Explore or reset? Pupil diameter transiently increases in self-chosen switches between cognitive labor and leisure in either direction

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Abstract

When people invest effort in cognitive work, they often keep an eye open for rewarding alternative activities. Previous research suggests that the norepinephrine (NE) system regulates such trade-offs between exploitation (of the current task) and exploration (of alternative possibilities). Here we examine the possibility that the NE-system is involved in a related trade-off, i.e., the trade-off between cognitive labor and leisure. We conducted two pre-registered studies (total N = 62) in which participants freely chose to perform either a paid 2-back task (labor) vs. a fun non-paid task (leisure), while we tracked their pupil diameter—which is an indicator of the state of the NE system. In both studies, consistent with prior work, we found (a) increases in pupil baseline and (b) decreases in pupil dilation when participants switched from labor to leisure. Unexpectedly, we found the same pattern when participants switched from leisure back to labor. Furthermore, exploratory analyses showed that participants with a stronger action orientation in everyday life showed stronger decreases in pupil dilation in switches towards labor, but weaker decreases in switches towards leisure. Collectively, these results are more consistent with Network Reset Theory, which suggests that NE plays a role in reorienting attention, than with Adaptive Gain Theory, which suggests that NE plays a role in motivation.

Keywords

Decision-making, cognitive effort, exploration-exploitation trade-off, motivation, norepinephrine, pupillometry

Explore or reset? Pupil diameter transiently increases in self-directed switches between cognitive labor and leisure in either direction

In their pursuit of rewards such as food, all organisms are continuously confronted with two choice options: they can either keep exploiting their current location to harvest rewards, or they can leave their current place to explore the environment for potentially more attractive alternatives. This fundamental dilemma between *exploitation* and *exploration* plays a central role in foraging models, which have a rich history in behavioral ecology (Charnov, 1976). Foraging models have proven valuable in various fields, including artificial intelligence, psychology, and neuroscience (Calhoun & Hayden, 2015; Hayden, 2018; Hills, Todd, Lazer, Redish, & Couzin, 2015). Most notably, recent advances in psychology and neuroscience suggest that foraging models can help understand how people make decisions between different choice options (Constantino & Daw, 2015; Kolling, Behrens, Mars, & Rushworth, 2012). In the present research, we examine a particular type of decisions, i.e., people's decisions to take *breaks*. Specifically, we study how and when people decide to quit *cognitive labor* (i.e., exerting effort to attain a reward) and shift to *cognitive leisure* (a non-demanding and non-profitable activity, e.g., relaxing; Kool & Botvinick, 2014).

In our research, we go beyond prior work in two ways. First, in contrast with prior work on this topic, we used a dual-task paradigm with two qualitatively different tasks. We chose to use this paradigm to model decisions in real life, where *labor* (e.g., working on a spreadsheet) usually comprises a vastly different activity than *leisure* (e.g., talking to colleagues). While labor typically involves physical or cognitive effort in return for rewards, leisure involves neither. However, leisure could hold utility by allowing for "mental exploration" akin to mind-wandering (Kool & Botvinick, 2014), which gives the opportunity to evaluate current and plan future activities (Baird, Smallwood, & Schooler, 2011). Second, by contrast to prior work on this topic, we examined transitions between labor and leisure in both directions. That is, we not only examined decisions to take breaks (while working), but

also examined when people decided to start working again (after taking a break). An important feature of our studies is that analysis plans were pre-registered before data collection. In what follows, we introduce the major biological theory linking the exploration-exploitation trade-off to neural processes, describe previous human research supporting this theory, and explain why our paradigm allows for a more comprehensive investigation of NE levels when humans switch from one behavioral state to the other.

A major theory linking the trade-off between exploration and exploitation to neural mechanisms is Adaptive Gain Theory (AGT), which connects these behavioral states to qualitatively different neural states of the locus coeruleus–norepinephrine (LC-NE) system (Aston-Jones & Cohen, 2005; Cohen, McClure, & Yu, 2007): During *exploitation*, baseline norepinephrine (NE) levels in the locus coeruleus (LC) are low, but bursts of NE release occur in response to focal target stimuli. Given that NE release in cortical areas increases neural responsivity to incoming information (Berridge & Waterhouse, 2003; Servan-Schreiber, Printz, & Cohen, 1990), this pattern is likely adaptive: it helps animals to direct attention to task-relevant information. In contrast, during *exploration*, baseline NE levels are chronically elevated, while target-related bursts are attenuated or even absent. It has been suggested that this pattern may widen attention, allowing people to better detect task-irrelevant—but nevertheless potentially interesting—stimuli (Cohen et al., 2007).

Importantly, NE levels are correlated with pupil diameter in both monkeys (Joshi, Li, Kalwani, & Gold, 2016; Rajkowski, Kubiak, & Aston-Jones, 1994) and humans (Murphy, O’Connell, O’Sullivan, Robertson, & Balsters, 2014; Murphy, Robertson, Balsters, & O’Connell, 2011). For example, in line with predictions from AGT, previous research found that pupil diameter covaried with task engagement and disengagement in a pitch discrimination task (Gilzenrat, Nieuwenhuis, Jepma, & Cohen, 2010). In this task, participants judged which of two tones had a higher pitch. Difficulty continuously increased while payoffs decreased with every error participants made. At any time, participants could reset task

settings by pressing an “escape” button, which the authors interpreted as exploration behavior. Changes in pupil dilation were also observed in transitions between bandit gambling machines (Jepma & Nieuwenhuis, 2011) and in a task that required people to solve Raven’s Matrices (Hayes & Petrov, 2016). Overall, in these studies, *exploitation* (or task engagement) was characterized by low baseline pupil diameter, combined with large pupil dilations in response to task stimuli. By contrast, *exploitation* (or task disengagement) was characterized by high baselines and smaller dilations in response to task-relevant stimuli.

While the studies described in the previous paragraph link the LC-NE system, and particularly pupil diameter as an observable correlate, to exploration–exploitation dilemmas, it is not yet clear whether the LC-NE system is involved in people’s decisions to take breaks. After all, prior studies operationalized exploration as brief transitions between extended phases of exploitation, making it impossible to disentangle disengagement from the previous task vs. re-engagement in the next task. Also, these studies manipulated task payoff and difficulty, thus incentivizing all participants to start exploration at a defined moment, instead of keeping the environment constant and tracking individual differences in participants’ natural drive for exploration. In contrast, we studied participants’ self-directed decisions to take a break (vs. to continue working), which are arguably similar in structure as exploration–exploitation dilemmas, because agents have to decide whether to (a) stay with a current activity and its payoff or (b) to quit this activity and explore the environment for more rewarding alternatives—at the risk of wasting time and foregoing rewards. Indeed, in research on fatigue and effort, the LC-NE system has been mentioned as a candidate mechanism for understanding labor-leisure transitions (Inzlicht, Schmeichel, & Macrae, 2014; Kurzban, Duckworth, Kable, & Myers, 2013). Yet, to our knowledge, this possibility has not been tested.

The present research

Based on AGT, we hypothesized that labor-to-leisure transitions (i.e., decisions to take a break from work) are preceded by (a) increases in pupil baseline and (b) decreases in pupil dilation. For leisure-to-labor transitions (i.e., decisions to start working after taking a break), predictions are somewhat less straightforward. On the one hand, based on AGT, we would predict that baselines stay high during the leisure phase to ensure a broadened attention that facilitates the detection of alternative activities. However, when switching back to labor, people need to focus on the labor task only, so that (a) pupil baseline should decrease and (b) pupil dilations should increase again. On the other hand, one could also pose that leisure-to-labor transitions are not different from labor-to-leisure transitions in that they constitute a case of task-switching. Task switches are linked to NE by *network reset theory* (NRT; Bouret & Sara, 2005; Dayan & Yu, 2006; Sara & Bouret, 2012), which suggests that NE is primarily released when people detect unexpected changes in the environment. When these changes happen, NE promotes reorientation towards stimuli that have become relevant in the new task environment, facilitating adaptation to new demands. So far, it has not been explored whether NE could have a similar function in humans' self-directed decisions to switch tasks. If this was the case, we would expect (a) increases in pupil baseline and (b) decreases in pupil dilation preceding both labor-to-leisure and leisure-to-labor transitions, because NRT assumes NE processes to be independent of the activity performed previously and the activity to-be-performed after the switch. By investigating leisure-to-labor transitions, our research directly tested AGT and NRT against each other.

