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Maintaining performance under pain is effortful: experimental and computational evidence

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Abstract

Pain creates a competing demand on attention, though its impact on performance remains debated. Motivational-intensity theory predicts that resource reallocation can preserve output until motivational or capacity limits are reached. Forty adults took part in two preregistered experiments. They completed parallel cognitive (choice-reaction, n=20) and motor (isometric hand-grip, n=20) tasks at three difficulty levels while receiving warm, low, or high-pain heat stimulation on the opposite forearm. Across both domains, participants maintained performance despite painful stimulation. This preservation, however, relied on increased effort mobilization: perceived effort rose with pain intensity, while pain perception decreased during motor and cognitive task execution. Trial-wise computational modelling revealed that perceived effort was better predicted by subjective pain experience than by stimulus temperature, supporting a compensatory regulatory mechanism. Thus, maintained performance under pain reflects active resource allocation via effort, generalizable across cognitive and motor domains, but achieved at the cost of increased perceived effort.

Introduction

Nociceptive stimulation elicits pain, a salient signal that captures attention and interferes with executive and motor functions (1, 2). From this perspective, pain is assumed to impair cognitive and motor performance by diverting resources away from task execution. Performance decrements in the presence of pain have been reported across cognitive and motor domains (1, 3–5); however, these effects are not systematic (6, 7). This dissociation suggests that compensatory mechanisms may allow performance to be maintained under certain conditions. However, a key question concerns the extent to which this reallocation of attentional resources is effortful. It may occur with no subjective cost, such that focusing on the task is sufficient and pain modulation emerges automatically as a consequence. Alternatively, this reallocation of resources is active and may entail costs, reflecting a deliberate attempt to ignore pain in order to maintain task focus, and reflected in higher perceived effort (8). Critically, if pain is actively inhibited, this compensatory process should also reduce subjective pain, yielding a task-induced hypoalgesic effect (9). Distinguishing between these possibilities is critical, as they have different implications for the use of distraction to reduce pain, which may be either universally beneficial or associated with costs. In this view, effort (i.e., intentional engagement of resources) is proposed to be the key variable mediating the relationship between pain and performance.

The motivational intensity theory provides a principled framework to formalize this trade-off (10, 11). According to this account, effort reflects the mobilization of resources required to meet task demands and can be flexibly adjusted in the presence of competing demands. For submaximal tasks, increased difficulty, such as induced by pain, can be accommodated through greater effort investment (12), thereby preserving performance. In contrast, when maximal motivation or capacity is reached, further increases in demand necessarily result in performance decrements or disengagement (10, 12).

Despite its central role, the determinants of perceived effort remain unclear. Because nociceptive stimulation introduces an additional demand on task execution, it remains unclear whether perceived effort is influenced by objective nociceptive input or subjective pain experience targeted by regulatory processes. Here, perceived effort is considered an index of resource allocation. Disentangling these two accounts requires a formal comparison of their predictions, enabled by computational modeling. To address these questions, we conducted two experiments: one cognitive and one motor, in which task demand (control, low, high) and thermal stimulation (warm, light pain, high pain) were independently manipulated. This design allowed us to test the preregistered hypothesis that performance can be maintained in the presence of pain through compensatory resource allocation. Specifically, we predicted that increasing pain would not systematically impair performance during submaximal task demands but would be associated with a graded increase in perceived effort. We expect that this compensatory process would be accompanied by task-induced hypoalgesia, reflected in reduced subjective pain during task execution relative to control conditions. Finally, to further test our hypotheses, we examined with computational modeling whether perceived effort is better predicted by subjective pain experience than by objective nociceptive stimulation.

Results

Figure 1A displays the overview of a trial during the motor (n=20) and cognitive (n=20) tasks. Each task included trials performed at three demand levels (control, low, high) in the presence of thermal stimulation inducing warm sensation (control), low pain or high pain. After each trial, participants reported the intensity of the perceived effort to do the task and their perceived warm or pain.

Performance and effort perception *(Figure 1B). During the cognitive tasks*, participants either fixated a central cross (control) or performed a modified Simon task with low or high cognitive demand for 15 s, manipulated through stimulus congruency and spatial position. In the presence of pain, participants reported a higher perceived effort [$F(2, 654)=26.78$, $p<.001$] to maintain cognitive performance [reaction time, $F(2, 436)=0.82$, $p=.443$; accuracy, $F(2, 436)=0.95$, $p=.387$]. *During the motor tasks*, participants either held a handgrip for 15 s without producing force (control) or matched as precisely and steadily as possible a target line corresponding to 5% or 30% of their maximal voluntary isometric handgrip force (low and high motor demand, respectively). In the presence of pain participants reported a higher perceived effort [$F(2, 664)=4.7$, $p=.009$] to maintain motor performance quantified with the force coefficient of variation [$F(2, 429.32)<0.001$, $p>.999$].

Pain perception *(Figure 1C).* In both experiments, pain decreased in response to higher task demands [Cognitive: $F(2, 648)=5.68$, $p=.004$; Motor: $F(2, 645.01)=5.98$, $p=.003$]. An exploratory analysis revealed an interaction between task demand and thermal stimulation on perception of pain: cognitive experiment $F(4, 654)=9.52$, $p<.001$; motor experiment $F(4, 645.01)=11.76$, $p<.001$. The pain decreased with task demand in low and high pain conditions but increased in the warm conditions.

