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# The feeling of effort during mental activity

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ABSTRACT

The feeling of effort is familiar to most, if not all, humans. Prior research shows that the feeling of effort shapes judgments (e.g., of agency) and decisions (e.g., to quit the current task) in various ways, but the proximal causes of the feeling of effort are not well understood. In this research, I address these proximal causes. In particular, I conducted two preregistered experiments in which participants performed a difficult vs. easy cognitive task, while I measured effort-related phenomenology (feeling of effort) and physiology (pupil dilation) on a moment-to-moment basis. In both experiments, difficult tasks increased the feeling of effort; however, this effect could not be explained by concurrent increases in physiological effort. To explain these findings, I suggest that the feeling of effort during mental activity stems from the decision to exert physiological effort, rather than from physiological effort itself.

## 1. Introduction

When people think hard, they tend to experience the *feeling of effort*. The feeling of effort is a basic state of consciousness, akin to hunger and pain, that is often thought to reflect the costs of ongoing actions (e.g., Hockey, 2013; Preston & Wegner, 2009). The feeling of effort shapes people's judgments and decisions in numerous ways (e.g., Reber & Greifeneder, 2017); accordingly, self-reports of effort have proven a valuable source of information for practitioners—e.g., for therapists, who wish to assess their patients' mental state (Radloff, 1977), and for education professionals, who wish to evaluate their teaching materials (Mattis, 2015). Yet, despite its everyday familiarity, and despite its long history as a topic of study (James, 1880), the proximal causes of the feeling of effort are not well understood, particularly when the feeling of effort emerges during mental activity (Shenhav et al., 2017). In this research, I examine these proximal causes of the feeling of effort. Thus, with this research, I aim to help clarify the origins of a familiar human experience. Relatedly, I aim to increase our ability to precisely interpret self-reports of effort: what does it mean when people say that some mental activity 'felt effortful'?

I will consider two possibilities. First, building on previous research on introspection, it can be expected that the feeling of effort arises from *physiological effort*—i.e., the investment of energetic resources (e.g., adenosine triphosphate [ATP], oxygen, glucose) in the service of goal-directed behavior (Gendolla, Wright, & Richter, 2011). Although it is unlikely that the brain consumes substantially more energetic resources during heavy (vs. light) cognitive activity (Kurzban, 2010), heavy (vs. light) cognitive activity still causes sympathetically-innervated organs, like the heart, to operate more vigorously (Gendolla et al., 2011; Richter, Gendolla, & Wright, 2016), suggesting that cognitive tasks can and do trigger physiological effort. Also, research suggests that people can readily detect such physiological changes via afferent pathways (Craig, 2002; Critchley, Wiens, Rotshtein, Öhman, & Dolan, 2004; Damasio & Carvalho, 2013; Laird, 2007). In experiments, afferent pathways have indeed been shown to contribute to physiology-related conscious experiences, such as hunger (Stevenson, Mahmut, & Rooney, 2015) and pain (Almeida, Roizenblatt, & Tufik, 2004). So, one possibility is that the feeling of effort emerges from physiological effort, via body-to-brain feedback. This *feedback model* (Fig. 1a) is in

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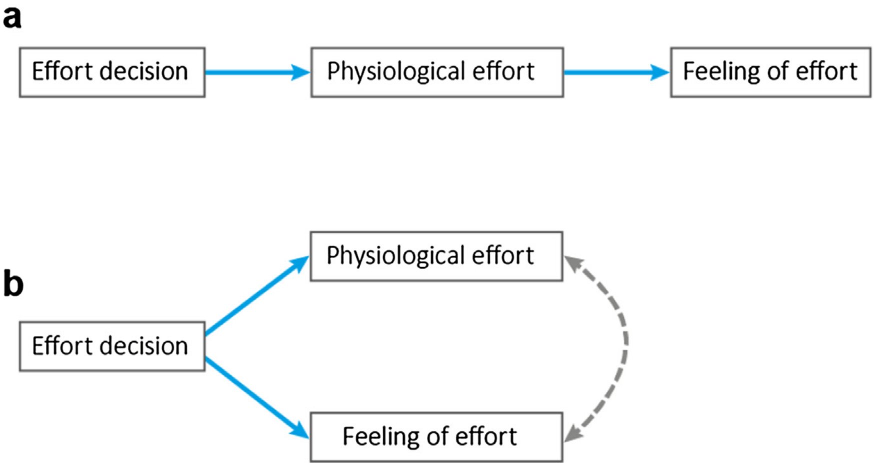

**Fig. 1.** Two models of the feeling of effort. (a) The feedback model; (b) the shared cause model. Solid, blue lines indicate causal pathways. The dashed, grey line indicates a spurious relationship.

line with the common-sense notion that the feeling of effort signals the current expenditure of energy.

Second, research from exercise physiology suggests an alternative possibility, namely, that the relationship between physiological effort and the feeling of effort is spurious, rather than causal (Marcora, 2009). This would work as follows: the *decision to exert* physiological effort directly causes the feeling of effort, independently of body-to-brain feedback. As a result, physiological effort and the feeling of effort correlate. Importantly, though, this correlation is not due to a causal relationship: it emerges only because both variables are affected by the same upstream decision-making process (Marcora, 2009; Naccache et al., 2005; Wegner, 2002). This *shared cause model* (Fig. 1b) predicts that feeling of effort should closely reflect decisions to exert extra effort—e.g., which occur when people face a difficult task—but not necessarily the actual expenditure of energy.