We operationalized *labor* as a 2-back memory task and *leisure* as an attractiveness rating task, following a paradigm by Kool and Botvinick (2014). We employed both linear and additive mixed models, which allowed us to more closely examine the onset and duration of pupil shifts. To shed light on functional role of the processes underlying pupil changes, we conducted exploratory analyses in which we correlated the magnitude of pupil changes with individual differences in self-reported procrastination and action orientation in everyday life.

To this end, we used well-validated questionnaires (Kuhl, 1994; Kuhl & Fuhrmann, 1998; Steel, 2010).

Below, we report Methods and Results for Studies 1 and 2 together, as protocols in both studies were identical except for two brief control assessments administered following the main task in Study 2. In our pre-registration for Study 1,[1] based on previous literature (Gilzenrat et al., 2010), we expected pupil shifts to occur prior to task switches, which would have allowed us to predict switches prospectively based on pupil diameter. As our hypotheses found no evidence in the pre-registered time window, we explored them in a later time window centered around the behavioral switch. We pre-registered these analyses for Study 2[2] to replicate our exploratory findings from Study 1.

Methods

Participants. In Study 1, 35 participants completed a 50-minute study in exchange for a €7.50 voucher and an extra cash payment of up to €5, depending on their task performance. We recruited participants in the age range 17–30 who had normal or corrected-to-normal vision (using contact lenses), understood English, and did not suffer from neurological disorders. In line with pre-registered exclusion criteria (see Supplementary Online Material S1), four participants were excluded from analyses, so that the final sample consisted of 31 participants (68% female, M_{age} = 22, SD_{age} = 2.7).

In Study 2, 35 participants completed a 60-minute study in exchange for a €10 shopping voucher and an extra cash payment of up to €5. Participants were recruited from the same population as in Study 1, using the same exclusion criteria (see S2). Four participants were excluded from analyses, so that the final sample consisted of 31 participants (65% female, M_{age} = 22, SD_{age} = 3.1). Studies were approved by the local ethics review board.

[1] Pre-registration for Study 1: https://osf.io/ypyha/register/5730e99a9ad5a102c5745a8a
[2] Pre-registration for Study 2: https://osf.io/48kyw/register/5730e99a9ad5a102c5745a8a

Procedure. Participants were welcomed in a room equipped with a stationary SMI iView X infrared eye-tracker (SensoMotoric Instruments, Teltow, Germany) sampling at 500 Hz. We placed this device's chin rest 72 cm away from a 24-inch monitor, on which the task stimuli were presented (using a script programmed in PsychoPy; Peirce, 2007). After they were seated, participants first completed a 9-point calibration of the eye-tracking device, followed by a 10 min practice phase, in which participants were familiarized with the labor and leisure tasks (which were first practiced separately), but also with labor-to-leisure and leisure-to-labor switches.

Next, participants completed the test phase, which took 25 min and which consisted of 500 trials. During both the practice and test phases, pupil size of their dominant eye was tracked. In Study 2, additionally, participants completed two control assessments of 80 trials each to exclude alternative interpretations of the findings of Study 1. Afterwards, in both studies, participants rated both tasks on the dimensions "work" and "fun" using a 7-point scale and filled in questionnaires assessing their procrastination tendency and action vs. state orientation. Finally, they were debriefed and paid.

Labor-Leisure Task. During the test phase, in each trial, participants could choose between performing an effortful 2-back task (labor task) or an easy attractiveness-rating task (leisure task; adapted from Kool & Botvinick, 2014). For each trial they spent on the labor task, they received 1 cent extra cash payment. It was announced in advance that participants with accuracy levels below 75% in the labor task would receive no extra payment, but that previous participants were able to easily achieve this level if they tried hard. This threshold was implemented in order to discourage participants from resting during the labor task and encourage switching to the leisure task in case they felt like taking a break. Participants' responses during the leisure task did not affect their monetary payout, allowing for an actual break from paid work.

Participants selected and performed tasks using a joystick. Specifically, participants selected tasks by moving the joystick sideways. When the joystick was moved to the left (or right; counterbalanced), participants performed the labor task; to the right (or left; counterbalanced), participants performed the leisure task. Both tasks were presented as labels at the upper corners of the screen ("2-back" and "attractiveness"). As a reminder, the currently-selected task was surrounded by a white frame. It was only possible to switch tasks when no stimulus was displayed, in order to prevent participants from employing the strategy of first viewing a face and then choosing which task to perform.

Regardless of the position of the joystick, on each trial, participants saw the following stimuli: a fixation cross (200 ms), a mask stimulus (800 ms), a face (1500 ms), and a blank screen (400–600 ms). Figure 1 depicts the course of one trial. When participants had selected the labor task, they were required to press the joystick trigger when the current face was the same face as two faces before (i.e., when the current face was a 2-back target; in case of a nontarget, they were required to refrain from responding). When participants had selected the leisure task, they were asked to press the joystick trigger when they saw an attractive face.

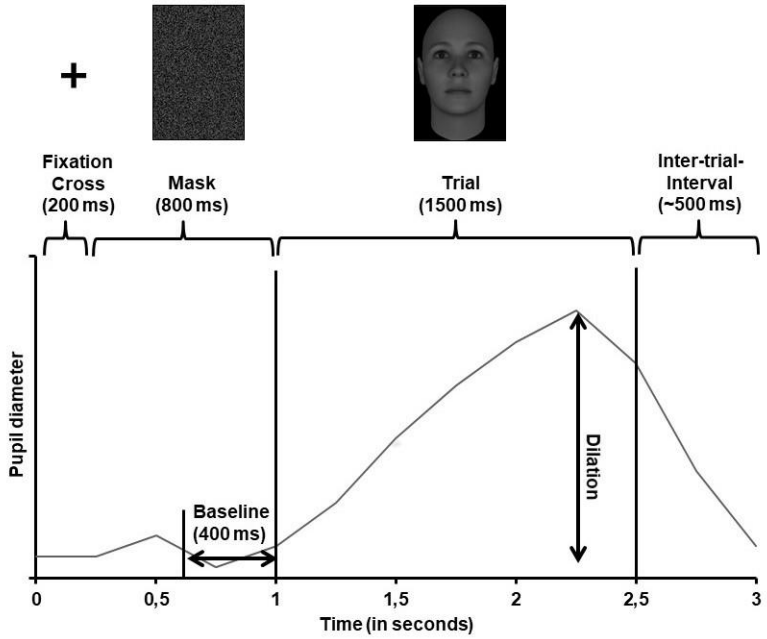

Figure 1. Overview of the time course of one trial in the labor-leisure task, including the parts of the trial in which we measured baselines and dilations, respectively. Face stimulus taken from Said and Todorov (2011).

Stimuli. Faces were selected from the Attractiveness Model Database (Said & Todorov, 2011), which contains artificially generated faces. Of the 20 faces used, 10 were drawn from the 5% most attractive faces of the database; the other 10 from the 5% least attractive faces. Ten faces were male faces; the other 10 were female faces. All stimuli were matched on mean luminance and had the same size (400 x 400 pixels). The mask consisted of the pixels of one of the faces randomly rearranged, resulting in the same mean luminance. For all practice phases and the final test phase, we generated a pseudo-random order of faces, with a 30% chance of a 2-back trial occurring. Fifty percent of trials showed attractive faces.

Control assessments. In Study 2, after the labor-leisure task, participants additionally completed two control assessments of 80 trials (5 min) each. Both conditions were identical to the labor-leisure task in trial structure, stimuli, and task labels, but different in instructions.

First, in the *motor control assessment*, participants were instructed to respond to one particular face (and not to any other face) by moving the joystick in a way as if they switched

between tasks in the labor-leisure task. This particular face was displayed on trials 5, 15, … 75, with each of these trials surrounded by 10 trials without any action, allowing for a similar analysis of "switches" as in the labor-leisure task. With this basic vigilance task, we intended to test whether pupil changes were driven by the motor activity occurring when moving the joystick.

