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On the physiology of flow: Bridging flow theory with the biopsychosocial model of challenge and threat[☆]

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ABSTRACT

We examined the relation between psychological flow and cardiovascular markers of challenge. According to flow theory and the biopsychosocial model of challenge and threat (BPS-CT) optimal motivational states (flow, challenge) arise during activities where task demands meet personal resources. Participants (N = 154) played Tetris in either an underload, fit, or overload condition. Cardiovascular responses were measured during the task and a flow state scale was completed afterwards. Unexpectedly, it was in the underload condition where cardiovascular responses developed in the direction of challenge. Moreover, it was under this condition where relative challenge related positively to both task performance and self-reported flow. Similar results were found for cardiovascular markers of task engagement. In line with the BPS-CT, when only selecting clearly task-engaged participants a tendency towards challenge was found in the fit condition. We discuss why flow and challenge might have co-occurred in the underload condition, as well as the further theoretical and methodological implications of the study. We conclude that at least under some circumstances flow and challenge relate to each other but that future research should examine this relation further.

Flow is “the holistic experience that people feel when they act with full involvement” (Csikszentmihalyi, 1975, p. 32). More specifically, flow concerns the mental state where one is fully immersed in a goal-directed activity, and person and activity seem to merge in an energized focus towards the goal. Flow can emerge during a variety of tasks like running, analyzing data, or even relatively simple household chores. Moreover, flow can arise during individual tasks, like being immersed in a computer game, but also during group tasks, like in sports teams or symphony orchestras. Flow is considered to be an important psychological state as it relates to general well-being and performance in a diversity of domains like work and sports (Bakker et al., 2011; Csikszentmihalyi, 1990; Nakamura and Csikszentmihalyi, 2009; Engeser and Schiepe-Tiska, 2021; Ilies et al., 2017).

In research on flow, the concept has mainly been measured retrospectively, using self-report measures like the “Day Reconstruction Method” (Kahneman et al., 2004) and the “Experience Sampling Method” (cf. Engeser and Baumann, 2016). Although these measures have been instrumental in developing flow theory and documenting the rich phenomenology of the flow experience, self-report measures have limitations as well (Keller and Bloman, 2008). For example, while a sense of *continuity* is a core aspect of the flow experience, this aspect is only poorly captured by measures that are taken only at one discrete moment in time. Moreover, asking people to reflect on their flow experience during task performance is likely to interrupt the flow, making it almost impossible to measure the state of flow “in the moment” using self-reports. Finally, self-report measures rely on the assumption that people have conscious access to their psychological states, which is also not at all self-evident (Blascovich and Mendes, 2000).

To address these limitations, we propose a psychophysiological approach to flow, based on an integration of flow theory and principles derived from the biopsychosocial model of challenge and threat (BPS-CT; Blascovich, 2008). The BPS-CT describes specific cardiovascular (CV) markers of challenge and threat motivational states during task performance. As will be outlined in more detail below, these CV indices can be obtained in a continuous and unobtrusive way. Moreover, flow as

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conceptualized within flow theory, and challenge as conceptualized within the BPS-CT, share the same appraisal component: Both arise when personal resources are balanced with task demands. We therefore propose that the challenge CV profile as described by the BPS-CT forms potentially an important physiological dimension of flow.

In the current research we aim to bridge flow theory with the BPS-CT. Before describing our rationale and study in more detail, we first describe flow theory and the BPS-CT.

1. Flow

Flow theory describes both the necessary task requirements to enter a state of flow as well as the psychological experience of being in flow (Engeser and Schiepe-Tiska, 2021; Nakamura and Csikszentmihalyi, 2009). In order to enter a state of flow, an activity should have a clear *goal*, and during the task one should receive *feedback* about the extent to which one progresses towards that goal. Moreover, to enter a state of flow there should be a *balance* between the demands of the activity and the resources the person brings into the situation to deal with these demands (Keller and Bless, 2008). When resources are (much) greater than demands, the person gets bored; when demands are (much) greater than resources the person gets anxious or threatened; however, when there is a fit between demands and resources, the person is likely to enter a state of flow.