Figure 1. *Panel A* shows the trial sequence: thermal stimulation rises to the target temperature over 2.5 s, remains at plateau for 15 s, and returns to baseline over 2.5 s. During the plateau,

participants perform a cognitive or motor task. Immediately afterward, they rate the effort invested with a visual analog scale (VAS), report whether the stimulation felt warm or painful, and then rate its intensity with a VAS. *Panels B and C* depict effort and pain perceptions, respectively, as a function of thermal level (panel B) or task demand (panel C), separately for each task demand/thermal stimulation and experiment type (cognitive, blue; motor, red). In both panels, bold circles indicate means, and shaded lines represent individual participants. $ denotes post-hoc tests for main effects and * for interactions: One, two and three symbols for p<.05, p<.01, p<.001, respectively.

Modelling of perceived effort (Figure 2). Computational analyses used maximum likelihood estimation, and model comparisons relied on the Bayesian Information Criterion (BIC). Because Motivational intensity theory predicts a linear relationship between task demand and effort (10), whereas classic psychophysical laws such as Weber-Fechner suggest a logarithmic scaling of subjective experience (13), we compared, for each candidate model, linear and logarithmic formulations of task demand. We also compared objective thermal stimulation levels with subjective pain ratings, as proposed in our hypothesis. All models predicted trial-by-trial fluctuations in perceived effort. The analyses indicated that the logarithm of task demand better predicted effort perception in 67% of models, while the remaining 32% showed equivalent prediction. Perceived pain consistently (100%) outperformed thermal stimulation as a predictor of effort perception (Figure 2). Model specifications and BIC values are provided in the online supplementary information.

Figure 2. The figure displays Bayesian Information Criterion (BIC) values for the compared models. The figure contrasts models using perceived pain or thermal stimulation to predict effort perception in the cognitive (blue) and motor (red) experiments, indicating which predictor best accounts for the data. Only logarithmic models are displayed here; linear models show the same pattern. Numbers identify the models detailed in the online supplementary information.

Discussion

This study examined how pain interacts with task performance and perceived effort across cognitive and motor domains. We tested whether pain passively degrades performance by diverting resources, or whether performance can be actively preserved through compensatory mechanisms at the cost of increased effort. Across two experiments, our results support the latter account.

Despite pain, performance remained stable across task demands in both cognitive and motor tasks. This preservation was accompanied by increased perceived effort, indicating that participants actively mobilized additional resources to counteract nociceptive interference. These findings argue against a purely passive resource-diversion view and instead support a compensatory account in which effort links the relationship between pain and performance under submaximal demands. The convergence of results across cognitive and motor tasks further suggests a domain-general mechanism. In parallel, pain perception decreased as task demand increased. This task-induced hypoalgesia indicates that nociceptive processing is actively inhibited during goal-directed action. Critically, the co-occurrence of increased perceived effort and reduced pain supports the interpretation that maintaining performance relies on active cognitive control rather than simple attentional distraction. Effort thus indexes the subjective cost of modulating pain-related interference.

Computational analyses provide a formal account of the observed behavioral effects. Trial-by-trial fluctuations in perceived effort were better predicted by subjective pain ratings than by objective thermal stimulation, indicating that effort tracks experienced interference rather than physical nociceptive input. This supports the view that effort reflects the subjective cost of internal regulatory processes, including active pain modulation. Perceived effort scaled logarithmically, rather than linearly, with task demand, consistent with psychophysical principles (13) and inverted U-shaped account of effort investment (14). This observation places our submaximal tasks on the ascending part of the curve prior to motivational or capacity-limited disengagement, as predicted by the motivational intensity theory (10, 11, 15). Future studies should test demands beyond these limits to characterize disengagement.

Together, these findings support a unified framework in which effort mediates the relationship between pain and performance. Pain does not inevitably impair task performance but impact depends on the capacity to mobilize compensatory resources. The increased perception of effort reflects the subjective cost of this regulation, while task-induced hypoalgesia reflects its efficacy. By combining behavioral and computational approaches across domains, this study provides converging evidence for effort as a central variable integrating task demand and pain during goal-directed behavior.

Materials and Methods

Forty healthy adults (mean ± SD; age: 22 ± 1.7 years; 20 females) volunteered in the preregistered cognitive (n=20) and motor (n=20) experiments. All procedures were approved by the Ethics Committee of the Montreal Geriatrics Institute. Full methods are in supporting information appendix.

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Figures

Figure 1.