Here I report two experiments, in which participants carried out a working memory task, consisting of easy and difficult trials. Importantly, in both experiments, I measured physiological effort and the feeling of effort, concurrently, on a trial-by-trial basis. This novel design enabled me to examine predictions from the feedback and shared cause models in detail.

## 2. Experiment 1

In this research, non-controversially, I assume that task characteristics—mainly, task difficulty and time on task—are a primary driver of people's decisions to expend physiological effort (Gendolla et al., 2011; Richter et al., 2016). Accordingly, by varying task difficulty, I manipulated people's decisions to expend more vs. less effort. In addition, also non-controversially, I assume that physiological effort involves activity of the sympathetic branch of the autonomic nervous system. Via the paravertebral ganglia, this neural network boosts contractions of the heart, opens the bronchi in the lungs, and dilates the pupils of the eye, among a range of other, concurrent effects. Indeed, since the 1970s, pupil dilation has been considered a valid indicator of physiological effort during mental activity (Beatty & Lucero-Wagoner, 2000; Bijleveld, Custers, & Aarts, 2009; Kahneman, 1973; Laeng, Sirois, & Gredebäck, 2012)[1].

Given the above assumptions, the feedback model predicts that the effect of task difficulty (a proxy for effort decisions) on the feeling of effort is mediated by physiological effort. The shared cause model predicts that the association between physiological effort and the feeling of effort should weaken after controlling for task difficulty (Einhorn & Hogarth, 1986; and see Method). The most important goal of Experiment 1 was to provide an initial test of both these predictions.

In addition, as an exploratory analysis, I will examine the feedback model and the shared cause model in an alternative way. Specifically, research on *fatigue* suggests that people's effort decisions do not only depend on task difficulty—but that these decisions should also change over time. That is, with *time on task*, increasing amounts of effort are needed to uphold performance; thus, *time on task* may trigger decisions to exert more effort (Hockey, 2013). Based on this rationale, I will again test the feedback model and the shared cause model, but now with *time on task* as a proxy for effort decisions. In particular, to examine the feedback model, I will test whether the effect of time on task on the feeling of effort is mediated by physiological effort. To examine the shared cause model, I will test whether the association between physiological effort and the feeling of effort weakens after controlling for time on task.

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[1] In more recent years, researchers have uncovered the brain mechanisms that trigger physiological effort. While not the main focus of the present work, substantial evidence points to a key role for the Locus Coeruleus (Joshi, Li, Kalwani, & Gold, 2016; Murphy, O'Connell, O'Sullivan, Robertson, & Balsters, 2014; Samuels & Szabadi, 2008), the neural node that lies at the origin of the brain's norepinephrine pathways. This node directly sends impulses into the spinal cord, activating the sympathetic nervous system (Samuels & Szabadi, 2008), enabling the investment of energetic resources.

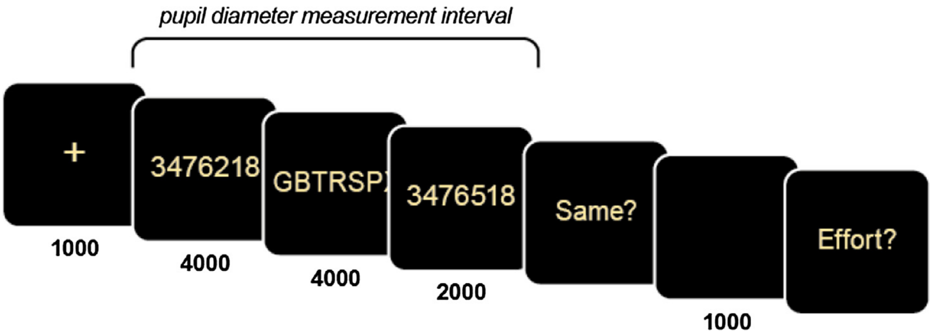

**Fig. 2.** Overview of the trial structure. This overview applies to both experiments. Bold numbers refer to durations in milliseconds.

## 2.1. Method

### 2.1.1. Data sharing

Materials, data, and code can be accessed on https://osf.io/658s5/.

### 2.1.2. Participants, procedure, and design

58 university students (mean age = 21.7; 42 females, 16 males) participated in Experiment 1, in exchange for either a gift voucher (worth €5) or course credits. Data from two participants were a priori excluded, because these data were unusable due to calibration problems. After informed consent was obtained, participants were seated behind a SMI iView X video-based eye tracker, which is a stationary eye-tracking setup which features a chin and forehead rest. The eye tracker sampled at 500 Hz throughout the session, recording the dominant eye. After calibration of the equipment, participants worked on the task that is described below. After they were done, participants were debriefed and they received their compensation. All sessions took place in a windowless room in which lighting was kept constant. The experiment had a 2(task difficulty: low vs. high) within-subjects design. The design, hypotheses, power analysis and analysis plan for Experiment 1 were pre-registered on the Open Science Framework; the pre-registration document can be found at https://osf.io/mwy42/.

Before conducting Study 1, I conducted two pilot studies. Results from these pilot studies are reported in the Supplementary Materials.

