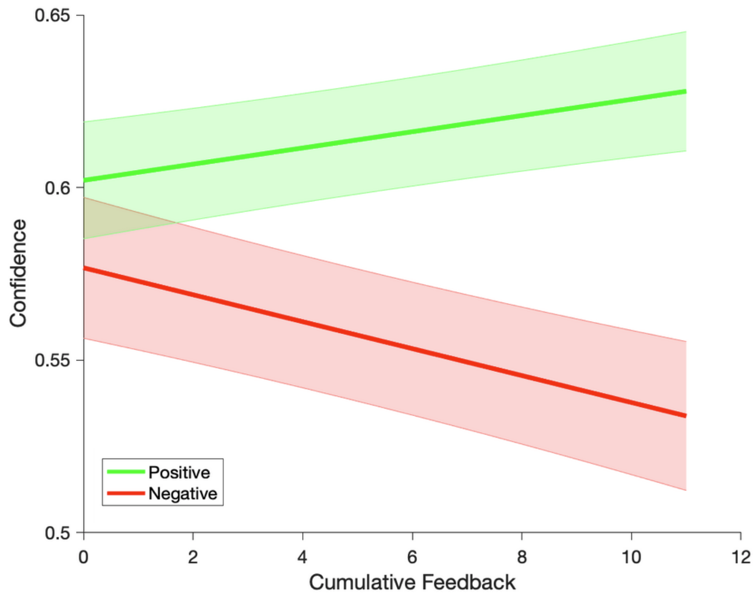

Figure 5. Effects of cumulative feedback on confidence. Confidence increased in the positive feedback condition over time but decreased in the negative feedback condition. This effect was not shown with effort exertion, accuracy, fatigue, or perceived exertion.

Table 4. Effects of feedback on confidence.

Coefficient	Estimate	SE	*t*-value	df	*p*-value
Intercept	0.602	0.008	71.00	69.3	$p < 0.001$
Cumulative Feedback	**0.002**	**0.001**	**3.81**	**140**	$\boldsymbol{p < 0.001}$
Negative - Positive Feedback	**-0.025**	**0.007**	**-3.58**	**83.5**	$\boldsymbol{p < 0.001}$
Cumulative Feedback:Negative Feedback	**-0.006**	**0.001**	**-6.6**	**96.5**	$\boldsymbol{p < 0.001}$

Note: We conducted linear mixed model analyses using the model “Confidence ~ 1 + Cumulative Feedback * Negative Feedback + (1 + Cumulative Feedback * Negative - Positive Feedback|Subject)”.

Discussion

In this study, we examined the relationship between performance monitoring and effort monitoring in a task that deconfounded feedback, performance and effort exertion. Specifically, participants had to meet a target grip force that varied from low grip force to high grip force and were presented with only negative (unbeknownst to them, non-veridical) feedback in a subset of trials in one condition and only positive feedback in another. This design meant that performance was independent of effort, and that participants could not rely on feedback to assess their true performance; for example, in the negative feedback condition, even if participants performed well, they would not be presented with positive feedback. Broadly, we found that feedback influences fatigue and confidence but not perceived exertion. Negative compared to positive feedback exacerbated the increase of fatigue over time, but did not modulate perceived exertion, or its increase with trial-by-trial grip force. Confidence ratings decreased in the negative feedback condition but increased in the positive feedback condition, suggesting that participants integrated feedback into their confidence ratings; this integration of feedback into confidence judgments was mirrored by a greater increase of effort exertion with increasing difficulty in the negative feedback condition, compared with the positive feedback condition. These findings corroborate that feedback affects effort monitoring and performance monitoring independently of true performance, and highlight dissociations between fatigue and perceived exertion as distinct experiences related to effort exertion.