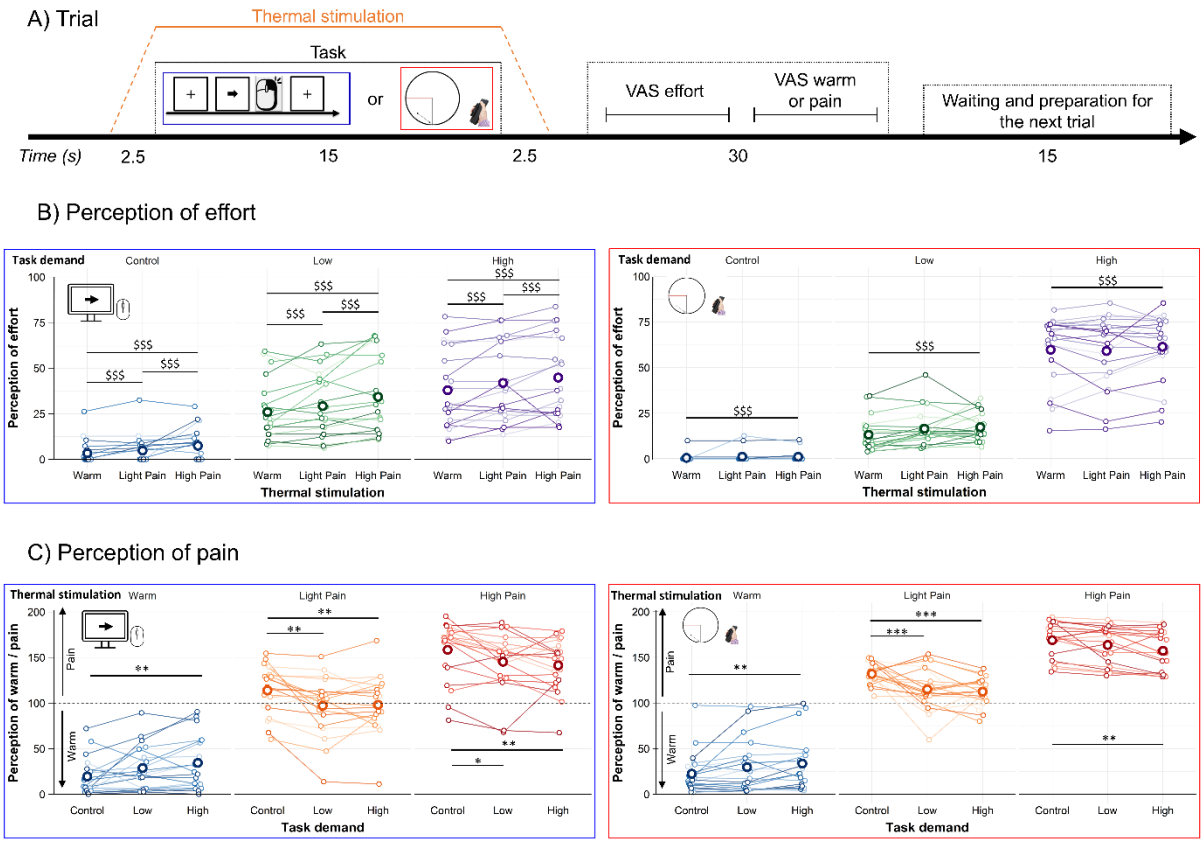


Figure 1. *Panel A* shows the trial sequence: thermal stimulation rises to the target temperature over 2.5 s, remains at plateau for 15 s, and returns to baseline over 2.5 s. During the plateau, participants perform a cognitive or motor task. Immediately afterward, they rate the effort invested with a visual analog scale (VAS), report whether the stimulation felt warm or painful, and then rate its intensity with a VAS. *Panels B and C* depict effort and pain perceptions, respectively, as a function of thermal level (panel B) or task demand (panel C), separately for each task demand/thermal stimulation and experiment type (cognitive, blue; motor, red). In both panels, bold circles indicate means, and shaded lines represent individual participants. $ denotes post-hoc tests for main effects and * for interactions: One, two and three symbols for p<.05, p<.01, p<.001, respectively.

Figure 2.

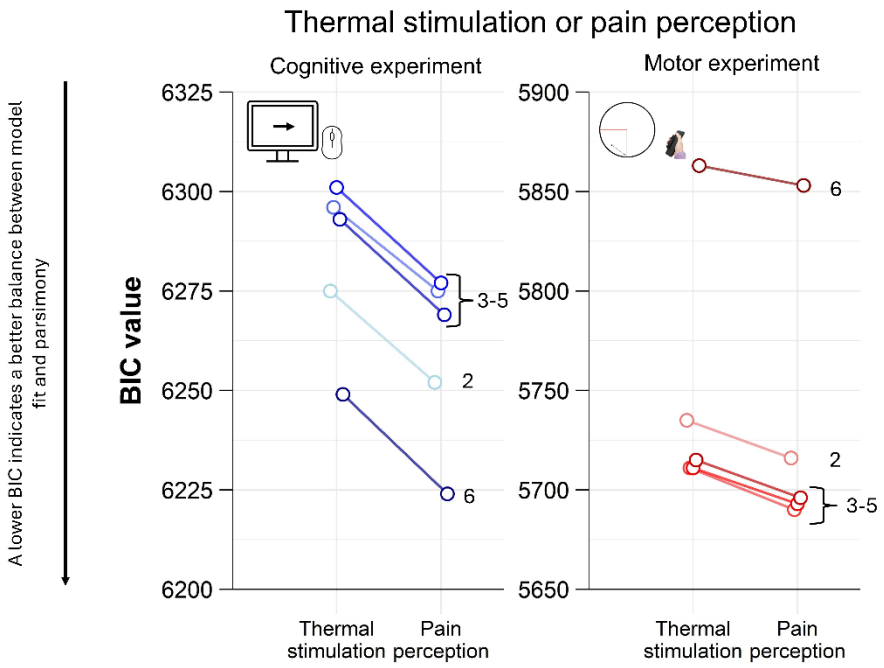


Figure 2. The figure displays Bayesian Information Criterion (BIC) values for the compared models. The figure contrasts models using perceived pain or thermal stimulation to predict effort perception in the cognitive (blue) and motor (red) experiments, indicating which predictor best accounts for the data. Only logarithmic models are displayed here, linear models show the same pattern. Numbers identify the models detailed in the online supplementary information.

Supplementary Information

The preregistrations for both experiments can be found respectively at the following links: [cognitive experiment: osf.io/wf8es; motor experiment: osf.io/5hgwk].

Study design

Participants. Twenty-one young adults participated in each study. One participant has been excluded from each experiment. During the cognitive experiment, one participant had difficulties staying awake, and closed his eyes between each trial. During the motor experiment, one participant reported not understanding the instructions. Both participants finished the experiment but were not included in the analyses. Final samples were composed of 20 participants for each experiment, including 10 females. Every participant identified their gender according to their sex attributed at birth. The mean (and SD) age for the 20 participants in cognitive and motor experiments is 21.9 (1.6) and 22.2 (1.8) respectively. The weight of the participants is 66.1kg (12.6kg) and 65.4kg (9.9kg) respectively, for a height of 171 cm (11 cm) and 169 cm (8 cm).