### 2.1.3. Task

Participants completed 56 trials, 28 per condition, presented in random order. An overview of the trial structure is presented in Fig. 2. Each trial started with a fixation cross. Then, participants saw a string of 7 digits. Depending on the trial type (low vs. high difficulty), that string was easy vs. difficult to retain. Specifically, while all digit strings had the same length (and thus the same brightness on screen), their Kolmogorov complexity was varied within-subjects so that strings were either easy (e.g., 4477733) vs. difficult (e.g., 8724153) to process (Mathy & Feldman, 2012). Subsequently, participants saw a string of 7 random letters (e.g., GBTRSPX). Next, participants again saw a digit string. On 50% of the trials, one digit (or, in the easy condition, one chunk of digits) had changed, relative to the first digit string. On the other 50% of the trials, digit strings were identical. It was participants' task to indicate whether the two strings were the same or different. They did so by clicking either of two buttons (labeled *same* and *different*), using the mouse. So, on each trial, participants had to (a) keep the first digit string in mind, (b) ignore the letter string, and (c) compare the second digit string to the first. Finally, participants responded to the question "How did this effort feel?" (Robinson & Morsella, 2014). They responded on a visual analogue scale. The end points of this scale were labeled *very light* (scored as 1; *heel licht* in Dutch) and *very intense* (scored as 100; *heel zwaar* in Dutch). After a brief inter-trial interval (2000 ms), the next trial started.

### 2.1.4. Data reduction

First, artefacts (e.g., due to eye-blinks) were removed from the pupil data and corrected by linear interpolation. Data were split up into 56 segments, so that each segment contained data from one trial. Pupil data were converted to millimeters and smoothed with a cubic spline function. Smoothing was done to reduce the potential impact of high-frequency noise (pupillary changes related to cognitive activity are relatively slow, typically < 4 Hz, e.g., Meindertsma, Kloosterman, Nolte, Engel, & Donner, 2017). Pupil diameter was operationalized as the average of the horizontal and the vertical pupil diameters, both of which were directly measured by the eye tracker. In line with existing, well-accepted methodological guidelines (Beatty & Lucero-Wagoner, 2000), baseline pupil diameter was measured during the last 500 ms of the fixation cross. In line with the same guidelines (Beatty & Lucero-Wagoner, 2000), pupil dilation (the *task-evoked pupillary response*; TEPR) was operationalized as the maximum pupil diameter, corrected for baseline, during the effortful part of the trial (i.e., the 10 s spanning the first digit string, the letter string, and the second digit string; see Fig. 2). Both baseline pupil diameter and pupil dilation were computed separately for each trial.

### 2.1.5. Statistical analyses

Both proposed models (Fig. 1) assume that the feeling of effort can fluctuate on a moment-to-moment basis. Accordingly, it is necessary to analyze the data on a trial-by-trial level, preserving the data's nested structure (trials nested within people). Thus, I used linear mixed-effects models (Barr, Levy, Scheepers, & Tily, 2013; Bates, Maechler, Bolker, & Walker, 2015). In all models, the trial was the unit of analysis—i.e., all variables varied at the trial level. By including a random intercept, models took into account that people may differ in their general level of the dependent variable (e.g., some people may generally feel more effort than others). Random slopes were included in all models for all within-subjects predictors (Barr et al., 2013). This was done to take into account that the relation between the independent and dependent variables may be stronger for some people than for others (e.g., for some people more than others, difficulty may more strongly affect the feeling of effort). Continuous independent variables were centered within participants. No trials were excluded from analysis.

To test the prediction from the feedback model (i.e., the effect of task difficulty on the feeling of effort is mediated by physiological effort), I used the approach by Imai, Keele, and Tingley (2010). In particular, Imai et al. (2010) developed a general approach to mediation—i.e., an approach that is not contingent on any specific statistical model. I selected this approach, because it fits the mixed-level modeling framework, and because it can readily be re-applied in future research, even if this future research involves changes to the task.

As a first step, the mediation approach by Imai et al. (2010) requires the researcher to fit two models: (a) a model that predicts the mediator from the independent variable, and (b) a model that predicts the dependent variable from the independent variable and the mediator. In turn, these two models are used as an input for simulations, which yield a set of estimates with confidence intervals, described below, that can be used to assess the presence and the strength of mediation. In this case, I fitted a mediation model in which difficulty was the independent variable, physiological effort (operationalized as pupil dilation) was the mediator, and the feeling of effort was the dependent variable.

To test the prediction from the shared cause model (i.e., the relation between physiological effort and the feeling of effort should weaken after controlling for task difficulty), I examined whether pupil dilation predicted the feeling of effort, before vs. after controlling for task difficulty. If this relationship weakens *after* controlling for difficulty, this suggests that the relationship between pupil dilation and the feeling of effort is (partially) spurious, as it can be (partially) explained from the effects of difficulty.

#### 2.1.6. *Assumptions and robustness*

After carrying out all analyses, I checked the assumptions of the mixed-level models I used (following Winter, 2013). A full report of this assumption check is presented in the Supplementary Materials. Although I did detect a violation of one of the model's assumptions (the distribution of the residuals was symmetrical, but not normal because the distribution's tails were too long), follow-up analyses (see Supplementary Materials) suggest that this violation does not challenge the conclusions I report in the main text. I also explored whether potential correlations between successive trials affected my parameter estimates. This was not the case (see Supplementary Materials).

### 2.2. *Results*

Unless otherwise noted, all analyses reported here were pre-registered.

#### 2.2.1. *Descriptives*

Across all trials from all participants ($N = 3{,}136$), mean TEPR was 0.23 mm ($SD = .26$). Mean feeling of effort was 33.5 ($SD = 25.3$). Participants were accurate on 92% of the trials.