The flow experience itself consists of several facets. First, people in flow typically report a deep *involvement* in the task, and a high level of *concentration*. Second, flow is associated with high levels of feeling in *control*. Third, being in flow typically results in *lowered levels of self-awareness* as activity and 'self' seem to merge. A fourth aspect of flow is a *distorted experience of time*, in the sense that hours seem to pass like minutes. A fifth and final aspect of the flow experience is that engagement in the task is experienced as *rewarding in and of itself*, which has also been referred to as 'autotelic experience' (Engeser and Schiepe-Tiska, 2021; Keller and Bless, 2008; Nakamura and Csikszentmihalyi, 2009).

2. Physiological correlates of flow

In order to identify yet another, more objective, aspect of the flow concept, researchers started to explore its neural- and physiological correlates (de Manzano et al., 2013; Klasen et al., 2012; Ulrich et al., 2016; Ulrich et al., 2014; see Khoshnoud et al., 2020; Peifer, 2012, for overviews). Particularly relevant for the current research are studies using measures for autonomic arousal during task performance. Work in this direction has mainly focused on the relation between heart rate variability (HRV) and flow (de Manzano et al., 2010; Harmat et al., 2015; Keller et al., 2011; Tozman et al., 2015). The main finding in this work has been that flow lowers HRV, which has been interpreted as indicative for vagal withdrawal or increased sympathetic arousal. As a more nuanced version of this prediction, Peifer et al. (2014) presented evidence that the relation between sympathetic arousal and flow takes the form of an inverted U-shape: A moderate level of sympathetic arousal seems optimal for flow. There is also evidence that flow relates to reduced HRV in combination with increased respiratory depth, suggesting a co-activation of the sympathetic and parasympathetic nervous system (Harmat et al., 2015; Jaque et al., 2020; de Manzano et al., 2010; Khoshnoud et al., 2020).

Although several studies have found a negative relation between HRV and flow, Mansfield et al. (2012) did not find evidence for such a relationship. In their work, Mansfield and colleagues examined a HRV-based measure referred to as "coherence": A particular pattern of low frequency heart rate variability (HRV) that has been related to optimal performance and positive mental states. In their research they used two tasks: A task that was known to induce coherence and a task that was known to induce flow. Results indicated a dissociation between (psychological) flow and (physiological) coherence. Mansfield and colleagues conclude that although both flow and coherence are positive psychological states, they can occur independently of each other.

Thus, previous research provides at least some evidence for activation of the sympathetic nervous system during flow, for example, as indicated by a reduced HRV (see also Murch et al., 2020). In the current work we build on this observation but zoom in more on the specific quality of this sympathetic arousal. More in particular, by employing the BPS-CT we draw a distinction between CV indices of *threat* and *challenge* motivational states. As will be outlined in more detail below, although sympathetic arousal lies at the basis of both challenge and threat, the specific CV response patterns described by the BPS-CT make it possible to interpret the quality of this sympathetic arousal in terms of more benign (challenge) or more maladaptive (threat) arousal.

3. The biopsychosocial model of challenge and threat

The BPS-CT describes specific cardiovascular (CV) markers of the motivational states of *threat* and *challenge* during so-called *motivated performance situations* (e.g., athletic performance, negotiating, doing a math test, giving a speech). According to the model, threat and challenge result from the appraisal of the motivated performance situation in terms of its demands (e.g., required effort, uncertainty, and danger), and the resources the person brings into the situation to deal with these demands (e.g., skills, knowledge, support, and dispositions). When demands outweigh resources, a threat motivational state arises, whereas when resources approach or exceed demands, a challenge motivational state arises (Blascovich, 2008; Blascovich and Mendes, 2010; Blascovich and Tomaka, 1996; Mendes and Park, 2014; Seery, 2011; Wormwood et al., 2019).