Protocol overview. Both the motor and cognitive study were composed of two laboratory visits spaced by 24h to one week. Both visits took place at the same time of the day (± 1h) to control the influence of the circadian cycle.

During visit 1 (~2h), participants were asked general questions to control for confounding factors (e.g., substances use such as cigarettes, caffeine, alcohol and drugs, physical activities practiced and the amount of sleep the night preceding the experiment) and they filled out the Pain Catastrophizing Scale Questionnaire. Successively, they went through a sensory calibration of thermal stimulations, a maximal voluntary contraction (MVC) peak force calculation (only for the motor experiment), a ramp-up of effort with familiarization of the visual analog scale (VAS) related to the perceptions of effort, and a familiarization with the motor or cognitive task consisting of only 6 trials.

In visit 2 (~1.5h) participants performed the motor or cognitive task in the presence of thermal stimulation. At the beginning of the visit, temperatures used for the thermal stimulation were validated and adjusted if necessary. Participants then completed either the cognitive or motor task. Both tasks consisted of 36 trials at three levels of difficulty: no demand (control), low or high demand (see Fig1.A). Simultaneously to the execution of each trial, participants received thermal stimulation at one of three individually calibrated temperatures to produce sensations of warmth (control), light or high pain. After each trial, participants reported their perception of the effort required to complete the task, followed by their perception of warmth or pain.

Task

Sensory calibration of the thermal stimulations. All the thermal stimuli were delivered using a 3 x 3 cm contact thermode applied to 4 skin sites on the volar surface of the non-dominant forearm (MEDOC, TSA-II Neurosensory Analyser). Stimuli were delivered between 40°C (slightly warm) and 50°C (max) with the speed of the temperature rise and fall adjusted to last 2 s each and a plateau duration of 15 s.

Participants first completed a tolerance test. In this test, the thermal stimulations at increasingly hot temperatures (from 42 to 49° C, increasing by 0.5° C at each trial) were applied to 4 skin sites on the non-dominant forearm of each participant. Subjects were asked to clearly say stop when they reach a temperature that they consider unbearable. This procedure was repeated two times to be sure about the maximal tolerated temperature.

For the sensory calibration, the method of constant stimuli was implemented to determine each participant's sensitivity to the thermal stimuli. Thermal stimuli were applied at random temperatures (never above the participant's tolerance) to 4 skin sites on the non-dominant forearm. For each participant, a stimulus-response function was calculated to determine 3 temperatures successively

used during each trial of the motor or cognitive task. The 3 temperatures were selected to produce a sensation of warm (no pain; ~30/200 VAS), low pain (~130/200 VAS), and strong pain (~170/200 VAS) on a 0-200 VAS.

MVC. The MVC peak torque was collected with a handgrip dynamometer (TSD121B-MRI, BIOPAC) connected to a MP150 system (BIOPAC).

The MVC was recorded with the participant seated on a chair with the elbow at 90° and a wrist brace to maintain the hand aligned with the forearm. Each participant was asked to maintain the handgrip dynamometer in his/her dominant hand and to squeeze the dynamometer as strong as possible to produce a maximal force without losing the arm position. Participants completed 3 MVCs of 3s each with a one-minute rest in between each contraction. The highest peak of the three signal force curves obtained in Acknowledge, represented the subjects' MVC. The MVC procedure was realized during both the 1st and 2nd visit. For the 1st visit, the MVC was used to set the template of the familiarization with the VAS for the effort perception. For the 2nd visit, particularly of the motor study, the MVC was used to set the three contractions intensities of the motor task: 0% MVC (rest, control condition), 5% MVC and 30% MVC.

Effort familiarization. For the cognitive experiment, the ramp-up of effort is made for participants to experiment different level of effort associated with different cognitive demands. Participants performed a series of a modified Simon task with increased difficulty on each trial by either reducing time allowed to answer or adding executive functions in the task (left-right Simon task, left-right with time reduced, left-right Simon task plus around 50% switching condition, left-right Simon task plus around 50% switching condition and reduced time, Random Simon task, Random Simon task with reduced time). To maximize task engagement, each time the participant makes an error or does not respond in time, a sound « bip » will alert the participant. When the most difficult task is reached, the difficulty will decrease until the easiest task. Each trial is interspaced by up to 35s. At the end of each trial, participants will be asked to rate their perception of effort to perform or trying to perform the task.

For the motor experiment, participants were familiarized with the use of the handgrip dynamometer and the visual analog scale (VAS) for rating their perceived effort. They executed a force-matching contraction with the dominant hand at the following intensities in the following order 5%, 15%, 30%, 60%, 80%, 60%, 30%, 15%, 5% of the individual MVC, and rated the perceived effort after each contraction on the VAS (0-100). Each contraction last for 10 s and was interspaced by up to 35s.

Motor task. The motor task was a visuomotor force-matching task consisting of executing voluntary submaximal isometric handgrip contractions to match a force feedback line using a handgrip dynamometer (TSD121B-MRI, BIOPAC) connected to a MP150 system (BIOPAC).

The isometric handgrip contractions involved 15-s isometric prehensions with the dominant hand at the following intensities: 12 x low force (5% MVC), 12 x high force (30% MVC) and 12 x control (holding the handgrip without producing force). The order of these intensities was randomized. Visual feedback of the force produced during the contraction was provided on the screen, and participants had to match a force target line. To control for the anticipation of the force contraction, the target always remained at the same position on the screen, but more or less force was required to match it, depending on the trials condition. The onset and offset of the muscle contraction was indicated by an auditory signal. For the control condition (i.e., not producing any force), participants were asked to simply hold the handgrip dynamometer, hence there were no auditory signals.