Second, in the *visual control assessment*, participants were instructed to passively watch a series of trials without any action. In trials 5, 15, … 75, the frame highlighting the 2-back or attractiveness-rating task label was automatically shifted to the respective other task label. With this control assessment, we intended to test whether watching the moving frame was sufficient to induce the observed pupil changes.

Questionnaires. In both studies, after people had completed the tasks and left the eye-tracker, we administered three questionnaires:

The Irrational Procrastination Scale (IPS; Steel, 2010) measures general procrastination tendencies using nine items such as "I often regret not getting to task sooner". People responded on a 7-point scale ranging from strongly disagree (1) to strongly agree (7).

The Action Control Scale (ACS-24; Kuhl, 1994) consists of 24 descriptions of scenarios, with two possible strategies to act in each situation. Participants are asked to select the strategy that describes best how they would react. It comprises two subscales: the action orientation subsequent to failure vs. preoccupation (AOF) subscale contains scenarios about dealing with failures such as "When several things go wrong on the same day", where the action-oriented response is "I just keep on going as though nothing had happened" and the state-oriented one is "I don't know how to deal with it." In contrast, the prospective and decision-related action orientation vs. hesitation (AOD) subscale contains items related to planning and starting activities such as "When I have an obligation to do something that is boring and uninteresting" with the action-oriented response "I do it and get it over with" and the state-oriented response "It usually takes a while before I get around to doing it."

Furthermore, we selected three subscales from the Self-Government Inventory (SSI-K3; Kuhl & Fuhrmann, 1998): the self-regulation (competence) subscale relates to feelings of autonomy, intrinsic motivation, and dealing with nervousness and contains items such as "When my perseverance subsides, I know exactly how to motivate myself again." The self-control subscale comprises items about planning, prospection, and self-confidence such as "If I have a lot to do, I work according to a plan (i.e. I have a schedule for my tasks)." The volitional development (action development) subscale consists of items reflecting initiative and readiness to act in contrast to postponement and procrastination such as "If something has to be done, I begin doing it immediately." Participants rated how much each item applied to themselves on a four-point scale from "not at all" to "completely." For each of the scales, we calculated participants' average scores.

Data analysis.

Pre-processing of eye-tracking data. Pre-processing of the pupil raw data included removing values of zero, removing abnormally fast pupil changes, deleting outliers, and finally imputing missing values using linear interpolation. Our exact analysis script has been built on previous experimental work (Bijleveld, 2018) and it is available on https://osf.io/b9z4c/ (Study 1) and https://osf.io/ukgsh/ (Study 2).

Pupil measures. For each trial, baseline pupil diameter and maximal pupil dilation were computed. Baseline pupil diameter was defined as the average pupil size during the last 400 ms of the mask presentation. Pupil dilation was defined as the difference between the maximal pupil size during face stimulus presentation and the baseline pupil diameter (for an illustration, see Figure 1).

Generalized additive mixed models. To account for auto-correlation in the pupil data, we followed recent suggestions (Baayen, Vasishth, Kliegl, & Bates, 2017) to fit generalized additive mixed models (GAMMs) to time-series data using the mgcv package (version 1.8.22; Wood, 2017) in R (version 3.4.3; R Core Team, 2017). The unit of analysis

were single trials. Trials were nested in *bouts*, with a bout formed by the five trials before and five trials after a switch. We used either pupil baseline or pupil dilation as the dependent variable, each maximum normalized per person.[3] We used (a) trial number relative to switch and (b) the interaction between trial number and switch type (labor-to leisure vs. leisure-to-labor) as predictors. We fitted GAMMs with random slopes for trial number for each bout of each participant, which effectively reduced auto-correlation to levels < .15.[4] When testing for differences between switch types, we coded the predictor switch types as an ordered factor.

Note that GAMMs fit a smooth (consisting of thin plate regression splines) through all data points and test whether this smooth is significantly different from a straight line (i.e. from zero) at any time point during the selected time window. Thus, GAMMs do not qualify the shape (e.g., linear vs. curvilinear) or direction (e.g., increase vs. decrease) of a change. Hence, we additionally fitted linear mixed-effects models to test for linear increases or decreases in pupil baseline and pupil dilation. In our interpretations, we gave priority to the results of the GAMMs as those (a) account for auto-correlations, and (b) our hypotheses were agnostic about how early and how long the predicted changes would occur.

Linear mixed-effects models. We fitted linear mixed-effects models (LMEMs) using the lme4-package (version 1.1.15; Bates, Mächler, Bolker, & Walker, 2015) with pupil baseline or pupil dilation as outcome variable and trial number relative to switch as sole predictor. When comparing the effects of switch types, we added the factor switch type and the interaction between trial number and switch type. Both outcome measures and relative

[3] Maximum-normalization was implemented by subtracting the minimum of an individual from all their values and dividing them by the person's maximum. This transformed each individual's values into the range from 0 to 1, reducing the effect of outliers. All analyses were repeated with the raw pupil measures as well as with these measures z-standardized per person. In both cases, the same pattern of significant and non-significant results was obtained.

[4] As a control, we also fitted GAMMs with random smooths, featuring an ARIMA(1)-model based on the model with random slopes to account for auto-correlation. However, given that each bout comprised at most 10 (and often less) data points, fitting separate smooths for each bout restricted us to using 8 knots for each smooth only, further constraining the "wigglyness" of the underlying smooth we could possibly fit. Auto-correlations were hardly any further reduced. These models yielded *F*- and *p*-values that were highly similar to those of the models with random slopes and led to the same conclusions.

trial numbers were standardized, so that regression coefficients can be interpreted as standardized regression weights. For the factor switch type, we employed sum-to-zero coding. Models contained a maximal random effects structure (Barr, Levy, Scheepers, & Tily, 2013), with random intercepts and random slopes of trial number, switch type, and their interaction, both for each participant and for each bout of adjacent trials of each participant, and with all possible random correlations. We computed type-3 like *p*-values using *F*-tests with Kenward-Roger approximation for degrees of freedom (Singmann, Bolker, Westfall, & Aust, 2017).

Power estimation. We checked in a small pilot study (N = 7) whether participants followed the task instructions and switched between tasks often enough to yield sufficient power for testing our hypotheses with N = 30. Participants switched on average 8.4 times from labor to leisure. Given N = 30 and our initial hypothesis of analyzing the last ten but one trial before switches (see below), we expected to obtain 2,268 usable trials. In our pilot data, we obtained intra-class correlations of .67 for baselines and .37 for dilations. Following Aarts, Verhage, Veenvliet, Dolan, and van der Sluis (2014), we estimated effective sample sizes of 357 trials for baselines and 597 trials for dilations, which allowed us to detect effects of $\beta > .14$ for baselines and $\beta > .11$ for dilations with 80% power (power sensitivity analysis for linear bivariate regression in G*Power 3; Faul, Erdfelder, Lang, & Buchner, 2007).

Results

Manipulation Check

In Study 1, participants rated the 2-back task as significantly more work (M = 5.87, SD = 0.85) than fun (M = 2.58, SD = 0.92), $t(30) = 15.06$, $p < .001$, $d = 2.71$, and the attractiveness-rating task as significantly more fun (M = 3.70, SD = 1.53) than work (M = 2.00, SD = 1.03), $t(30) = -5.05$, $p < .001$, $d = -0.91$. They perceived the 2-back task as more work compared to the rating task, $t(30) = 17.13$, $p < .001$, $d = 3.08$, but the rating task as more fun compared to the 2-back task, $t(30) = -4.25$, $p < .001$, $d = -0.76$.

In Study 2, participants rated the 2-back on average as more work (M = 5.32, SD = 1.45) than fun (M = 2.84, SD = 1.37), $t(30) = 6.55$, $p < .001$, $d = 1.18$ and the attractiveness-rating task as more fun (M = 2.94; SD = 1.34) than work (M = 2.32, SD = 1.25), $t(30) = 2.13$, $p = .042$; $d = -0.38$. Also, the 2-back task was perceived as more work than the rating task, $t(30) = 8.09$, $p < .001$, $d = 1.45$, but the rating task was not perceived as more fun than the 2-back task, $t(30) = 0.31$, $p = .756$, $d = -0.06$. This resulted from a lower "fun"-rating of the rating task compared to Study 1, which might have been due to the fact that in Study 2, between the test phase and the ratings, participants completed the control assessments for another ten minutes. Hence, their memory of the tasks might have faded. Overall, we conclude that in both studies, the tasks successfully implemented labor in contrast to leisure.