Previous studies have shown that feedback influences the motivation to invest effort and perceived effort exertion **(**Hutchinson et al., 2008; Raaijmakers et al., 2017; Venables & Fairclough, 2009**)**. However, in these studies, more effort resulted in better task performance (Hutchinson et al., 2008; Raaijmakers et al., 2017; Venables & Fairclough, 2009), making it impossible to tease apart the impact of feedback from participants' awareness of how they should adjust their performance. We found that when these are explicitly dissociated, feedback did not influence perceived exertion. Instead, perceived exertion was tied to effort output, suggesting that participants relied on cues other than their performance outcome to evaluate perceived exertion. This is consistent with the proposal that perceived exertion is characterized as a sensation of physical effort itself (Borg, 1982; Chen, Fan, & Moe, 2002; de Morree and Marcora, 2015; Marcora, 2009; Marcora, 2010; Morree et al., 2012; Pageaux & Lepers, 2016) and may be tied to central motor commands from the brain to active muscles that drive muscle exertion (corollary discharge) (Abbiss et al., 2015; de Morree and Marcora, 2015; Marcora, 2009; Marcora, 2010). Yet, participants did rely on feedback to adjust their effort expenditure on the subsequent trial, specifically increasing effort expenditure on harder trials following negative feedback. Because this feedback was non-veridical and selective, such that participants could not learn their true performance based on feedback alone, these results suggest that, while participants may not have used feedback to evaluate perceived exertion, they did interpret negative feedback, in general, as a signal to increase effort expenditure.

Unlike perceived exertion, feedback did influence participants' experience of fatigue. When receiving negative feedback, participants reported experiencing greater fatigue over time than when they were receiving positive feedback. The finding that feedback modulated ratings of fatigue but not perceived effort exertion may be accounted for by the different roles these measures play in the subjective experience of effort. Specifically, perceived exertion has typically been tied to momentary evaluations of effort investment, while fatigue has been tied to accumulating evaluations of effort cost, i.e., increasingly reduced willingness to exert effort (Massar et al., 2018; Müller & Apps, 2019; Müller et al., 2021). These findings corroborate the notion that fatigue, unlike perceived exertion, seems to be motivational. While perceived exertion reflects how hard it feels to exert force onto the dynamometer, fatigue may reflect the accumulated costs of exerting force onto the dynamometer (which have to be weighed against the rewards/value of this force exertion) as time elapses. With its role as a signal to improve performance (by either increasing or decreasing effort), feedback informs how effort should be invested (Kluger & DeNisi, 1996). Fatigue, as an experience more directly tied to motivation and the long-term valuation of effort investment (Müller & Apps, 2019), may therefore be better suited as an experience more influenced by feedback, compared with perceived exertion, which is more tied to the momentary sensation of physical effort exertion itself. The greater increase in fatigue levels over time with negative feedback (versus with positive feedback) further supports a view of negative feedback as adding to this perceived cumulative cost of exerting effort, though whether this cumulative cost signal is based on cognitive engagement during the task, physical effort exertion alone, or both is beyond the scope of the study.

Our findings dovetail with a recent study that found that performance-contingent negative feedback (i.e., on error trials) led to increases in fatigue on mentally demanding tasks (Matthews et al., 2023). While that study also examined fatigue due to physical effort, there were insufficient errors to test for a similar relationship in that domain. Our findings not only fill this important gap but also potentially shed new light on the source of their findings in the cognitive domain. Unlike in that study, participants in our study were given feedback that was non-contingent on their performance, and our physical effort task was designed so that it was difficult to determine accuracy while exerting effort during the trial. Collectively, these factors made it so that participants in our study were unable to anticipate feedback based on online monitoring of effort or confidence while performing the task. Thus, in addition to revealing a complementary finding to this previous study in the physical effort domain, our findings point to the intriguing possibility that error-related fatigue in the cognitive effort domain may relate more to the anticipation of negative outcomes rather than errors per se.