Cognitive task. Participants performed 15s of cognitive tasks, answering by clicking on a mouse with their dominant hand at the following cognitive demands: 12 × low demand (left-right Simon task), 12 × high demand (Random Simon task) and 12 × control (fixing a fixation cross). Task completion was performed concomitantly to thermal stimulation applied to the non-used arm. The order of these tasks was randomized. After the task, participants rated their perception of effort to accomplish or trying

to accomplish the task, and then their perception of warm or pain induced by the thermal stimulation. Data of these 3 tests was saved on E-Prime 3.0 (version 3.0.3.80).

A trial of the left-right Simon task (low demand) consists of a series of 10 arrows display in the middle of the screen. First a fixation cross appears in the middle of the screen for 250ms. Then an arrow pointing either on the right or left side appears until the participant answers or for a maximal of 1000ms, if the participant does not answer. This is followed by a fixation cross in the middle of the screen for the remaining of the 1000ms of the stimulus presentation plus 250ms. The participants are instructed to click as fast and accurate as possible to indicate the direction of the arrow. If the arrow is pointing toward the right, they have to click on the right button of the mouse, and if the arrow is pointing toward the left, they have to click on the left button. Each trial last 15s.

A trial of the random Simon task (high demand) follows the same time course than the left-right task. However, around 50% (fully randomized) of the first fixation cross is encompass by a circle. This clue indicates to the participants to answer by clicking to the opposite direction of the arrow (if the arrow point to the left, participants must click on the right button). Furthermore, the arrows are not displayed in the middle of the screen but at either 15% or 85% of the screen on the X axis.

Trials. During both the motor and cognitive study, participants executed two blocks of 18 trials while receiving concomitant thermal stimulations.

Each trial consisted of 20s thermal stimulation during which participants performed the motor or cognitive task. The motor and cognitive task always started 2.5s after the beginning of the thermal stimulation, meaning at its plateau.

The thermal stimulation and motor or cognitive task were followed by a 40s recovery period used to record perceptions of effort and pain as well as a recovery period to limit the development of fatigue. During the 40s recovery period, participants first rated the intensity of the perceived effort to perform the task on a validated VAS (0-100). Second, they had to indicate if the thermal stimulation was painful or warm but not painful, by choosing between two buttons labelled “pain” and “warm” presented on the screen. Depending on the selected button (pain or warm), participants rated the intensity of the thermal stimulation using a VAS (0-100).

The experimenter moved the thermal stimulator to a different arm spot each trial (4 different arm spots of the non-dominant forearm) to prevent a possible sensitization of the stimulated area. The order of the warm vs low pain vs high pain conditions, as well as the control vs 5% vs 30% MVC conditions were pseudorandomized across trials.

Statistical analyses

Sensitivity analysis. For both experiments, the primary rational for our sample size was linked to the financial resources available for our project.

A preliminary pilot study with 7 participants allowed us to determine that the effect size for the interaction on the perception of effort in physical task between Effort (5 vs 50% of the MVC) and Thermal stimulation (41.5, 44, 46.5 and 49°C) was equal to $\eta_p^2 = .568$. However, we think that this effect size is overestimated, especially for perception of effort in mental task. We think that a η_p^2 around .300 is more realistic.

A sensitivity analyses for a repeated measure ANOVA with “*option as in SPSS*”, alpha risk = .05 and a sample size of 20 and 6 measure indicated that we have 80% of chance to observe an effect size of $f = 0.378$ or higher (which is equal to η_p^2 of 0.125). Because our estimated effect size is higher, we have a high probability of observing the expected behavioral results.

Statistical tests. The statistical analyses were conducted on R (version 4.4.1) using multilevel modeling, with task demand and pain as fixed effects, and participants as a cluster variable. The post-hoc comparisons were performed using the estimated marginal means, with the Holm-Bonferroni

correction. Computational analyses were performed using the maximum likelihood estimate, and the optimization function was either Nelder-Mead or BFGS, depending on the convergence of the models. The computational analyses were conducted in two stages. The first stage involved creating simple mathematical models and progressively adding predictors to increase the complexity of the models. We also varied the models by using either task demand or the logarithm of task demand to predict the perception of effort. Additionally, we tested models incorporating either thermal stimulation levels (objective) or perceived pain (subjective) as predictors of effort perception. In the second stage, we tried to model the theoretical framework of motivational intensity theory. For both types of analyses, the Bayesian Information Criterion (BIC) was used to determine which model best fit the data.

Models

Acronym:

TD = Task Demand

PE = Perception of Effort

PP = Perception of Pain

Models are the same for both experiments

To assess motivation, fatigue, and boredom, three self-reported measures were collected: prior to the start of the task, at the midpoint (after 18 trials), and immediately following the final trial. To model the evolution of these states at the level of individual trials, values were linearly interpolated between each pair of successive measurement points. Specifically, the value assigned to trial 1 corresponded to the pre-task rating, while that of trial 18 matched the mid-task rating; intermediate trials were assigned values based on linear progression between these two endpoints. For instance, if a participant reported a fatigue level of 67 before the task and 85 at mid-task, the value increased by (85–67)/17 per trial until trial 18. The same procedure was applied between trials 19 and 36, interpolating between the mid-task and post-task ratings.

Model 1: This is the simplest model that includes only task demand.

Model 1: $PE = \beta 0 + \beta 1 * TD$

Model 1 log: $PE = \beta 0 + \beta 1 * \log(TD)$

Model 2: This model adds stimulation (temperature or perception of pain), that allows to compare both on prediction of perception of effort. There is also the interaction between task demand and stimulation.