Task performance. In Study 1, on average, participants spent 396 (SD = 53) out of 500 trials on the labor task; they switched 7.97 times (SD = 7.64) from labor to leisure. In the labor task, participants gave on average 84% (SD = 4%) correct responses. In the leisure task, they responded in 27% (SD = 14%) of trials, indicating that participants actively engaged in this task. In Study 2, participants spent on average 352 trials (SD = 123) on the labor task; they switched 8.77 times (SD = 6.58) from labor to leisure. In the labor task, they responded in 84% of trials (SD = 6%) correctly. During the leisure task, they responded in 28% (SD = 17%) of trials. We conclude that in both studies, participants were engaged in both tasks, even though performance on the leisure task had no impact on their payout. See S3 for details on accuracy directly before switches to leisure, S4 for differences in accuracy before compared to after periods of leisure, and S5 for correlations of overall baseline pupil diameter and pupil dilations with performance measures.

Pre-registered confirmatory analyses of Study 1.

In our original pre-registration, we decided to select the last ten but one trials before labor-to-leisure switches, and fit LMEMs with the outcomes baseline pupil diameter or pupil dilations and the sole predictor trial number relative to the switch (-10 till -2). There was no

evidence for an increase in baseline pupil diameter, β = .01, 95% CI [-0.04, 0.06], $F(1, 23.50) = 0.11$, $p = .743$, nor for a decrease in pupil dilations, β = -.03, 95% CI [-0.08, 0.02], $F(1, 25.68) = 1.33$, $p = .260$, during the pre-registered time window.

Exploratory analyses Study 1 and pre-registered analyses Study 2

As a next step, we ran exploratory analyses. For this purpose, we (a) considered a different range of trials, namely the last five trials before and the first five trials after switches, centered on the trial on which participants decided to switch. This allowed us to investigate whether pupil changes started later than we initially expected, namely only 1-2 trials before the switch. Also, we (b) investigated both switches from labor to leisure and from leisure to labor. Unless otherwise indicated, all analyses reported below were pre-registered for Study 2.

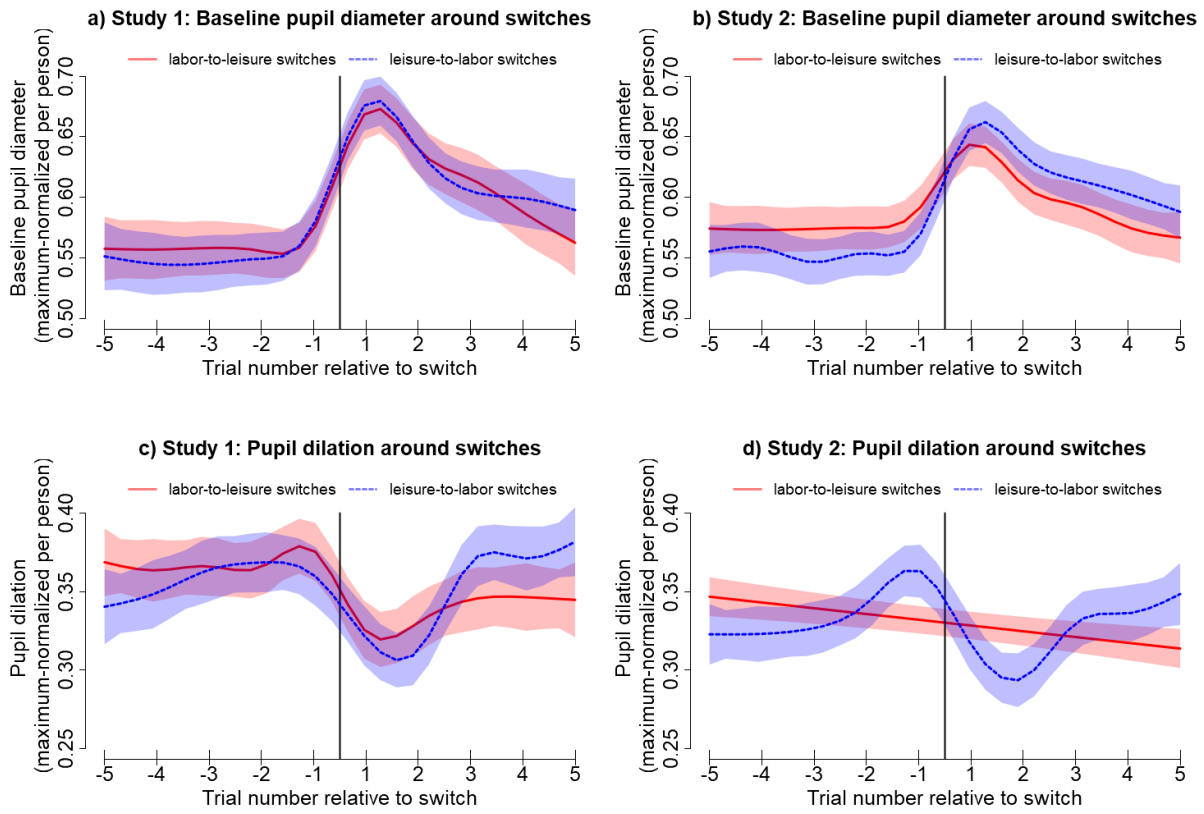

Figure 2. Top panels: Time course of baseline pupil diameter around labor-to-leisure and leisure-to-labor switches in Studies 1 (A) and 2 (B). Bottom panels: Time course of pupil dilations around labor-to-leisure and leisure-to-labor switches in Studies 1 (C) and 2 (D). Plots are based on the GAMMs described in the main text (van Rij, Wieling, Baayen, & van Rijn, 2017). Shades indicate 95%-CIs. Vertical lines indicate the time point of the switch.

Changes in baseline pupil diameter.

In Study 1, GAMMs indicated that the time course (smooth) of baseline pupil diameter was overall significantly different from zero for both labor-to-leisure switches, $F(8.54, 3577.26) = 23.65$, $p < .001$, and leisure-to-labor switches, $F(8.50, 3577.26) = 23.95$, $p < .001$, with no evidence for a difference between switch types, $F(1.00, 3584.57) = 1.16$, $p = .281$ (see Figure 2a).

In subsequent LMEMs, consistent with our hypothesis, we found significant increases in baselines for labor-to-leisure switches, $\beta = .12$, 95% CI [.04, .19], $F(1, 25.88) = 9.89$, $p = .004$, which is predicted by both AGT and NRT. Also, we found such an increase for leisure-

to-labor switches, β = .16, 95% CI [.09, .24], $F(1, 27.85) = 19.35$, $p < .001$. While this increase is in line with NRT, AGT would have actually predicted a decrease in baselines. In a model with the predictors relative trial number, switch type, and their interaction, neither the main effect of switch type, β = -.03, 95% CI [-.10, .04], $F(1, 18.17) = 0.45$, $p = .512$, nor the interaction were significant, β = -.02, 95% CI [-.08, .03], $F(1, 26.56) = 0.96$, $p = .336$, providing no evidence for differences in time course between both switch types.

In Study 2, replicating the results from Study 1, GAMMs indicated that the time courses of pupil baselines were significant different from zero for both labor-to-leisure, $F(8.30, 4257.04) = 11.43$, $p < .001$, and leisure-to-labor switches, $F(8.57, 4257.04) = 21.46$, $p < .001$ (see Figure 2b). The smooths of both switch types were significantly different from each other, $F(3.33, 4261.67) = 4.06$, $p = .005$, with baselines being higher three to five trials after leisure-to-labor switches compared to leisure-to-labor switches (also see Figure 2b).