#### 2.2.2. *Preliminary analyses*

Before testing the proposed models, I first examined the effectiveness of the task difficulty manipulation. Supporting the effectiveness of the task difficulty manipulation, difficult strings triggered greater pupil dilation than easy strings, Est = 0.03, CI[0.01, 0.05], $t(55) = 3.2$, $p = .002$, indicating greater physiological effort (Fig. 3a). Also, difficult strings triggered a greater feeling of effort than easy strings, Est = 29.3, CI[24.2, 34.3], $t(55) = 11.4$, $p < .001$ (Fig. 3b).

#### 2.2.3. *Task difficulty*

To test the feedback model, I used mediation analysis (Imai et al., 2010). This analysis was used to decompose the total effect (TE) of task difficulty on the feeling of effort into a direct effect (difficulty → feeling of effort; the Average Direct Effect [ADE]) and an indirect effect (difficulty → pupil dilation → feeling of effort; the Average Causal Mediation Effect [ACME]). Parameter estimates and confidence intervals for these effects are presented in Fig. 3c. Analyses indicated that the ADE was significant, $p < .001$, and that it accounted for 99.6% of the TE. Although the ACME was significant too, $p = .046$, it explained only a negligible proportion of the TE (0.4%). Thus, this analysis provides only weak, if any, support for the main prediction from the feedback model.

If a relation between X and Y is due to shared cause C, the relation between X and Y should weaken after controlling for C (Einhorn & Hogarth, 1986). First, I used pupil dilation (X) to predict the feeling of effort (Y)—then, I tested whether this relationship weakened after controlling for task difficulty (C). Parameter estimates for the relation between pupil dilation and the feeling of effort—with and without task difficulty in the model—are presented in Fig. 3e. Findings indicated that pupil dilation and the feeling of effort were initially strongly related, Est = 12.3, CI[6.4, 18.2]. However, including difficulty as a control variable (as a proxy for people's decisions to exert effort) significantly weakened this relationship, $t_{\text{none}\rightarrow\text{D}}(55) = 6.8$, $p < .001$, $d = 0.91$. So, in support of the prediction from the shared cause model, physiological effort was related to the feeling of effort, but this relationship could be explained, at least in part, by both variables being affected by task difficulty.