Furthermore, the BPS-CT describes validated CV response profiles that mark challenge and threat. In the context of the BPS-CT four CV measures are typically used: Heart rate (HR), Pre-Ejection Period (PEP), Cardiac Output (CO) and Total Peripheral Resistance (TPR). A defining aspect of motivated performance is a certain level of *task engagement* which is at the physiological level marked by increased HR and decreased PEP (Blascovich and Mendes, 2010; Richter et al., 2016; Seery, 2011); that is, the heart starts pumping faster, and with more force. This physiological pattern is due to increased sympathetic activation, which thus underlies both challenge and threat. Given task engagement, challenge and threat can in turn be distinguished on the basis of CO and TPR reactivity. In terms of reactivity compared to baseline levels (so-called *absolute* patterns of challenge and threat; Blascovich et al., 2001), challenge is marked by increased CO and decreased TPR, which facilitates the efficient mobilization and transportation of energy during motivated performance. Threat, by contrast, is marked by increased TPR and stable or even decreased CO, which is a less efficient CV response profile during motivated performance (Blascovich and Mendes, 2010).

In addition to these absolute patterns of challenge and threat, in more recent formulations of the BPS-CT more emphasis is put on *relative* differences in challenge and threat between experimental conditions (de Wit et al., 2012; Lamarche et al., 2020; Peters et al., 2018; Saltsman et al., 2019; Scheepers et al., 2012). Here, challenge is indicated by relatively high CO and low TPR, and threat by relatively high TPR and low CO. As a further elaboration of these relative differences in challenge and threat motivational states, CO and TPR can also be combined in a single threat–challenge index (TCI: Blascovich et al., 2004; Kassam et al., 2009; Seery et al., 2010).

Recently there has also been more attention devoted to "nonresponders" in work on the BPS-CT (Hase et al., 2020; Wormwood et al., 2019). Using a data-driven machine-learning approach, Wormwood and colleagues showed three clusters of participants regarding CV reactivity during motivated performance: a challenge group, a threat group, and a group of "nonresponders". The latter observation can also be related to what in more clinically-oriented work has been referred to as "blunted cardiovascular reactivity", i.e., disengagement from (potentially) stressful situations (see Hase et al., 2020 for a discussion). Because according to the BPS-CT, a certain level of engagement is a prerequisite for motivational states of challenge and threat to develop, some researchers have selected for their threat-challenge analyses the data of only those participants who show clear CV signs of engagement (Hase et al., 2019; Seery et al., 2004; Seery et al., 2009; Weisbuch et al., 2009).

The CV indices of challenge and threat have been validated and applied in dozens of studies, and provided a new motivational perspective on a variety of topics in psychology, ranging from social facilitation and decision-making to inter-ethnic interactions and athletic performance (see Blascovich and Mendes, 2010; Seery, 2011 for overviews). While the challenge CV response profile has been related to improved performance outcomes (Behnke and Kaczmarek, 2018; Hase et al., 2018), the threat CV response profile has been related to negative health outcomes (Blascovich, 2008; Derks and Scheepers, 2018; Hase et al., 2020).

The CV markers of challenge and threat (HR, PEP, CO, TPR) are typically measured using a combination of electrocardiography (ECG), impedance cardiopgraphy (ICG), and continuous blood pressure assessments (Sherwood et al., 1990). Importantly, using this methodology it is possible to tap into the unconscious aspects of motivation (Blascovich and Mendes, 2010). Moreover, these physiological measures can be taken online, continuously, and are less subject to demand concerns than self-report measures are. Given all these features, as well as the similar appraisal profile in terms of a fit between demands and resources, the BPS-CT seems ideal to capture the physiological dimension of flow.

4. The current research

We conducted a study in which participants played a game of "Tetris", which is a commonly-used game to induce flow (e.g., Keller and Bless, 2008). We created three conditions: 1. An underload condition where the task was rather simple; 2. A fit condition where the level of the task adapted to the skills of the participant; and 3. An overload condition where the task was far too difficult. Throughout the task we measured CV markers of challenge and threat. In addition to performance, we also measured self-reported flow after the task. We predicted that in the fit condition highest levels of flow and a CV pattern indicative of a challenge motivational state would be observed. Moreover, we predicted that flow would be positively correlated with relative challenge and performance.