Subsequent LMEMs showed no effect in labor-to-leisure switches, β = .03, 95% CI [-.02, .08], $F(1, 26.14) = 1.56$, $p = .222$, but a significant increase in baseline pupil diameter in leisure-to-labor switches, β = .12, 95% CI [.07, .17], $F(1, 23.46) = 23.46$, $p < .001$. In Figure 2b based on the respective GAMM, still, an increase can also be observed in labor-to-leisure switches. Potentially, as baseline levels fully returned to pre-switch levels until the end of the selected time window, the LMEM was unable to detect a net increase in this condition. Refitting the model on the time window of two trials before until two trials after a switch yielded in fact a significant increase, β = .13, 95% CI [.07, .20], $F(1, 27.30) = 13.19$, $p = .001$. In a model with the predictors relative trial number, switch type, and their interaction, there was neither a significant main effect of switch type, β = -.04, 95% CI [-.11, .02], $F(1, 21.87) = 1.61$, $p = .217$, nor a significant interaction effect, β = .04 , 95% CI [-.09, .01], $F(1, 26.72) = 3.51$, $p = .072$, providing no evidence for any difference between switch types. Results were consistent and comparable in amplitude to those of Study 1 (see Figures 2a vs. 2b), again supporting NRT, but not AGT.

Changes in pupil dilation.

For Study 1, GAMMs indicated that the time course of pupil dilation was significantly different from zero for both labor-to-leisure switches, $F(7.76, 4012.88) = 2.91$, $p = .003$, and leisure-to-labor switches, $F(7.91, 4012.88) = 5.13$, $p < .001$, and that it did vary between switch types, $F(1.80, 4002.19) = 4.16$, $p = .019$. Dilations were higher three to five trials after leisure-to-labor switches compared to labor-to-leisure switches (see Figure 2c). This would be in line with the prediction of AGT that pupil dilations should be higher during focused labor than leisure.

Using LMEMs, we found the predicted significant decrease in pupil dilations for labor-to-leisure switches, $\beta = -.07$, 95% CI [-.14, -.01], $F(1, 27.75) = 4.90$, $p = .035$, but not for leisure-to-labor switches, $\beta = .001$, 95% CI [-.07, .06], $F(1, 28.17) = 0$, $p = .962$. In Figure 2c based on the respective GAMM, a decrease in leisure-to-labor switches can be observed from two trials before until two trials after switches, but this might have been too limited for the LMEM to detect a net decrease in the selected time window. Refitting the model on these trials only yielded in fact a significant decrease, $\beta = -.16$, 95% CI [-.24, -.08], $F(1, 21.94) = 15.36$, $p < .001$. Again, both findings are predicted by NRT, while AGT predicts only the former, but the opposite of the latter finding. Running a model with trial position, switch type, and their interaction as predictors, neither the main effect of switch type, $\beta = -.01$, 95% CI [-.04, .02], $F(1, 23.63) = 0.19$, $p = .663$, nor the interaction were non-significant, $\beta = -.04$, 95% CI [-.09, .02], $F(1, 28.54) = 1.95$, $p = .174$[5], providing no evidence for a difference between switch types (see Figure 2c).

In Study 2, GAMMs showed that the time course of pupil dilations was significantly different from zero for both labor-to-leisure switches, $F(1, 4688.12) = 13.31$, $p < .001$, and

[5] Due to convergence warnings, we simplified the model by dropping the random slopes per bout, but keeping the random slopes per subject. In the model with the full random effects structure (which did not converge), the main effect of switch type was not significant, and the interaction only marginally significant, $F(1, 27.55) = 3.42$, $p = .075$.

leisure-to-labor switches $F(7.66, 4688.12) = 5.24$; $p < .001$ (see Figure 2d), and did vary between switch types, $F(7.76, 4687.73) = 6.29$, $p < .001$: Dilations were higher five trials before and two trials after labor-to-leisure switches, but lower one trial before and five trials after labor-to-leisure switches compared to leisure-to-labor switches (see Figure 2d).

Subsequent LMEMs yielded a significant decrease in pupil dilation in labor-to-leisure switches, $\beta = -.06$, 95% CI [-.02, .11], $F(1, 26.43) = 6.71$, $p = .015$, but again not in leisure-to-labor switches, $\beta = .01$, 95% CI [-.02, .05], $F(1, 20.07) = 0.51$, $p = .482$. As for Study 1, there was a decrease also in leisure-to-labor switches (see Figure 2d), but only from two trials before until two trials after the switch, which was detected LMEM fitted on only these trials, $\beta = -.13$, 95% CI [-.19, -.07], $F(1, 21.07) = 17.41$, $p < .001$. In a model with the predictors relative trial position, switch type, and their interaction, the main effect of switch type was not significant, $\beta = .01$, 95% CI [-.02, .03], $F(1, 501.84) = 0.17$, $p = .68$, but the interaction effect was, $\beta = -.03$, 95% CI [-.06, -.01], $F(1, 520.93) = 7.79$, $p = .005$,[6] indicating that the effect of trial-number was significantly more negative for labor-to-leisure than for leisure-to-labor switches. Dilation patterns were consistent with and comparable in amplitude to those of Study 1 (see *Figure 2c and 2d*).

In conclusion, across both studies, we found increases in pupil baseline levels and decreases in pupil dilations both around labor-to-leisure and leisure-to-labor task switches. The size of baseline increases and dilation decreases was largely comparable between both switch types and across both studies (see *Figure 2*). These results were fully predicted by NRT. Only the patterns observed for labor-to-leisure switches, but not the pattern for leisure-to-labor switches was consistent with AGT. In sum, our data provided support for NRT, which proposes that pupil shifts across both types of task switches reflect processes involved in task-switching, independent of the motivational nature of the task. However, one might argue that these shifts

[6] Due to convergence warnings, we simplified the model by dropping the random slopes per subject, keeping the random slopes per bout. In the model with the full random effects structure (which did not converge), the main effect of switch type nor the interaction was significant either.

are comparable across switches types and studies because they do not reflect neural processes underlying task switching, but rather a) motor processes initiating the movement of the joystick, or b) visual processes of observing the frame highlighting the current task moving from one task label to the other. Although these alternative explanations seem rather unlikely given the prolonged elevation of pupil baselines until twelve seconds after the behavioral switch, we aimed to rule out those alternative explanations via two additional assessments.

Control assessments (Study 2 only).

Motor control assessment.

A GAMM indicated that contrary to our expectations, the time course of baseline pupil diameter around motor actions was significantly different from zero, $F(8.93, 1535.64) = 40.40$, $p < .001$ (see Figure S6a), and a LMEM yielded a significant increase, $\beta = .11$, 95% CI [.05, .16], $F(1, 22.00) = 15.25$, $p < .001$. Additionally, contrary to our expectations, a GAMM indicated that the time course of pupil dilation was significant different from zero, $F(8.94, 1665.19) = 20.47$, $p < .001$ (see Figure S6c), with a LMEM yielding a significant decrease, $\beta = -.08$, 95% CI [-.12, -.03], $F(1, 21.99) = 10.63$, $p = .004$.

Several factors might account for this unexpected finding. First, we expected this condition to be an easy task, but participants committed a considerable amount of errors (217 out of 2,480 trials, i.e. 10% of all trials; with 148 false-positive switches and 69 false-negative non-switches).[7] This indicates that the task was more difficult (or less engaging) than expected, and effortful processes different from mere motor activation (e.g. working memory) might have contributed to pupil changes (Kahneman, 1973). Second, it seemed that pupil dilations were particularly high in the motor control assessments on the very last trial before a switch, i.e. the trial participants saw the face that triggered them to switch, which could reflect increased effort (Kahneman, 1973). In an exploratory analysis, we directly contrasted the time courses in the

[7] For appropriate exclusion of participants and trials from the following analyses, see SOM S2.

motion control assessment with those around leisure-to-labor switches,[8] using a GAMM with the interaction between trial number and the ordered factor switch type (motor control assessment vs. leisure-to-labor). The differences in the time course of pupil dilation was indeed significant, $F(8.93, 3975.57) = 12.88$, $p < .001$, indicating that pupil dilations were higher in the motor control assessment on the very last trial before a switch, but higher in leisure-to-labor switches on the very first trial after a switch (see Figure S6d). Third, it seemed that baseline increases in motor control assessments were restricted to the very first trial after a switch, but more sustained in labor-to-leisure and leisure-to-labor switches. When directly contrasting the time courses of pupil baselines of motor control assessments and leisure-to-labor switches, we indeed found significant differences, $F(8.57, 3657.29) =12.27$, $p < .001$: baselines were higher in leisure-to-labor switches from five till one trial before the switch and from two to five trials after the switch, but the motor control assessment was only higher on the very first trial after a switch (see Figure S6b).