We found additional evidence that confidence judgments integrate previous experiences related to the task (Rouault et al., 2019). Specifically, we found that participants integrate the feedback presented to them, even when this feedback is decoupled from true performance and when more effort does not necessarily translate to better performance. Participants reported more confidence with each instance of positive feedback, and less confidence with each instance of negative feedback. This is notable for two reasons. First, it suggests that participants were not basing these confidence ratings on their actual performance (i.e., accuracy), which was in fact quite stable (and poor) over the course of the session. Second, veridicality notwithstanding, the feedback itself did not indicate that participants were better or worse in one condition than the other, nor that their performance was improving or worsening overall. Instead, participants were told that they would only receive feedback on a subset of trials on which they had performed well (positive feedback blocks) or poorly (negative feedback blocks); this sporadic feedback distribution meant participants could have reasonably inferred that the trials where feedback was omitted were trials in which their performance were contrary to the feedback condition block. The finding that they instead adjusted their confidence flexibly around accumulated feedback, in the context of this feedback manipulation, adds to the literature on how strongly individuals may rely on feedback when monitoring their performance, particularly in the absence of other reliable sources of information (Holroyd & Coles, 2002; Kluger & DeNisi, 1996; Rouault et al., 2019).

This disconnect between true performance and the integration of feedback into performance monitoring was further reflected in effort output. As the target grip force increased (i.e., when task difficulty increased), participants were prone to overshoot and increase their effort output, an effect that was enhanced in the negative feedback condition relative to the positive feedback condition. Because our experimental paradigm orthogonalized task performance (i.e., accuracy) from physical effort exertion, this increase in effort exertion was not directly tied to accuracy. Here, we show that even if more effort exertion does not actually improve accuracy, participants may *perceive* that they should exert more effort to improve performance in the presence of negative feedback. Though it is often true that more effort leads to better performance, this finding highlights that people may overgeneralize this strategy to instances where it is not adaptive, such as in cases when a fine calibration of grip force is needed (rather than simply greater grip force).

Overall, these results may imply that feedback can be adaptively tailored to influence experiences related to effort monitoring and performance monitoring, providing another avenue of research relevant to applications for interventions in sports performance (Schenk & Miltenberger, 2019). For example, an athlete's performance may be limited by either how tired they feel or their perceived exertion (Marcora, 2009; Van Cutsem et al., 2017). Our findings suggest that if the main limitation to an athlete's performance is fatigue, feedback interventions aimed at improving performance over the course of a session may be aided by the use of positive feedback emphasizing when an athlete is performing well, rather than negative feedback. In fact, in the motor domain, people specifically seek and learn better from (performance contingent) positive feedback (Chiviacowsky & Wulf, 2002; 2005; 2007). If these results are extendable to cognitive effort, another important avenue of research may be in the domain of education (Covington, 2000; Tricomi & DePasque, 2016). While feedback interventions are widely used to improve student performance, improvements on these interventions' efficacy requires understanding the interactions between how feedback is provided and its subsequent effects on motivation (Covington, 2000; Fishbach et al., 2010; Ilgen & Davis, 2000; Krenn et al., 2013). Here, our findings suggest that one potential moderator of how feedback interventions translate into effort exertion strategies and subsequent performance may lie in how feedback is integrated into effort and performance monitoring. Thus, it is worth further investigating the different properties of feedback. For example, future research on feedback may find interest in using a neutral feedback condition to examine the effects of negative feedback in particular. Examining whether these findings generalize to more informative feedback, such as feedback detailing how to correct task performance, may be of interest as well (e.g., Kim et al., 2018).

Materials and Method

Participants

68 participants, aged 18-45 (mean = 19.3, SD = 1.54; 46 females, 22 males) with normal or corrected-to-normal vision, were recruited from Brown University's psychological experiments subject pool. Participants were compensated either $10 or 1 course credit per hour for their time.

Procedure

Participants were asked to meet a target grip force, indicated by a band on the thermometer, for the majority of the trial duration. Prior to this main task, to calibrate the handgrip strength for each participant, maximum voluntary contraction (MVC) was assessed, before participants completed three practice rounds. After the main task, we debriefed the participants about the task.

Main Task

On each trial, participants saw a fixation cross (1s), followed by a thermometer that was overlaid with a black band that indicated the target grip force range (2.5s). The thermometer height mapped onto each participants' maximum grip force, and the target grip force varied along it across trials. While the thermometer was on the screen, participants had to attempt to exert the level of grip force indicated by the black box. Their performance was considered accurate so long as their grip force remained within this target range. We started calculating accuracy after a 500 ms offset when the trial initiated, making a total time of 2 seconds out of 2.5 seconds during which participants were expected to be in the box. After a trial was over, for a subset of trials following their effort exertion, participants were shown either feedback on whether they met the goal, or a prompt to rate their confidence, periodically followed by prompts to rate their effort exertion and fatigue (Figure 1).