The study was approved by the ethical review board of the department of psychology at Leiden university (CEP16–0308118); materials and data are available at https://osf.io/tcg3f/.

5. Method

5.1. Participants and design

Based on a heuristic of including at least 50 participants per condition (Simmons et al., 2013), 154 students (66 % female; age: $M = 22$, range: 18–35) were recruited. Participants were compensated for their participation with partial course credit or €3,50 and were randomly assigned to one of the three conditions of a single-factor design (Condition: Underload vs. Fit. vs. Overload). During data collection, one participant fainted, leaving a final sample of $N = 153$. Due to technical problems, signal loss, or motion artifact, there was some missing data for the CV measures, resulting in lower degrees of freedom for the statistical tests regarding these measures. Participants were relatively inexperienced Tetris players, as 66 % of them indicated to have never played Tetris before.

5.2. Procedure

The whole experiment was run on computers such that all information, tasks and manipulations were delivered via the computer. After arriving at the lab, participants received a short explanation about the experiment and its procedures. After providing consent, the participant was seated in a cubicle, where sensors for physiological recording were applied. After completing several pre-measures,[1] five minutes of baseline CV responses were collected during which the participant sat quietly and relaxed. Then, as the main task, participants played "Tetris" for six minutes. After the task participants completed the flow state scale (Jackson and Marsh, 1996), answered some background questions, were debriefed, compensated for their participation, and finally dismissed.

5.3. Task

We used the same Tetris task as in our prior research (Keller and Bless, 2008; see also Keller et al., 2011, Exp. 2; Keller and Bloman, 2008) but reduced the time of task engagement to 6 min (cf. Keller and Bless, 2008, and Keller and Bloman, 2008: 8 min; Keller et al., 2011, Exp. 2: 15 min). The aim of Tetris is to adjust the orientation of "falling" objects so that they form completely filled lines at the bottom of the playing field. The objects can be moved to the right or left and rotated in 90° steps.

Three versions of the task were used for the three experimental conditions. In the "underload" condition, the task started at the lowest level, where the objects fall very slowly, resulting in a rather easy task. Moreover, in the underload condition participants stayed at this lowest level for the full task, regardless of their performance. Thus, it was expected that in this condition the participant's skills outweigh the demands of the task. In the "fit" condition the task started at an average level which was then adapted to the participant's performance. That is, when the participant performed well, the task moved up one level, and when the task became too difficult it moved down a level. Thus, in the fit condition a situation was created where task demands fitted the person's skills. Finally, in the "overload" condition participants started at a very high level and remained at that level, regardless of their performance. Thus, different from the fit condition, in the overload conditions participants did not move down a level when the task was too difficult (which was expected to be the default situation in this condition). In each condition, participants played Tetris for six minutes.

5.4. Flow state scale

The flow state scale (Jackson and Marsh, 1996) consists of 36 items, divided across nine sub-scales comprising four items each. The subscales cover the nine core dimensions of flow: "autotelic experience" (e.g., "Playing the game was rewarding"), "clear goals" (e.g., "During the game I knew what to do"), "challenge-skill balance" (e.g., "My abilities matched the demands of the task"), "loss of self-consciousness" (e.g., "During the game I was not concerned with others"), "distortion of time" (e.g., "During the game, time seemed to move differently than normal"), "concentration" (e.g., "I was completely focused on the task"), "control" (e.g., "During the game I felt in total control"), "feedback" (e.g., "During the game I knew how I was performing"), and "action-awareness merging" (e.g., "During the game I made movements without thinking"). Responses to the items were given on 7-point scales with "not at all" and "very much" as endpoints. The total flow state scale was reliable ($\alpha = 0.92$), and so were its sub-scales ($0.72 < \alpha\text{'s} < 0.89$).

5.5. Cardiovascular measures

To assess CV markers of challenge and threat motivational states, impedance cardiographic signals (ICG), electrocardiographic signals (EKG), and blood pressure were continuously measured using a Biopac

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[1] We included measures of action/state orientation, personality, optimism, self-esteem, Tetris-experience, perceived demands/resources, task motivation, and sport activities; these will not be discussed further in this report. All materials and data can be found at: https://osf.io/tcg3f/.