Taken together, the motor control assessment might have been more difficult for participants than we expected, as indicated by the high error rates and the strong pupil dilation on the last trial before the switch, which might reflect increased effort recruitment. Also, increases in the labor-to-leisure and leisure-to-labor switches continued for several trials after a switch, while the increase in the motor control assessment was only present on the very first trial after a switch. These findings render it unlikely that the pupil changes observed in labor-to-leisure and leisure-to-labor switches were fully reducible to processes underlying motor movements.

Visual control assessment.

[8] Pupil changes around leisure-to-labor switches were overall larger than those around labor-to-leisure switches and should thus be more similar to the time course in the motor control assessment, providing a more conservative test for differences. The same results were found when comparing switches in the motor control assessment to labor-to-leisure switches.

In the selected time window, contrary to our expectations, a GAMM indicated that the time course of baselines in the visual control assessment was significantly different from zero, $F(6.63, 2075.75) = 2.92$, $p = .006$. Visual inspection showed however that the time course was overall rather flat (Figure S6a).[9] A LMEM found no evidence for any net changes across the selected time window, $\beta = -.04$, 95% CI [-.09, .01], $F(1, 30.00) = 3.63$, $p = .067$. Similarly, a GAMM found no evidence for the time course of pupil dilations deviating from a flat line, $F(2.48, 2335.32) = 2.09$, $p = .112$ (see Figure S6b), and a LMEM found no evidence for net changes either, $\beta = .01$, 95% CI [-.03, .04], $F(1, 30.00) = 0.04$, $p = .835$. We conclude that the pupil changes observed in labor-to-leisure and leisure-to-labor switches do not stem from merely watching the frame highlighting task labels move.

Correlations with action orientation across both studies.

We initially pre-registered to run LMEMs with the predictors trial number, switch type, the respective questionnaire scale, and all interactions to check whether individual differences in procrastination and action orientation predicted the amplitude of pupil changes, and differently so for the different switch types. Since these models failed to converge, we instead re-used the simple models of baseline increases and dilation decreases reported above, extracted the best linear unbiased predictors (BLUPs),[10] i.e. the group-level fixed effect slope of trial number plus the respective random slope of trial number of each participant, and correlated those with participants' average scores on the questionnaires. Correlations between BLUPs and questionnaires are displayed in Table 1; descriptive statistics and intercorrelations between questionnaires in SOM S7. Note that pupil dilation *decreases* around switches, so BLUPs are typically negative; the more negative they are, the larger is the amplitude of the decrease. Most correlations were low. However, strikingly, the BLUPs of pupil dilation

[9] When fitted with random smooths on eight knots, the time course in the visual control assessment was not significantly different from a flat line, $F(2.88, 1695.85) = 2.21$, $p = 0.060$.

[10] BLUPs were fitted based on the total time window of interest. Even though on a group-level, there was no significant decrease in dilations across leisure-to-labor switches in either study. This does not exclude the existence of meaningful individual differences between participants.

decreases were *positively* associated with action orientation after failure (AOF) and self-regulation (SR) for labor-to-leisure switches, but *negatively* for leisure-to-labor switches. The same pattern, though weaker, was found for the subscales decision-related action orientation (AOD) and self-control (SC).[11] No associations were found with procrastination (IPS) and volitional development (VD). The negative correlations with BLUPs in leisure-to-labor switches imply that the higher participants scored on action orientation, the stronger were their decreases in pupil dilation in leisure-to-labor switches, but the weaker were their decreases in pupil dilation in labor-to-leisure switches.

Table 1

Correlations of Self-Reported Procrastination Tendencies and Action vs. State Orientation With the Best Linear Unbiased Predictors (BLUPs) of Pupil Baseline Diameter Increases and Pupil Dilation Decreases in Both Labor-to-Leisure and Leisure-to-Labor Switches

	BLUPs Baseline		BLUPs Dilation	
	Labor-to-leisure switches	Leisure-to-labor switches	Labor-to-leisure switches	Leisure-to-labor switches
IPS	-.04	.01	-.14	.01
ACS-24 AOF	.17	-.09	.19	-.28*
ACS-24 AOD	.14	.05	.07	-.13
SSI K3 SR	.07	-.11	.26*	-.27*
SSI K3 SC	-.04	.20	.16	-.25†
SSI K3 VD	-.01	-.14	.10	.03

Note. Higher IPS values indicate higher procrastination tendencies, and higher values on the other scales indicate higher action orientation. Samples of both studies (total $N = 62$) were combined. IPS = Irrational Procrastination Scale; ACS-24 AOF = ACS-24 Action orientation subsequent to failure vs. preoccupation subscale; ACS-24 AOD = ACS-24 Prospective and decision-related action orientation vs. hesitation subscale; SSI-K3 SR = SSI-K3 Self-regulation (Competence) subscale; SSI-K3 SC = SSI-K3 Self-control subscale; SSI-K3 VD = SSI-K3 Volitional development (Action development) subscale.

[11] All these patterns were also reflected in significant or marginally significant 3-way interactions in the initially pre-registered LMEMs, which however yielded convergence warnings.

† p < .10, * *p* < .05, uncorrected.

Discussion

In two pre-registered experiments, we found that pupil baseline levels increase and pupil dilations decrease around switches from cognitive labor to cognitive leisure, and back from leisure to labor. Our findings extend previous studies which found these pupil changes in disengagement from (and restart of) an auditory discrimination task (Gilzenrat et al., 2010), shifts between multiple bandit gambling machines (Jepma & Nieuwenhuis, 2011) and between strategies in solving Raven's Matrices (Hayes & Petrov, 2016). Crucially, in our paradigm, participants chose between two motivationally different tasks, namely an effortful, but profitable 2-back (labor) and an effortless, but unprofitable attractiveness rating task (leisure), and displayed pupil shifts in switches between them in either direction.

Our studies provide a fine-grained examination of the time course of baseline pupil diameter and pupil dilations around switches. For both switches from labor to leisure and vice versa, changes in baselines and dilations began later than initially expected: Baselines started to increase on the very last trial (three seconds) before a switch and levelled off around four trials (twelve seconds) after it (see Figure 2a and b). Dilations decreased gradually in labor-to-leisure switches, without a definite start and end, but were temporally restricted to two trials before until two trials after a switch in leisure to-labor switches (see Figure 2c and d). Overall, changes in baselines and dilations were comparable between both switch types and across both studies. Crucially, they returned to pre-switch levels after a few trials. This might be surprising if leisure is conceived as a state of ongoing exploration, potentially including mind-wandering, which would predict that pupil baselines are permanently elevated and dilations permanently muted, an expectation consistent with AGT. Rather, pupil changes seem to reflect processes that are restricted to the transitions between both activities, which would be in line with NRT.

Unexpectedly, similar pupil shifts occurred in shifts from labor and leisure and back to labor, the latter not being predicted by AGT. Hence, these shifts cannot be interpreted as reflecting the particular motivational drive to take a break. Rather, they might reflect cognitive processes that underlie task switches, more generally. This is in line with NRT, which proposes that pupil increases, i.e. NE releases, occur when reorientation towards a new environment is needed. In line with this account, previous research found increases in pupil diameter in response to environmental instabilities and surprises (Lavín, San Martín, & Rosales Jubal, 2014; Nassar et al., 2012; Preuschoff, ’t Hart, & Einhäuser, 2011) and when shifting rules in the Wisconsin Card Sorting Task was required (Pajkossy, Szőllősi, Demeter, & Racsmány, 2017). During task switching, increases in BOLD activity have been observed primarily in the ventromedial prefrontal cortex (Braver & Bongiolatti, 2002; Sakai, 2008), which synchronized to the LC (von der Gablentz, Tempelmann, Münte, & Heldmann, 2015).