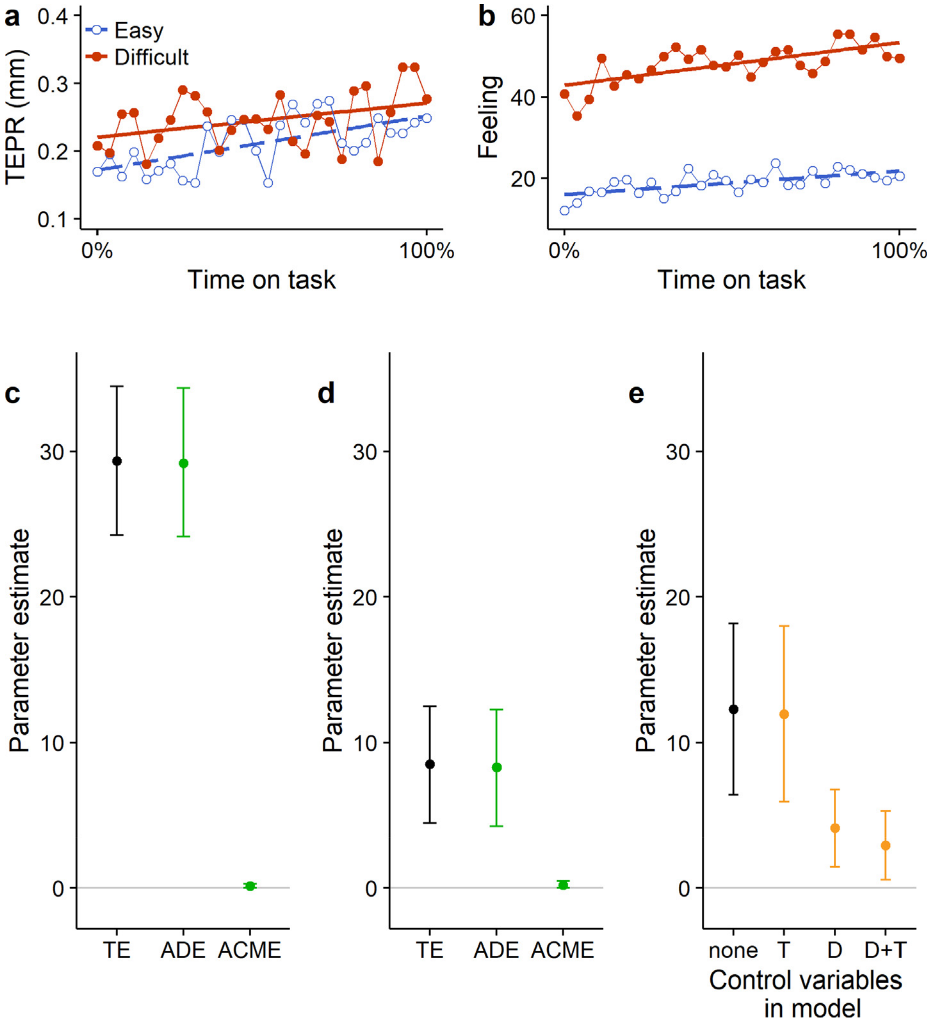

**Fig. 3.** Results from Experiment 1. (a) Task-Evoked Pupillary Response (TEPR) as a function of task difficulty and time on task. (b) Feeling of effort as a function of task difficulty and time on task. (c) Parameter estimates from mediation analysis, which decomposed the Total Effect (TE) of *task difficulty* on the feeling of effort into an Average Direct Effect (ADE; task difficulty → feeling of effort) vs. an Average Causal Mediation Effect (ACME; task difficulty → pupil dilation → feeling of effort). (d) Parameter estimates from mediation analysis, which decomposed the TE of *time on task* on the feeling of effort into an ADE (time on task → feeling of effort) vs. an ACME (time on task → pupil dilation → feeling of effort). (e) Parameter estimates of the relation between TEPR and the feeling of effort, without and with control variables in the model. T = Time on task; D = Difficulty. All error bars reflect 95% confidence intervals around the estimate.

### 2.2.4. *Time on task*

Research on fatigue shows that both physiological effort and the feeling of effort are affected by *time on task*—i.e., with time, it typically takes more effort to produce the same performance (Hockey, 2013). Findings were in line with this idea: time on task (operationalized as trial number) predicted both physiological effort, Est = 0.06, CI[0.02, 0.11], $t(55) = 2.9$, $p = .006$ (Fig. 3a), and the feeling of effort, Est = 8.5, CI[4.7, 12.3], $t(55) = 4.4$, $p < .001$ (Fig. 3b). These findings are consistent with the assumption that how long people have been working on a task (i.e., time on task), weighs into people's decisions to exert effort (Hockey, 2013). Based on this assumption, although I did not pre-register these analyses, I examined time on task as an additional proxy for people's decisions to exert effort.

First, I examined whether the effect of time on task on the feeling of effort was mediated by pupil dilation. If this would be the case, this would support the feedback model. Again using the approach by Imai et al. (2010), I decomposed the total effect (TE) of time on task on the feeling of effort into an Average Direct Effect (ADE; time on task → feeling of effort) and an Average Causal Mediation Effect (ACME; time on task → pupil dilation → feeling of effort). Like before, the ADE was significant, $p < .001$, accounting for 97.8% of the TE. Although the ACME was significant too, $p = .031$, it explained only a small proportion of the total effect (2.2%). So, these results provide some, but only weak, support for the feedback model's predictions. Parameter estimates are presented in Fig. 3d.

Second, I examined whether the relationship between pupil dilation and the feeling of effort would be reduced further after controlling for time on task in addition to difficulty (Fig. 3e). This was the case: after controlling for time on task, the relation between pupil dilation and the feeling of effort weakened further, $t_{\mathrm{D}\rightarrow\mathrm{D+T}}(55) = 7.0$, $p < .001$, $d = 0.93$, $t_{\mathrm{none}\rightarrow\mathrm{D+T}}(55) = 7.7$, $p < .001$, $d = 1.02$. This finding further supports the shared cause model.

## 3. Experiment 2

Experiment 1 supported the shared cause model's main prediction. Specifically, physiological effort and the feeling of effort *seemed* related on first sight, but this relationship could be explained by both variables being affected by task difficulty. In addition, the relationship between physiological effort and the feeling of effort could be explained further by both variables being associated with time on task. These findings are consistent with the idea that physiological effort *and* the feeling of effort are triggered by an effort-related decision-making process (Fig. 1b), that takes into account both task difficulty and time on task.

Experiment 1 did not convincingly support the feedback model (Fig. 1a). Specifically, although the relationship between difficulty and the feeling of effort was mediated by physiological effort, the mediation effect (difficulty → physiological effort → feeling of effort) explained only a small proportion of the total effect. Similarly, while the relationship between time on task and the feeling of effort was mediated by physiological effort, this mediation effect (time on task → physiological effort → feeling of effort) was again much weaker than the direct effect.

Despite that the support for the feedback model was weak, it would be premature to discard this model altogether (see also General Discussion). One could still argue that physiological effort affects the feeling of effort, just not in all situations. A more nuanced account could be as follows: (a) external cues about task difficulty affect the feeling of effort, especially when these cues are clear and valid; (b) however, when difficulty cues are weaker or more ambiguous, physiological effort serves as an input for the feeling of effort. If this account is true, is not surprising that physiological effort did *not* explain the feeling of effort in Experiment 1. After all, in Experiment 1, easy strings always included digit repetitions; difficult strings, never. Thus, in Experiment 1, people could rely on a clear and valid external cue about task difficulty. To create circumstances potentially more conductive to feedback from physiological effort, in Experiment 2, I manipulated difficulty in a subtler way.

### *3.1. Method*

#### *3.1.1. Participants, procedure and design*

50 students (mean age = 21.9; 34 females, 16 males) participated in Experiment 2, in exchange for either a gift voucher (worth €5) or course credits. Data from four participants were a priori excluded, because these data were unusable due to calibration problems. The procedure was identical to the procedure from Experiment 1. In the same way as Experiment 1, Experiment 2 was preregistered; the pre-registration document can be found at https://osf.io/z5kp2/.

#### *3.1.2. Task*

In Experiment 2, the task was identical to Experiment 1, except that task difficulty was manipulated in a subtler way. Specifically, on easy trials, people saw a seven-digit string that contained a segment of three consecutive digits (e.g., 3451692, 6589123, 5674238), either at the beginning or the end of the string. Difficult trials did not contain such a segment (e.g., 7326418, 4825196, 1875943). So, unlike in Experiment 1, people were always exposed to seven different digits. However, in the easy condition, these digits were somewhat higher in regularity in making them somewhat easier to process (Mathy & Feldman, 2012).