Feedback varied between two halves of the main task, such that participants were only ever presented with either positive or negative feedback. Participants were explicitly informed about this selective feedback and the current type in the beginning of each block. The order of feedback type was counterbalanced across participants, and feedback was sporadically provided for a third of the trials in each block (11 trials out of the 33 trials in each block). Unbeknownst to the participants, feedback was unrelated to their performance but presented on a pseudo-randomly selected third of the trials. We ensured that feedback trials were spread out across the entire duration of each block to avoid anticipation effects, and provided feedback only when performance fell within one quarter of each participants' maximum grip force around the target to avoid suspicion. We had found in previous pilots that within this range, participants could not judge their own performance.

If participants did not receive feedback for the trial, we asked them to rate their confidence in meeting the target for that trial. These confidence measures allowed us to probe participants' sensitivity to their own performance and to test whether participants would use feedback to inform these judgments.

To probe participants' subjective experience of effort during the task, we periodically asked participants, throughout each block (for around every 8 trials, i.e., a quarter of the trials in each block), to rate their perceived level of exertion, which reflects their perceived effort investment, and how tired they currently felt, which reflects their perceived effort costs (see Materials and Measures). The starting point on the scale in which participants would move with the cursor to give their ratings was randomized during the presentation of these ratings for each probe. All ratings were made on a visual analog scale with participants' non-dominant hand.

The main task was split up into 6 blocks of 33 trials each (198 trials total) and participants were instructed to take at least a 1-minute break before continuing to the next block to avoid becoming overly fatigued.

Calibration

To calibrate the required grip force and display, we recorded each participants' maximum voluntary contraction (MVC). We asked participants to grip as hard as possible for two seconds, and we then took the average of 250 points of handgrip measurements for this time interval (i.e., sampling rate of 125 Hz) as our MVC measure.

Practice Rounds

Prior to the main task, participants completed three practice rounds. Participants were first acquainted with the handgrip and how their grip force translates to the thermometer displayed on the screen. They performed three trials of ten seconds each, in which their current grip force was displayed online as the mercury level on the thermometer. Participants were not given a specific target, but just asked to explore.

In the second round, participants had to meet a target grip force, indicated with a band on the thermometer, for the majority of the trial duration. They received online feedback on whether they were in the target range (indicated by the band turning green), and how much time in that range they had accumulated (indicated by an additional progress bar). On the progress bar, we displayed a green tick mark that indicated the target duration of time participants had to maintain their target grip force for the trial. Successful performance for the trial was indicated by the progress bar passing this green tick mark. At the end of each trial, participants were shown how long they maintained the target grip force during the trial.

In the third practice round, participants performed the same task, but without any online feedback about their task performance. At the end of each trial, we asked participants to rate their confidence.

The second and third practice rounds comprised a total of 10 trials each, with a 1s fixation point in between each trial.

Materials and Measures

We used MATLAB version R2009b (Psychtoolbox version 3.0.0) to present stimuli on a computer screen and to log handgrip and keyboard responses. Handgrip responses were recorded from Biopac's isometric dynamometer TSD121C using the acquisition system Biopac MP150 at a rate of 200 Hz over the whole duration of a trial (2.5s).

Physical effort was quantified as average grip force for each trial, where average grip force is proportional to each participants' maximum grip force (range 0 to 1).

Performance accuracy was quantified as the proportion of the trial duration that was spent within the target range (0 to 1). We started calculating performance accuracy after a 500 ms offset occurring when the trial initiated. The minimum average accuracy score we instructed participants to attempt to meet was equivalent to 0.75 for each trial (i.e., 1.5 seconds in the target range).