Model 2 Temperature: $PE = \beta 0 + \beta 1 * TD + \beta 2 * Temperature + \beta 3 * TD * Temperature$

Model 2 PP: $PE = \beta 0 + \beta 1 * TD + \beta 2 * PP + \beta 3 * TD * PP$

Model 2 Temperature log: $PE = \beta 0 + \beta 1 * \log(TD) + \beta 2 * Temperature + \beta 3 * \log(TD) * Temperature$

Model 2 PP log: $PE = \beta 0 + \beta 1 * \log(TD) + \beta 2 * PP + \beta 3 * \log(TD) * PP$

Model 3: This model extends the previous specification by adding *Performance* and its interactions with Task Demand and Temperature as predictors. Performance is conceptually linked to perceived effort. It is generally accepted that performance tends to improve when individuals increase their voluntary effort, particularly in controlled laboratory contexts (Halperin & Vigotsky, 2024).
In the cognitive experiment, performance is quantified using the inverse efficiency score (IES), which combines response speed and accuracy (see Mangin et al., 2022).

In the motor experiment, performance corresponds to the coefficient of variation of force, normalized by the participant's maximal voluntary contraction (MVC).

Model 3 Temperature: PE = β0 + β1*TD + β2*Temperature + β3*TD*Temperature + β4*Performance + β5*TD*Performance + β6*Performance*Temperature + β7*TD*Performance*Temperature

Model 3 PP: PE = β0 + β1*TD+ β2*PP + β3*TD*PP + β4*Performance + β5*TD*Performance + β6*Performance*PP + β7*TD*Performance*PP

Model 3 Temperature log: PE = β0 + β1*log(TD) + β2*Temperature + β3*log(TD)*Temperature + β4*Performance + β5*log(TD)*Performance + β6*Performance*Temperature + β7*log(TD)*Performance*Temperature

Model 3 PP log: PE = β0 + β1*log(TD) + β2*PP + β3*log(TD)*PP + β4*Performance + β5*log(TD)*Performance + β6*Performance*PP + β7*log(TD)*Performance*PP

Model 4: This model extends the previous specification by adding *Motivation* as an additional predictor of perceived effort, allowing us to account for potential variance in PE attributable to motivational state.

Model 4 Temperature: PE = β0 + β1*Task demand + β2*Temperature + β3*TD*Temperature + β4*Performance + β5*TD*Performance + β6*Performance*Temperature + β7*TD*Performance*Temperature + β8*Motivation

Model 4 PP: PE = β0 + β1*TD+ β2*PP + β3*TD*PP + β4*Performance + β5*TD*Performance + β6*Performance*PP + β7*TD*Performance*PP + β8*Motivation

Model 4 Temperature log: PE = β0 + β1*log(TD) + β2*Temperature + β3*log(TD)*Temperature + β4*Performance + β5*log(TD)*Performance + β6*Performance*Temperature + β7*log(TD)*Performance*Temperature + β8*Motivation

Model 4 PP log: PE = β0 + β1*log(TD) + β2*PP + β3*log(TD)*PP + β4*Performance + β5*log(TD)*Performance + β6*Performance*PP + β7*log(TD)*Performance*PP + β8*Motivation

Model 5: This model extends the model 3 specification by adding *Fatigue* as an additional predictor of perceived effort, allowing us to account for potential variance in PE attributable to fatigue state. Fatigue increases the perceived difficulty of a task, then participant must increase their effort to perform it (see Richter et al., 2016).

Model 5 Temperature: PE = β0 + β1*TD+ β2*Temperature + β3*TD*Temperature + β4*Performance + β5*TD*Performance + β6*Performance*Temperature + β7*TD*Performance*Temperature + β8*Fatigue

Model 5 PP: PE = β0 + β1*TD+ β2*PP + β3*TD*PP + β4*Performance + β5*TD*Performance + β6*Performance*PP + β7*TD*Performance*PP + β8*Fatigue

Model 5 Temperature log: PE = β0 + β1*log(TD) + β2*Temperature + β3*log(TD)*Temperature + β4*Performance + β5*log(TD)*Performance + β6*Performance*Temperature + β7*log(TD)*Performance*Temperature + β8*Fatigue

Model 5 PP log: PE = β0 + β1*log(TD) + β2*PP + β3*log(TD)*PP + β4*Performance + β5*log(TD)*Performance + β6*Performance*PP + β7*log(TD)*Performance*PP + β8*Fatigue

Model 6: This model is a formalization of the motivational intensity theory (see Richter et al., 2016; Brehm & Self, 1989).

Model 6 MIT Temperature: Effort = (β1*TD + 0.1) * (β2*Motivation – β5*Boredom)

Distractor = β3*Temperature

PE = β0 + Effort + (β4*Fatigue + distractor)

Model 6 MIT Temperature log: Effort = (β1*log(TD) + 0.1) * (β2*Motivation – β5*Boredom)

Distractor = β3*Temperature

PE = β0 + Effort + (β4*Fatigue + distractor)

Model 6 MIT Pain: Effort = (β1*TD + 0.1) * (β2*Motivation – β5*Boredom)

Distractor = β3*PP

PE = β0 + Effort + (β4*Fatigue + distractor)

Model 6 MIT Pain log: Effort = (β1*log(TD) + 0.1) * (β2*Motivation – β5*Boredom)

Distractor = β3*PP

PE = β0 + Effort + (β4*Fatigue + distractor)

The models and the associated BIC

The red color indicates the winning model for each experiment.