Interestingly, in our study, task switches were neither unexpected nor induced by environmental changes, but implementations of participants’ own decisions. Hence, our results extend NRT in that NE releases typically induced by the detection of environmental changes, such as threats or dangers, might as well be induced by the autonomous decision to switch tasks. Given this reasoning, NE might be rather involved in the implementation of task mindset shifts than in their motivation. This is in line with recent electrophysiological work in monkeys which showed that (a) the activity of dopaminergic neurons in the substantia nigra correlates with motivational variables such as expected levels of reward and effort, potentially integrating different signals into one single decision, but (b) activity of NE neurons in the LC correlates with actual effort exertion, potentially aiding the execution of this decision (Varazzani, San-Galli, Gilardeau, & Bouret, 2015). Following this reasoning, we cannot preclude the possibility that previous studies on shifts from exploitation to exploration (Gilzenrat et al., 2010; Hayes & Petrov, 2016; Jepma & Nieuwenhuis, 2011; Kane et al., 2017; Pajkossy et al., 2017) did not observe NE promoting motivational shifts, but rather NE

facilitating the execution of task switching. Crucially, by contrast to this prior work, our paradigm used two qualitatively distinct tasks, enabling us to distinguish between shifts from exploitation and exploration vs. those back to exploitation. Due to this design feature, our study could make visible that the motivational direction does not seem to matter.

In our exploratory analyses, individual differences in dilation decreases around switches were correlated with individual differences in self-reported action orientation: participants with high action orientation showed attenuated decreases in switches from labor to leisure, but stronger decreases in switches from leisure to labor. This association might be plausible when the neural processes reflected by dilation decreases help humans inhibit an old task mindset and prepare a new one, as proposed by NRT. In this case, inhibition and preparation are especially needed when going back to labor, as labor is both effortful and returns rewards, but not when switching to leisure. One might speculate that people who more selectively use their reorientation mechanisms in situations in which they are actually needed, i.e. when preparing an effortful task, might also approach challenges more proactively in everyday life. Previous research indeed found action-oriented individuals to use their working memory capacity more effectively (Jostmann & Koole, 2007) than state-oriented individuals. A similar association was recently discussed for fluent intelligence (Hayes & Petrov, 2016), suggesting that highly intelligent individuals show stronger pupil dilations compared to average-intelligent individuals in challenging tasks (van der Meer et al., 2010), but weaker dilations in simple tasks (Ahern & Beatty, 1979). However, given that we did not predict this association a-priori, this interpretation needs further corroboration by future work. Furthermore, no such correlations were found for differences in baseline increases. Future research needs to clarify whether and why pupil dilations might be a more reliable measure of individual differences in task switching ability than pupil baseline levels.

Taken together, our results suggest that pupil changes that were conceived by AGT to reflect shifts from exploitation to exploration do also occur in shifts from exploration back to

exploitation, or generally attentional set shifts as predicted by NRT. Different from previous research, switches between tasks followed from participants' own decisions and were not externally induced by changes in task payoff or difficulty. Furthermore, our exploratory analyses indicate that individual differences in pupil changes might be associated with how people approach challenging tasks in everyday life. Future research might test the independence of pupil changes from the motivational nature of tasks more directly, e.g. by studying task switches between two demanding "labor" or between two easy "leisure" tasks. Such a study would constitute a stronger test of the independence of pupil changes from motivational task features, such as reward or effort. Also, one might test whether the same pupil changes occur when task switches are externally induced, e.g. when participants see a countdown that requires them to switch. Such a study could better disambiguate whether pupil changes reflect the self-directed decision to switch tasks, or rather the implementation of such switches even when they are externally induced. Finally, it might be interesting to further investigate whether the magnitude of pupil changes is moderated by the difficulty of an upcoming task or by individual differences in action orientation. In conclusion, our results suggest that sudden shifts in NE might be a global mechanism in shifting mental task sets and adapting to changing demands rather than a motivational drive towards leisure.

Data and Code Availability

Materials used in data collection as well as data and code to reproduce our analyses are available under https://osf.io/b9z4c/ (Study 1) and https://osf.io/ukgsh/ (Study 2).

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Supplementary Online Materials

Explore or reset? Pupil diameter transiently increases in self-chosen switches between cognitive labor and leisure in either direction

Appendix S1

Participant- and Trial-Based Data Inclusion in Study 1

Four of the 35 participants were excluded from all analyses in accordance with our pre-registered criteria: Two of them did never switch to the leisure task, but only performed the labor task; one performed below 50% accuracy in the labor task, and one participant's eye-tracking data were unusable due to a high percentage of missing values.

For the *pre-registered* analyses of pupil data, we selected the last ten but one trials before each labor-to-leisure switch. The adjacent trials preceding the same switch were treated as belonging to the same *bout*, with trials nested in bouts and bouts nested in participants, yielding 201 bouts (1,809 trials).

For the *exploratory* analyses of pupil data, we selected the last five trials before each switch and the first five trials after each switch. The trials around one single switch were treated as belonging to the same *bout* of adjacent trials, with trials nested in bouts and bouts nested in participants. This resulted in a final data set with 247 labor-to-leisure switches (2,225 trials) and 247 leisure-to-labor switches (2,180 trials).

Appendix S2

Participant- and Trial-Based Data Inclusion in Study 2

In line with our pre-registered criteria, we excluded two participants from all our analyses as they only performed the labor task and never switched, and two further participants because their eye-tracking data were unusable due to high rates of missing values. This left a sample of 31 participants that was used in all analyses.

We selected again the last five trials before each switch between tasks and the first five trials after each switch. Here, also the joystick movements in the motor control assessment phase and the observed frame movements in the visual control assessment were treated as switches. In total, we analyzed 272 switches from labor to leisure (2,594 trials), 273 switches from leisure to labor (2,535 trials), and 248 visual switches (2,480 trials).

Regarding the motor control assessment, unexpectedly, participants committed a considerable amount of errors (217 out of 2,480 trials, i.e. 10% of all trials; of which 148 were false-positive switches and 69 false-negative non-switches). As a liberal exclusion criterion, to keep as many correct trials as possible, we decided to first exclude eight participants, as each of their eight bouts, i.e. required movements of the joystick surrounded by ten trials, contained at least one error. This left 39 trials with errors (11 false positives, 28 false negatives), which we deleted in a second step, resulting in 164 remaining bouts (1,880 trials). As a more conservative exclusion criterion, we excluded all bouts with any errors, resulting in 155 bouts (1,550 trials). The pattern of significant and non-significant results was the same for both exclusion criteria. In the main text, we report results based on the liberal exclusion.

Appendix S3

Testing Accuracy Decrements Before Breaks

A potential reason for participants' decision to switch from the labor to the leisure task might be that they recognize a decrease in their performance, are afraid that they might forfeit their chance for an extra monetary bonus, and thus decide to take a break in order to rest and restore their ability to concentrate. Under this explanation, one might assume that switches could be induced by error monitoring, independent of changes in motivation or NE levels.

However, note that participants did not receive any error feedback during the tasks, and thus had imperfect knowledge about their performance. Furthermore, AGT itself predicts that increased tonic NE levels will lead to decreases in accuracy, which is supported by behavioral evidence: animal work found switches from exploitation to exploration to be accompanied by increased false alarm rates (Cohen, McClure, & Yu, 2007), and increased pupil diameter has been found associated with lapses in attention in humans (Hopstaken, van der Linden, Bakker, & Kompier, 2015; Unsworth & Robison, 2016). Hence, decreases in accuracy might not be an independent mechanism, but a side-effect of changes in NE levels.

In exploratory analyses, we tested whether decreases in accuracy would occur during the last five trials before switches from labor to leisure. We used generalized linear mixed effects models (GLMEMs) in the package lme4 (Bates, Mächler, Bolker, & Walker, 2015) in R (R Core Team, 2017) with accuracy (binary: correct or incorrect) as outcome and trial number relative to switch as predictor. The predictor was standardized. We added a random intercept and a random slope of trial number for each participant and for each bout of each participant to the model, including all possible random correlations. *P*-values were calculated using likelihood ratio tests as implemented in the package afex (Singmann, Bolker, Westfall, & Aust, 2018), since *F*-tests are not available for GLMEMs. We computed 95% confidence

intervals via bootstrapping with 1,000 simulations using lme4's bootMer function, which uses the boot package (version 1.3.18, Canto & Ripley, 2016). Effectively, we analyzed of 376 switches (1,525 trials) in Study 1 and 372 switches (1,591 trials) in Study 2.