Ratings were performed on a visual analog scale by moving a tick mark using the left and right arrow keys on a standard keyboard. To prevent the starting tick mark location from anchoring participants' ratings, the tick mark was initially displayed at a random location on the scale. To rate their confidence, participants were prompted with the message: "Please rate on the scale where represents how confident you are that for majority of the trial, your grip force was within the range of the black box." and the anchors "certainly not within the box" and "certainly within." To rate their perceived exertion, participants were prompted with the message: "Please rate where on the scale describes your level of exertion (how hard you feel you are working)." and the anchors "extremely light effort" and "extremely hard effort." Finally, to rate how tired they felt, participants were prompted with “Please rate where on the scale represents how tired you felt for the past few trials.” and the anchors “not tired at all” and “extremely tired.” All ratings were scaled to a range of 0 to 1.

Analyses

All analyses were conducted using MATLAB 2022b. The following independent variables related to the main task were considered: time (measured as a z-score of overall trial number within the task), effort demand (measured as a z-score of the target grip force which was indicated by the center of the box location on the thermometer in pixels; this ranged from 38% of their MVC to 53%), and feedback condition (measured as either 1 if participants were in the negative feedback condition or 0 if they were in the positive feedback condition). The dependent variables of interest consisted of physical effort exertion measured by grip force, performance accuracy, and each measure of participants’ subjective experiences (confidence, perceived exertion, and fatigue).

We analyzed data using linear mixed-effects models with MATLAB’s *fitlme* function, fitting fixed and random slopes for each independent variable, as well as random intercepts for each participant (Barr et al., 2013). Degrees of freedom for fixed effects were estimated using Satterthwaite approximation.

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Supplementary Material

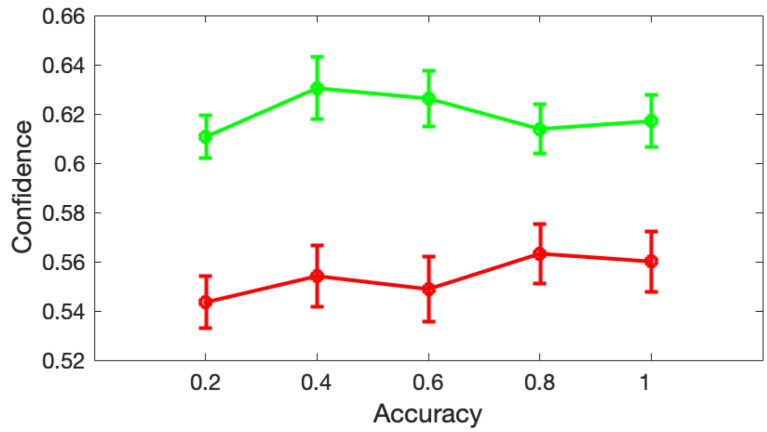

Figure S1. Raw values of confidence by accuracy.
The raw values of confidence are plotted against increasing, binned levels of accuracy in participants, showing similar levels of confidence regardless of accuracy level across both feedback conditions. The green curve reflects confidence and accuracy under the positive feedback condition, while the red curve reflects them under the negative feedback condition. Error bars reflect standard error.

Table S1. Effects of effort output (grip force) and trial number on fatigue and perceived exertion

Coefficient	Estimate	SE	*t*-value	df	*p*-value
(Intercept)	0.56	0.01	53.66	65.63	< 0.001
isFatigue - isPerceivedExertion	-0.001	0.008	-0.17	65.17	0.87
Confidence (z-scored)	-0.004	0.002	-1.56	58.51	0.12
Grip Force (z-scored)	**0.01**	**0.002**	**4.71**	**30.38**	**< 0.001**
Trial Number (z-scored)	**0.013**	**0.003**	**3.75**	**67.33**	**< 0.001**
isFatigue:Grip Force	**-0.01**	**0.003**	**-3.28**	**31.72**	**0.003**
isFatigue:Trial Number	**0.013**	**0.003**	**4.43**	**66.69**	**< 0.001**

Note. We conducted linear mixed model analyses using the model "Rating Value ~ 1 + isFatigue * Grip Force + isFatigue * Trial Number + Confidence + (1 + isFatigue * Grip Force + isFatigue * Trial Number + Confidence|Subject)", where Rating Value is the value participants rated during the probe and isFatigue - isPerceivedExertion indicates whether a rating was made in response to a fatigue probe versus a perceived exertion probe.