#### *3.1.3. Data reduction and analysis, and availability*

Data reduction and analysis were done in the same way as in Experiment 1. I pre-registered the same analytic strategy as I did for Experiment 1. Materials, data, and code can be accessed on https://osf.io/658s5/.

### *3.2. Results*

Unless otherwise noted, all analyses reported here were pre-registered.

#### *3.2.1. Descriptives*

Across all trials from all participants ($N = 2{,}576$), mean TEPR was 0.22 mm ($SD = .24$). Mean feeling of effort was 38.5 ($SD = 22.2$). Participants were accurate on 90% of the trials.

#### *3.2.2. Preliminary analyses*

Like in Experiment 1, I first checked whether task difficulty affected pupil dilation and the feeling of effort. By contrast to expectations, difficult strings triggered no greater pupil dilation than easy strings (Fig. 4a), Est = 0.00, CI[−0.03, 0.02], $t(45) = 0.4$, $p = .660$. However, difficult strings did trigger a greater feeling of effort than easy strings (Fig. 4b), Est = 6.3, CI[4.5, 8.1], $t(45) = 6.9$, $p < .001$, though this effect was less pronounced compared to Experiment 1 (see Fig. 3b vs. 4b). Together, these results suggest that external difficulty cues were weaker than in Experiment 1, as planned. However, the finding that task difficulty no longer affected pupil dilation is somewhat problematic. In fact, the existence of this effect is a prerequisite for interpreting the pre-registered analyses in a meaningful way (e.g., one cannot expect to find mediation, if the independent variable is not correlated with the mediator).

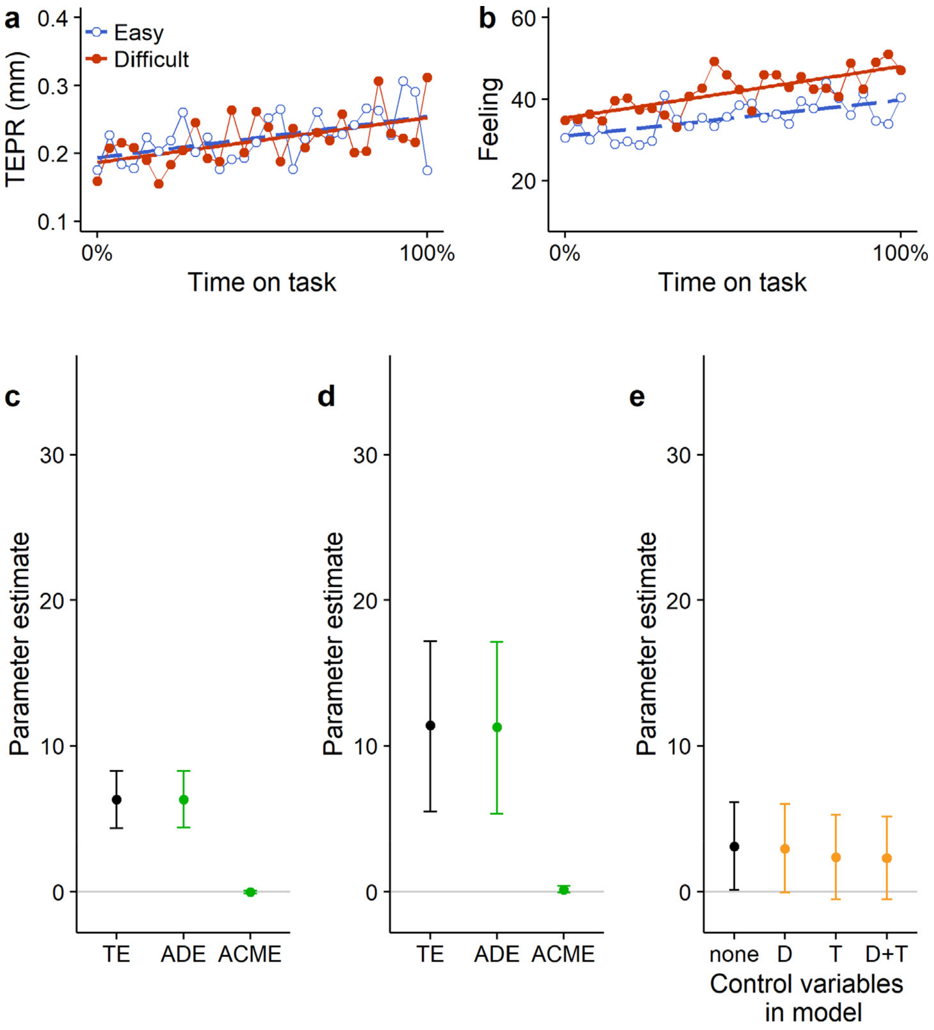

**Fig. 4.** Results from Experiment 2. (a) Task-Evoked Pupillary Response (TEPR) as a function of task difficulty and time on task. (b) Feeling of effort as a function of task difficulty and time on task. (c) Parameter estimates from mediation analysis, which decomposed the Total Effect (TE) of *task difficulty* on the feeling of effort into an Average Direct Effect (ADE; task difficulty → feeling of effort) vs. an Average Causal Mediation Effect (ACME; task difficulty → pupil dilation → feeling of effort). (d) Parameter estimates from mediation analysis, which decomposed the TE of *time on task* on the feeling of effort into an ADE (time on task → feeling of effort) vs. an ACME (time on task → pupil dilation → feeling of effort). (e) Parameter estimates of the relation between TEPR and the feeling of effort, without and with control variables in the model. T = Time on task; D = Difficulty. All error bars reflect 95% confidence intervals around the estimate.