MP150 system (Biopac Systems Inc., Goleta, CA), using the same laboratory and apparatus, and following the same procedures, as described by Scheepers et al. (2015). Physiological data were stored using *Acqknowledge* software (Biopac Systems, Goleta, CA). Heart Rate was derived from the ECG. The ICG complexes were scored using AMS-IMP software (Free University, Amsterdam, the Netherlands), yielding measures of PEP and CO. The blood pressure machine provided a continuous measure of Mean Arterial Pressure (MAP) which was in combination with CO used to calculate TPR using the following formula: TPR = (MAP/CO) x 80 (Sherwood et al., 1990).

6. Results

6.1. Flow state scale

The flow state scale and its different sub-scales were analyzed using ONEWAY analyses of variance with condition (Underload, Fit, Overload) as factor. On the total flow state scale there was an effect of condition, $F(2, 150) = 38.95$, $p < .001$. As expected, participants in the fit condition reported more flow ($M = 4.42$; $SD = 0.75$) than participants in the overload condition ($M = 3.62$; $SD = 0.62$), $p < .001$. Unexpectedly however, participants in the underload condition reported even slightly higher levels of flow ($M = 4.77$; $SD = 0.66$) than participants in the fit condition, $p = .027$.

Analyses of the different subscales yielded generally the same pattern of results as for the total flow state scale. There were significant between-condition differences on all sub-scales (*F*s > 3.53; *p*s < 0.032) except "distortion of time", $F = 0.29$, *ns*. As can be seen in Table 1 and Fig. 1, on the sub-scales "autotelic experience", "challenge-skill balance", "loss of self-consciousness", and "concentration", participants in the overload condition reported lower flow than participants in the fit and underload condition. The same pattern appeared on "control", "clear goals", "feedback", and "action-awareness merging" subscales although on these dimensions participants in the underload condition also reported significantly higher levels of flow than participants in the fit condition.

The results on self-reported flow can be summarized as follows. Participants in the fit condition reported higher levels of flow than participants in the overload condition, in line with expectations. However, contrary to expectations, participants in the underload condition did not score *lower* on flow than participants in the fit condition; rather, on some dimensions they even scored significantly higher. We provide explanations for this unexpected finding in the discussion. However, because the different conditions yielded meaningful differences in self-reported flow, we could still relate these to CV patterns of challenge and threat motivational states. The relevant analyses will be reported next.

Table 1
Flow state scale and its different components.

	Underload *M* (*SD*)	Fit *M* (*SD*)	Overload *M* (*SD*)
Antecedents of flow			
Clear goals	5.46_a (1.10)	4.88_b (1.11)	4.07_c (1.29)
Unambiguous feedback	5.03_a (1.13)	4.42_b (1.04)	3.82_c (1.00)
Challenge-skill balance	4.50_a (0.98)	4.37_a (1.10)	2.52_b (0.86)
Elements of flow experience			
Control	5.27_a (1.16)	4.48_b (1.16)	3.29_c (1.15)
Concentration on task	5.64_{ab} (1.09)	5.85_a (1.02)	5.26_b (1.28)
Loss of self-consciousness	5.02_a (1.49)	4.53_{ab} (1.39)	4.09_b (1.33)
Action-awareness merging	4.54_a (1.17)	3.96_b (1.16)	2.95_c (1.08)
Transformation of time	3.59 (1.33)	3.43 (1.07)	3.47 (1.09)
Autotelic experience	3.90_a (1.04)	3.83_a (1.22)	3.11_b (1.11)
Flow state scale	4.77_a (0.66)	4.42_b (0.75)	3.62_c (0.62)

Means in rows with different subscripts differ at $p < .05$ (Bonferroni).