In Study 1, there was a non-significant trend of decreasing accuracy during the last five trials before switches from labor to leisure, $\beta = -.10$, 95% CI [-.25, .05], $\chi^2(1) = 2.85$, $p = .091$. In Study 2, there was a significant decrease in accuracy, $\beta = -.26$, 95% CI [-.47, -.06], $\chi^2(1) = 4.90$, $p = .027$. We conclude that there was mixed evidence for accuracy decreasing directly before a break.

Appendix S4

Testing Accuracy Restoration After Compared to Before Breaks

As explained in S3, subjects might use breaks as a chance to restore their ability to concentrate. We thus tested in exploratory analyses whether accuracy was significantly better in the first five trials after a break (i.e. a series of leisure trials) compared to the last five trials before a break.

We used GLMEMs with accuracy as outcome and a binary factor indicating whether trials were before or after the leisure bout as the sole predictor. Treatment-coding was applied. We added random intercepts and slopes of trial number for each participant to the model, including all random correlations. Again, *p* values were computed with likelihood ratio tests. We analyzed 247 breaks (2,181 trials) in Study 1 and 272 breaks (2,338 trials) in Study 2.

In Study 1, indeed, mean accuracy was slightly higher during the first five labor trials after a switch from leisure back to labor (M = .85, SD = .36), than during the last five trials before a switch from labor to leisure (M = .80, SD = .40), β = .15, 95% CI [.01, .27], $\chi^2(1)$ = 5.23, p = .022. In Study 2, however, there was no significant increase in average accuracy from before a break, (M = .79, SD = .41) to after a break (M = .81, SD = .39), β = .03, 95% CI [-.11, .16], $\chi^2(1)$ = 0.63, p = .427. Hence, we obtained mixed evidence for the hypothesis that performing the leisure task had a recreational function and immediately improved participants performance.

Appendix S5

Correlations of Overall Average Baseline Pupil Diameter and Pupil Dilations With Performance Measures Across Both Studies

Variable	*2*	*3*	*4*	*5*	*6*
1. Average pupil baselines	-.37**	-.03	.29*	-.12	.26*
2. Average pupil dilations	-	.01	-.19	.01	.08
3. # trials spent on labor		-	-.33**	.35**	.27
4. # switches away from labor			-	.38**	-.09
5. % button presses during labor				-	.38**
6. % correct responses during labor					-

Note. Pearson correlations of aggregated raw baseline pupil diameter and aggregated raw pupil dilations with counts of events (trials, switches) and percentages (button presses, correct responses) during labor trials across both studies (N = 62).

* $p < .05$, ** $p < .01$, uncorrected.

Appendix S6

Time Course of Pupil Baseline Diameter and Pupil Dilations in the Motor and Visual Control Assessment in Study 2.

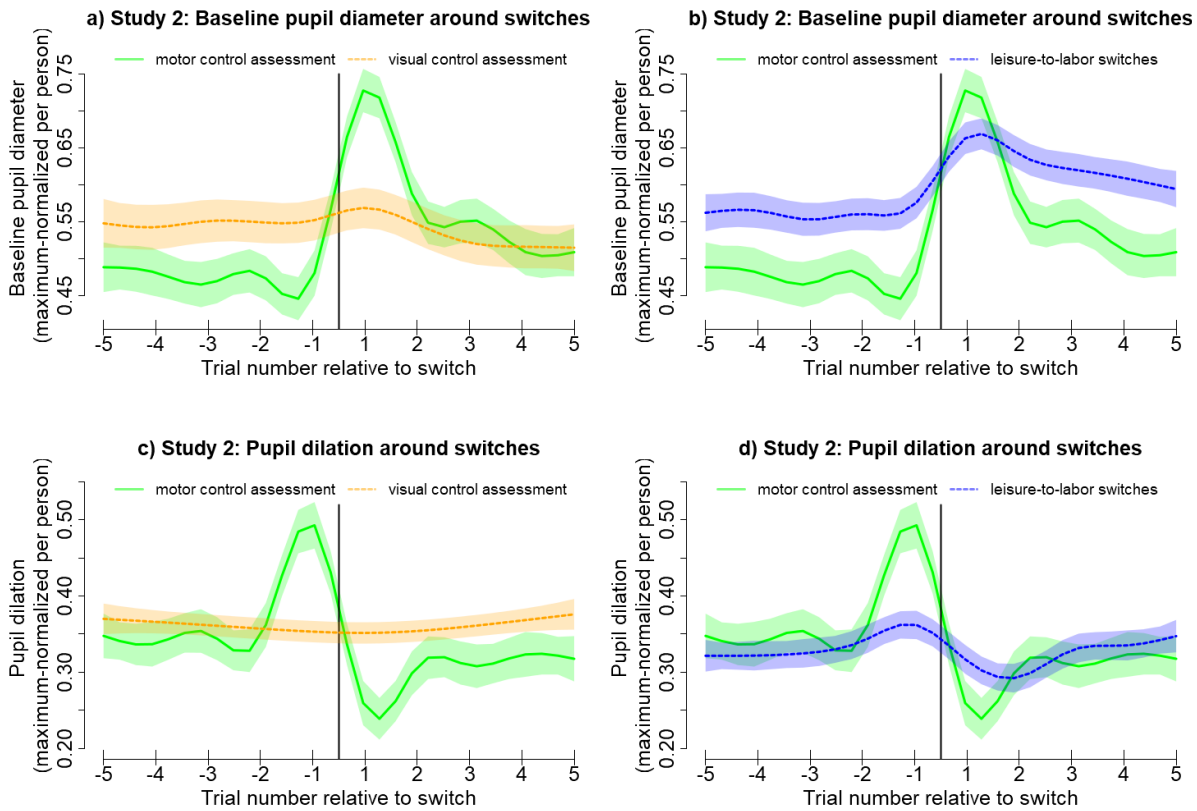

Figure 3. Time course of in pupil baseline diameter (a) and pupil dilations (c) in the motor and visual control assessment in Study 2. For both baselines and dilations, there was a significant increase and subsequent decrease around switches in the motor condition, but not in the visual condition. The baseline changes in the motor condition were more peaked, but also more short-lived than those in leisure-to-labor switches (b). The dilation increase in the motor condition was unparalleled in leisure-to-labor switches (d). Plots are based on the GAMMs computed. Shades indicate 95%-CIs. Vertical lines indicate the time point of the switch.

Appendix S7

Group-Level Means, Standard Deviations, Cronbach's Alpha, and Correlations Between Self-Reported Procrastination Tendency and Action- vs. State Orientation

Measure	*2*	*3*	*4*	*5*	*6*	*M*	*SD*	*α*
1. IPS	-.07	-.67**	-.48**	-.17	-.76**	3.01	0.62	.86
2. ACS-24 AOF	–	.47**	.58**	.17	.09	4.76	3.26	.81
3. ACS-24 AOD		–	.50**	.20	.59**	5.98	3.28	.80
4. SSI-K3 SR			–	.33*	.28*	2.57	0.42	.80
5. SSI-K3 SC				–	.19	2.60	0.43	.74
6. SSI-K3 VD					–	2.52	0.48	.84

Note. Higher IPS values indicate higher procrastination tendencies, and higher values on the other scales indicate higher action orientation. Samples of both studies (total N = 62) were combined. IPS = Irrational Procrastination Scale; ACS-24 AOF = ACS-24 Action orientation subsequent to failure vs. preoccupation subscale; ACS-24 AOD = ACS-24 Prospective and decision-related action orientation vs. hesitation subscale; SSI-K3 SR = SSI-K3 Self-regulation (Competence) subscale; SSI-K3 SC = SSI-K3 Self-control subscale; SSI-K3 VD = SSI-K3 Volitional development (Action development) subscale.

* $p < .05$, ** $p < .01$, uncorrected.

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