Nevertheless, data from Experiment 2 can still prove informative, as *time on task* was again associated with greater pupil dilation, Est = .06, CI[0.02, 0.11], $t(45) = 2.9$, $p = .006$ (Fig. 4a), and with greater feelings of effort, Est = 11.4, CI[5.9, 16.9], $t(45) = 4.0$, $p < .001$ (Fig. 4b). For consistency, I will report the pre-registered analyses first, while keeping in mind that these are difficult to interpret. Next, I will discuss analyses regarding time on task.

### 3.2.3. Task difficulty

I tested the feedback model in the same way as in Experiment 1—i.e., by decomposing the total effect of difficulty on the feeling of effort into an ADE and an ACME (Fig. 4c). Like in Experiment 1, the ADE was significant, $p < .001$; it fully accounted for the total effect (~100%). The ACME was of negligible importance: it was not significant, $p = .630$, its confidence interval included zero, and it accounted for ~0% of the TE. Strictly, this null finding can be seen as further absence of evidence for the feedback model. It is important to keep in mind, though, that this null-finding is also rather trivial, as preliminary analyses did not show a significant effect of task difficulty (the independent variable) on pupil dilation (the mediator). It is thus not surprising to find no significant ACME.

Next, for completeness, I examined the shared cause model in the same way as in Experiment 1—i.e., by examining the relationship between pupil dilation and the feeling of effort, before and after including task difficulty in the model (Fig. 4e). Before including task difficulty, pupil dilation was weakly, but significantly related to the feeling of effort, Est = 3.1, CI[0.1, 6.1]. This relationship weakened after adding difficulty to the model, $t_{\text{none}\rightarrow\text{D}}(45) = 0.8$, $p = .443$, $d = 0.11$, but this change was not significant. Also here, as there was no significant effect of task difficulty on pupil dilation to begin with, results from this analysis are difficult to interpret.

### 3.2.4. Time on task

Like in Experiment 1, I examined whether the effect of time on task on the feeling of effort was mediated by pupil dilation. If this would be the case, this would support the feedback model. Like before, following Imai et al. (2010), I decomposed the Total Effect (TE) into an Average Direct Effect (ADE; time on task → feeling of effort) and an Average Causal Mediation Effect (ACME; time on task → pupil dilation → feeling of effort). Parameter estimates are presented in Fig. 4d. Results were similar to results from Experiment 1. So, the ADE was significant, $p < .001$, accounting for 99.0% of the TE. The ACME was not significant, $p = .251$, accounting for 1.0% of the TE. Thus, these results provide no support for the feedback model.

Second, I examined whether the association between pupil dilation and the feeling of effort would weaken, after including time on task in the model. This turned out to be the case, $t_{none \rightarrow T}(45) = 3.2$, $p = .002$, $d = 0.47$, $t_{\mathrm{none} \rightarrow \mathrm{D+T}}(45) = 3.0$, $p = .005$, $d = 0.44$. This finding suggests that the relation between physiological effort and the feeling effort, can in part be explained by both variables being related to time on task. This finding supports the shared cause model.

### 3.3. Discussion

A limitation of Experiment 1 was that participants received strong external cues about task difficulty. As these strong cues may have overshadowed any effects of afferent feedback on the feeling of effort, external cues about task difficulty were drastically weakened in Experiment 2. I expected to find stronger evidence for the feedback model in Experiment 2. Nevertheless, I found no such evidence. First, the relationship between *task difficulty* and the *feeling of effort* was *not* significantly mediated by physiological effort. Second, the relationship between *time on task* and the *feeling of effort* was *not* significantly mediated by physiological effort, either. The former null finding can be explained by the weakness of the difficulty manipulation (difficulty did not increase physiological effort), but the latter null finding cannot be explained in this way (time on task was clearly associated with greater physiological effort). So, even though I removed strong cues about task difficulty, findings from Experiment 2 still did not support the feedback model.

With regard to the shared cause model, findings were as follows. First, the relationship between physiological effort and the feeling of effort did *not* significantly weaken after controlling for task difficulty. However, this null finding is difficult to interpret (specifically, task difficulty cannot be expected to explain a relation between variables X and Y, if task difficulty is not related to X). Second, the relationship between physiological effort and the feeling of effort did weaken after controlling for time on task. This finding replicates Experiment 1, providing further support for the shared cause model.

## 4. General discussion

Results from two studies suggest that the link between physiological effort and the feeling of effort is spurious, not causal. Task difficulty (Experiment 1) and time on task (Experiment 1 and 2) directly predicted the feeling of effort, not (or not convincingly) mediated by physiological effort. Although physiological effort was related to the feeling of effort on first sight—which explains why correlations are sometimes reported in the literature (Hopstaken, van der Linden, Bakker, & Kompier, 2015)—this relationship weakened (or disappeared altogether) after controlling for task difficulty (Experiment 1) and time on task (Experiment 1 and 2). Together, these findings support predictions derived from the shared cause model (Fig. 1b), but not the feedback model (Fig. 1a). So, these experiments do not support the idea that the feeling of effort stems from actual physiological effort. Instead, I suggest that the feeling of effort during mental activity originates from the upstream *decision to exert* effort (e.g., made when facing a difficult or a long task).