6.2. Cardiovascular responses

Mean levels of HR (Heart Rate), PEP (Pre-Ejection Period), CO (Cardiac Output), and TPR (Total Peripheral Resistance) were calculated for the last minute of the baseline, and each minute of the task. There were no significant between-condition differences on the baseline scores of the four measures, *F*s < 1. In line with standard practice, reactivity scores were then created for the four measures by subtracting the baseline scores from each of the six task scores (i.e., one for each task minute). Univariate outliers (defined as 3.3*SD* above/below the mean) were assigned a value of 1 % higher/lower than the adjacent non-extreme value (Blascovich et al., 2004; Mendes et al., 2002; Seery et al., 2008). Finally, we calculated combined Threat-Challenge Indices (TCI) by calculating *Z*-scores of CO and TPR reactivity, then multiplying TPR with −1 and summing the result with the CO *Z*-score (Blascovich et al., 2004; Kassam et al., 2009; Seery et al., 2010). Higher scores on the resulting index—which maximizes the reliability of the CV measures (Seery et al., 2010)—indicate a greater challenge motivational state, whereas lower scores indicate a greater threat motivational state. Similarly, we also created a single "engagement index" (see Seery et al., 2009) by combining PEP and HR reactivity using the formula: *Z*hr – *Z*pep.

6.2.1. Task engagement

We first tested for task engagement by testing the PEP and HR reactivity scores against 0 (i.e., baseline). Overall, PEP decreased from baseline ($M = -6.19$; $SD = 10.59$), $t(142) = -6.99$, $p < .001$, while HR increased from baseline ($M = 1.95$; $SD = 5.41$), $t(149) = 4.40$, $p < .001$. Moreover, at each minute of the task PEP (*p*s < 0.001) and HR (*p*s < 0.010) differed significantly from zero, providing clear evidence for task engagement throughout the task.

We then tested for between-condition differences in task engagement by submitting the combined engagement index to a repeated-measure GLM with condition as between-participant factor, and task minute as within-participant factor. This yielded an interaction between condition and task minute, $F(10, 274) = 2.41$, $p = .009$. As can be seen in Table 2 and Fig. 2, at the onset of the task, participants in the overload condition were relatively engaged, but this levelled-off over the course of the task. In the underload condition the opposite pattern was observed; at the onset of the task, engagement was relatively low, but engagement increased over the course of the task. Participants in the fit condition scored somewhat in between the underload and overload condition.

6.2.2. Challenge and threat

CO reactivity, TPR reactivity, and the TCI were analyzed using repeated-measure GLMs with condition as between-participant factor, and task minute as within-participant factor. Regarding CO there was a significant main effect for task minute, $F(5, 136) = 7.81$, $p < .001$, which was qualified by a marginally-significant interaction between condition and task minute, $F(10, 274) = 1.69$, $p = .084$ (see Table 3). Regarding TPR there was a significant main effect for task minute, $F(5, 133) = 4.99$, $p < .001$, which was not qualified by a significant interaction between condition and task minute, $F(10, 268) = 1.52$, $p = .131$ (see Table 3).

On the combined TCI there was only a marginally-significant interaction between condition and task minute, $F(10, 268) = 1.71$, $p = .079$ (see Table 3; Fig. 3). As can be seen in Fig. 3, mirroring the pattern on engagement, participants in the overload condition started relatively challenged but during the task this developed in the direction of threat. By contrast, participants in the underload condition started relatively threatened, but during the task this developed in the direction of challenge. Participants in the fit condition scored somewhere in between those in the underload and overload conditions. Importantly, however, despite the resembling patterns on the engagement index and the TCI, the interaction between condition and task-minute on the TCI remained virtually unchanged when controlling for engagement across the task, $F(10, 266) = 1.71$, $p = .077$.