Table S2. Additional feedback interaction effects on fatigue and perceived exertion

Coefficient	Estimate	SE	t-value	DF	p-value
A. Fatigue					
Intercept	0.551	0.011	51.422	61.806	1.94E-52
Trial Number (z-scored)	0.030	0.005	6.528	55.705	2.12E-08
Grip Force (z-scored)	-0.005	0.003	-1.959	37.449	0.058
Negative Feedback - Positive Feedback	0.015	0.008	1.896	49.613	0.064
Perceived Exertion (z-scored)	0.025	0.005	4.943	78.043	4.30E-06
Confidence (z-scored)	-0.003	0.002	-1.802	95.420	0.075
Trial Number:Grip Force	0.002	0.002	1.026	39.215	0.311
Negative Feedback:Grip Force	0.007	0.004	1.842	33.889	0.074
B. Perceived Exertion					
(Intercept)	0.558	0.008	68.028	53.185	2.13E-53
Trial Number (z-scored)	0.005	0.003	1.557	55.220	0.125
Grip Force (z-scored)	0.010	0.002	4.589	46.253	3.42E-05
Negative Feedback - Positive Feedback	0.002	0.004	0.605	76.707	0.547
Fatigue (z-scored)	0.038	0.004	9.016	77.858	1.02E-13
Confidence (z-scored)	0.002	0.002	0.728	53.344	0.470
Trial Number:Grip Force	-0.002	0.002	-1.152	55.594	0.254
Negative Feedback:Trial Number	-0.002	0.006	-0.414	63.102	0.681

Note. We conducted linear mixed model analyses using the model "Fatigue ~ 1 + Negative - Positive Feedback * Trial Number + Grip Force + Trial Number * Grip Force + Confidence + (1 + Negative - Positive Feedback * Trial Number + Grip Force + Trial Number * Grip Force + Confidence|Subject)" to analyze feedback effects associated with fatigue. To analyze feedback effects associated with perceived exertion, we used the model "Perceived Exertion ~ 1 + Negative Feedback * Grip Force + Trial Number +

Trial Number * Grip Force + Confidence + (1 + Negative - Positive Feedback * Grip Force + Trial Number + Trial Number * Grip Force + Confidence|Subject)".

Table S3. Feedback interaction effects on grip force.

Coefficient	Estimate	SE	*t*-value	df	*p*-value
Intercept	0.164	0.012	13.35	67	< 0.001
Trial Number (z-scored)	**-0.019**	**0.006**	**-3.28**	**66.8**	**< 0.001**
Negative - Positive Feedback	0.008	0.007	1.24	66.3	0.22
Difficulty (z-scored)	**0.043**	**0.003**	**12.82**	**65.2**	**< 0.001**
Trial Number:Negative Feedback	0.001	0.008	0.12	67	0.90
Trial Number:Difficulty	**-0.004**	**0.002**	**-2.24**	**64.3**	**0.03**
Negative Feedback:Difficulty	**0.005**	**0.002**	**2.63**	**56.2**	**0.01**
Trial Number:Negative Feedback:Difficulty	-0.002	0.003	-0.56	74.3	0.58

Note. We conducted linear mixed model analyses using the model "Grip Force ~ 1 + Negative - Positive Feedback * Difficulty * Trial Number + (1 + Negative - Positive Feedback * Difficulty * Trial Number|Subject)".

Table S4. Association between confidence and other variables of interest

Coefficient	Estimate	SE	*t*-value	df	*p*-value
Accuracy (z-scored)	0.004	0.003	1.34	49.1	0.19
Grip Force (z-scored)	-0.002	0.003	-0.58	35.8	0.57
Fatigue (z-scored)	-0.01	0.006	-1.62	61.5	0.11
Perceived Exertion	-.0.001	0.006	-0.13	59.5	0.9

Note. We conducted separate linear mixed model analyses assessing the association between confidence and other variables. For example, estimates for accuracy were calculated using the model "Confidence ~ 1 + Accuracy + (1 + Accuracy|Subject)".