In interpreting these findings, it is important to keep in mind two methodological limitations. First, the hypotheses derived from both theoretical models were tested using a null-hypothesis significance testing (NHST) approach. As a result, conclusions can be drawn only *in favor* of the models, not *against* them. Also, as I did not (and cannot) explicitly compare both models, but as I tested predictions from both models separately, the present findings do not mean that there is 'more support' for either of the models. The experiments simply revealed positive evidence for the shared cause model, and no (or very weak) positive evidence for the feedback model. It would be an error to interpret this pattern of findings as evidence against the feedback model.

A second limitation of these experiments is that I used just one measure of physiological effort, i.e., pupil dilation. Pupil diameter is a function of the contraction of two opposing muscles in the iris: the sphincter muscle (constricting the pupil; parasympathetically innervated) and the dilator muscle (dilating the pupil; sympathetically innervated). Pupil diameter thus reflects the balance between sympathetic innervation *relative to* parasympathetic innervation. It is worth noting, however, that some researchers conceptualize physiological effort as being exclusively tied to sympathetic innervation, but not parasympathetic innervation (e.g., Gendolla et al., 2011). Adopting this somewhat stricter conceptualization would require different physiological measures (ideally, pre-ejection period [PEP], which is a measure of cardiac contractility; e.g., Kuipers et al., 2017). It is clear, though, from dozens of experiments (for a review, see Beatty & Lucero-Wagoner, 2000), that pupil dilation reliably increases with task difficulty during cognitive tasks (Kahneman, 1973). In addition to its reliability, an advantage of pupil dilation is that it responds to task difficulty within seconds. Thus, I consider pupil dilation to be a suitable measure of physiological effort for the present purposes, noting that it is important to keep in mind that pupil dilation reflects a sympathetic/parasympathetic balance.

Arguably, a strength of the present experiments is that the duration of the cognitive work was kept constant. That is, regardless of whether a given trial was easy or difficult, people always worked for 10 s. This feature of the task enabled me to examine pupil dilation and the feeling of effort without having to worry about within- and between-person differences in trial duration. Nevertheless, in real life, the feeling of effort may well be affected by the duration of cognitive work. Specifically, when people detect that they needed more time to complete some task (Questienne, Atas, Burle, & Gevers, 2018; Schmitz, Veling, & Bijleveld, 2017), or when they detect some hesitation in their response (Questienne et al., 2018), they may infer—or even *feel*—that they expended more effort. In future research, it would be interesting to further explore the nature of this inference process.

The present research contributes to a broad, ongoing debate about what it means when people feel effort during cognitive activity (Kurzban, 2016). According to one position in this debate (Craig, 2013), the feeling of effort reflects the *energetic costs* of mental activity. This perspective suggests that effort self-reports can be interpreted as a gauge of the energetic resources that are currently being expended. According to a second position (Kurzban, Duckworth, Kable, & Myers, 2013; Shenhav et al., 2017), effort self-reports reflect the *non-energetic costs* of mental activity. This perspective suggests that the use of cognitive capacity is costly in and by itself. Specifically, when people use cognitive capacity to perform a task, this implies that they forego other, potentially interesting, opportunities (Cohen, McClure, & Yu, 2007). For example, during difficult tasks, people are less likely to process non-task stimuli (which could have led to rewards) or to carry out alternative actions (which could have been pleasant) at the same time. The feeling of effort, then, may reflect these economic–but–not–energetic costs of using cognitive capacity. As I found no direct link between physiological effort and the feeling of effort, the present research is consistent with the second (non-energetic costs), but not the first (energetic costs), perspective. Future research is needed to clarify the nature of these non-energetic costs (for a discussion, see Shenhav et al., 2017, pp. 101–106).

In this research, I used a new paradigm to study the nature of effort. Going beyond prior work (but see Kuipers et al., 2017; Questienne et al., 2018; Treadway, Buckholtz, Schwartzman, Lambert, & Zald, 2009), a key feature of this paradigm is that it allows researchers to model both the expenditure and the feeling of effort on a moment-to-moment, or trial-by-trial, basis. In future research, this paradigm (i.e., the task, the measures, combined with the statistical approach) can be used to deepen our understanding of social aspects of effort allocation (Lockwood et al., 2017), of phenomenological aspects of task performance (Questienne et al., 2018; Robinson & Morsella, 2014), and of effort-related disturbances, which occur in a range of mental disorders, including major depressive disorder and schizophrenia.

### 4.1. Conclusion

This research set out to examine the proximal causes of the feeling of effort during mental activity. As the findings suggest that the feeling of effort stems from effort-related decisions (with little support for a clear role for physiological effort), these findings also tell us something about what it means when cognitive activity is accompanied by a feeling of effort. Intuitively, one might think that this feeling means that energy is being spent, or that some internal battery is being depleted. Consistent with recent theoretical work (Inzlicht, Schmeichel, & Macrae, 2014; Kurzban et al., 2013; Morsella, Godwin, Jantz, Krieger, & Gazzaley, 2016), the present findings challenge this intuition. The conscious sense of effort may directly reflect people's decision to devote their mind to the ongoing task, at the cost of other possible thoughts and actions.

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## Appendix A. Supplementary material

Supplementary data associated with this article can be found, in the online version, at https://doi.org/10.1016/j.concog.2018.05.013.

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