Model	Linear or Logarithm	Thermal stimulation or pain	Experiment	BIC value
1	Linear	NA	Cognitive	6294
1	Logarithm	NA	Cognitive	6276
2	Linear	Thermal stimulation	Cognitive	6292
2	Logarithm	Thermal stimulation	Cognitive	6275
2	Linear	Pain	Cognitive	6272
2	Logarithm	Pain	Cognitive	6252
3	Linear	Thermal stimulation	Cognitive	6296
3	Logarithm	Thermal stimulation	Cognitive	6296
3	Linear	Pain	Cognitive	6275
3	Logarithm	Pain	Cognitive	6275
4	Linear	Thermal stimulation	Cognitive	6301
4	Logarithm	Thermal stimulation	Cognitive	6301

4	Linear	Pain	Cognitive	6277
4	Logarithm	Pain	Cognitive	6277
5	Linear	Thermal stimulation	Cognitive	6293
5	Logarithm	Thermal stimulation	Cognitive	6293
5	Linear	Pain	Cognitive	6269
5	Logarithm	Pain	Cognitive	6269
6	Linear	Thermal stimulation	Cognitive	6268
6	Logarithm	Thermal stimulation	Cognitive	6249
6	Linear	Pain	Cognitive	6246
6	Logarithm	Pain	Cognitive	6224
1	Linear	NA	Motor	5732
1	Logarithm	NA	Motor	5725
2	Linear	Thermal stimulation	Motor	5742
2	Logarithm	Thermal stimulation	Motor	5735
2	Linear	Pain	Motor	5724
2	Logarithm	Pain	Motor	5716
3	Linear	Thermal stimulation	Motor	5712
3	Logarithm	Thermal stimulation	Motor	5711
3	Linear	Pain	Motor	5692
3	Logarithm	Pain	Motor	5690
4	Linear	Thermal stimulation	Motor	5713
4	Logarithm	Thermal stimulation	Motor	5711
4	Linear	Pain	Motor	5695
4	Logarithm	Pain	Motor	5693
5	Linear	Thermal stimulation	Motor	5717

5	Logarithm	Thermal stimulation	Motor	5715
5	Linear	Pain	Motor	5698
5	Logarithm	Pain	Motor	5696
6	Linear	Thermal stimulation	Motor	5869
6	Logarithm	Thermal stimulation	Motor	5863
6	Linear	Pain	Motor	5859
6	Logarithm	Pain	Motor	5853

Betas values of the winning model for each experiment.

Cognitive experiment

Winning model is model 6 with logarithm of task demand and pain perception.

Effort = (-0.31*log(TD) + 0.1) * (-1.45*Motivation – 0.42*Boredom)

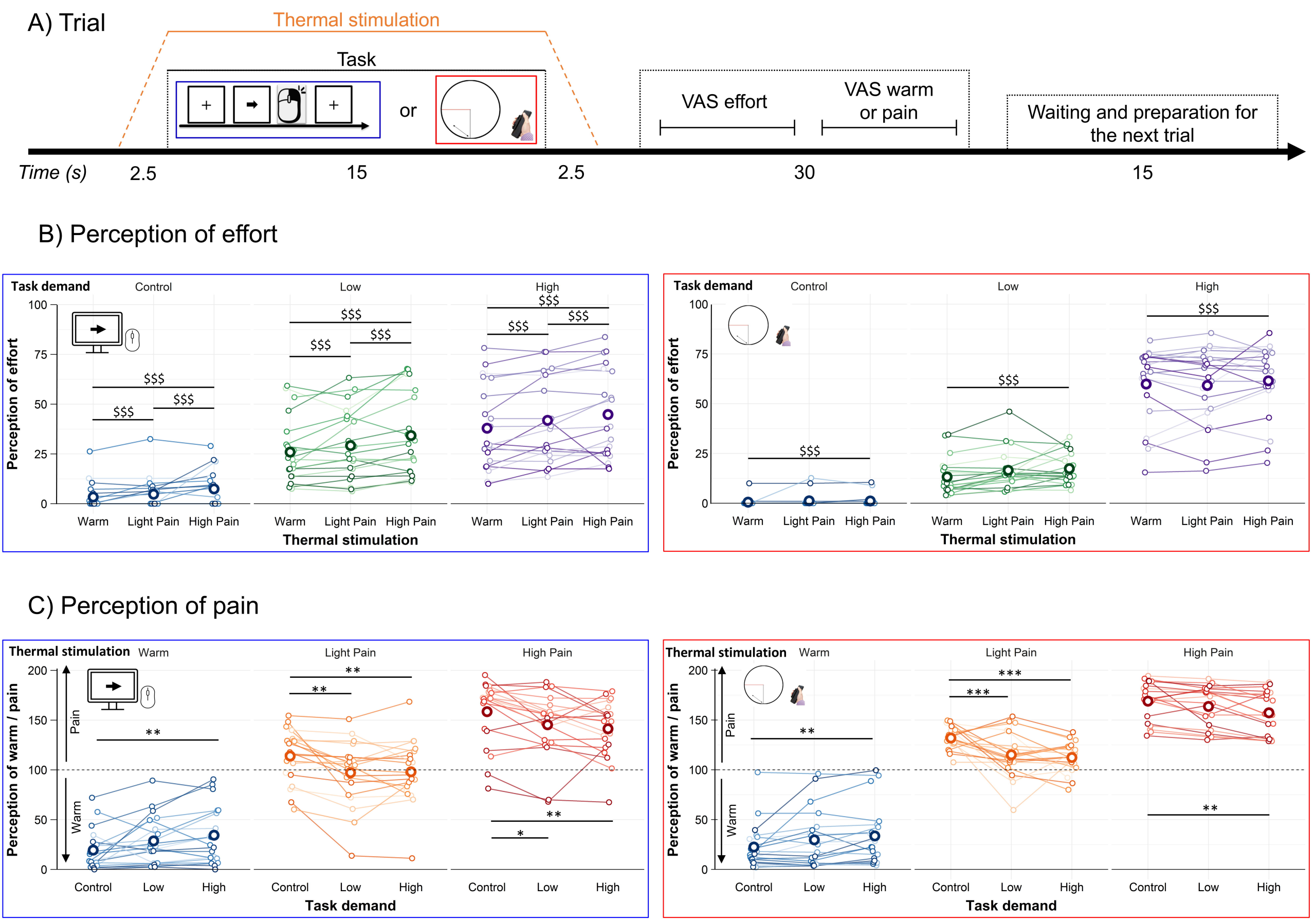
Distractor = 0.07*PP

PE = 2.94 + Effort + (0.13*Fatigue + distractor)

Motor experiment

Winning model is model 3 with logarithm of task demand and pain perception.

PE = 0.693 + 184.819*log(TD) + 0.006*PP + 0.126*log(TD)*PP + 0.051*Performance + 7.204*log(TD)*Performance + 0.019*Performance*PP - 0.056*log(TD)*Performance*PP


A) Trial
Thermal stimulation
Task
or
VAS effort
VAS warm or pain
Waiting and preparation for the next trial
Time (s)
2.5
15
2.5
30
15
B) Perception of effort
Task demand
Control
Low
High
Perception of effort
Warm
Light Pain
High Pain
Thermal stimulation
$$$
C) Perception of pain
Thermal stimulation
Warm
Light Pain
High Pain
Perception of warm / pain
Pain
Warm
Control
Low
High
Task demand
**
*
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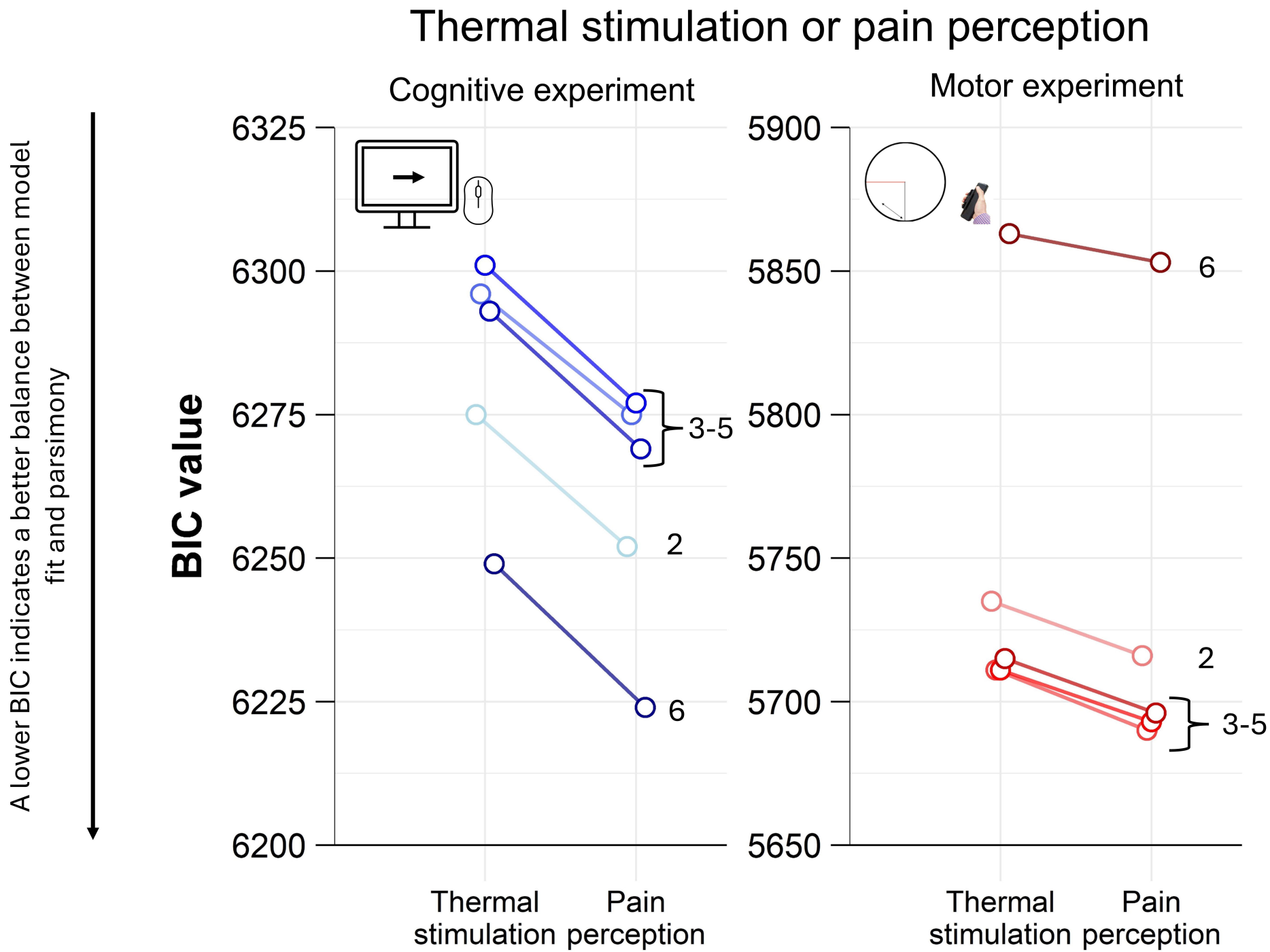
Thermal stimulation or pain perception
Cognitive experiment
Motor experiment
A lower BIC indicates a better balance between model fit and parsimony
BIC value
6325
6300
6275
6250
6225
6200
5900
5850
5800
5750
5700
5650
3-5
2
6
Thermal stimulation
Pain perception