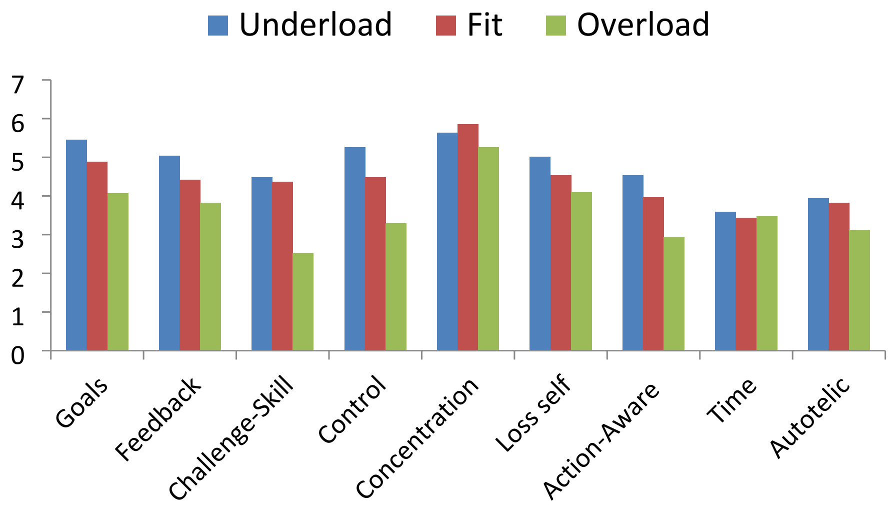

Fig. 1. Different subscales of flow state scale as a function of condition.

Table 2
Cardiovascular indices of task engagement (heart rate, pre-ejection period, engagement index).

Task minute	1 *M* (*SD*)	2 *M* (*SD*)	3 *M* (*SD*)	4 *M* (*SD*)	5 *M* (*SD*)	6 *M* (*SD*)
Heart Rate						
Underload	1.32 (6.46)	0.83 (5.75)	2.04 (5.15)	2.21 (4.65)	2.41 (5.11)	2.75 (6.04)
Fit	1.97 (7.77)	0.76 (6.36)	0.64 (5.83)	1.22 (4.80)	1.58 (4.63)	2.17 (5.52)
Overload	3.75 (7.96)	2.63 (6.58)	1.94 (6.26)	1.96 (5.49)	2.44 (6.16)	2.31 (5.38)
Pre-Ejection Period						
Underload	−5.25 (9.23)	−4.75 (9.14)	−5.92 (9.52)	−5.08 (10.13)	−5.08 (10.91)	−3.83 (9.90)
Fit	−8.54 (12.65)	−7.06 (11.98)	−5.93 (12.45)	−4.71 (10.92)	−4.54 (12.37)	−5.85 (14.97)
Overload	−9.15 (11.94)	−8.50 (11.84)	−7.52 (12.06)	−6.78 (11.25)	−6.13 (10.64)	−6.69 (12.50)
Engagement Index						
Underload	−0.37 (1.39)	−0.30 (1.41)	0.02 (1.38)	0.01 (1.47)	0.03 (1.55)	−0.08 (1.48)
Fit	−0.03 (1.94)	−0.12 (1.90)	−0.23 (1.90)	−0.23 (1.70)	−0.22 (1.59)	−0.06 (1.86)
Overload	0.30 (1.81)	0.32 (1.75)	0.11 (1.64)	0.11 (1.63)	0.10 (1.64)	0.03 (1.51)

In sum, the patterns on engagement and the TCI are largely in line with the effects on self-reported flow: In the underload condition participants became relatively more engaged and challenged during the task, and shortly afterwards they reported relatively high flow. In the overload condition participants became less engaged and more threatened during the task, and directly after the task they reported relatively low flow.

We then examined the (within-condition) correlations between CV indices of engagement and challenge and threat, self-reported flow, and performance (see Tables 4 and 5). During the final two minutes of the task, engagement and the TCI were significantly correlated with both performance and self-reported flow for participants in the underload condition. In the other conditions, correlations were low and non-significant.

6.2.3. *Exploratory analysis*

Although there were, over-all, CV signs of task engagement (see above), there was still substantial between-participant variation in engagement. We therefore performed, in a more exploratory fashion, an internal analysis for which we repeated the analyses on the TCI for only the participants who showed clear signs of task engagement (see e.g., Hase et al., 2019; Seery et al., 2004; Seery et al., 2009; Weisbuch et al., 2009 for a similar strategy). More specifically, we selected only those participants who showed a shorter PEP during the task than during baseline. In total, 98 participants (69 %) with valid physiological data showed PEP reactivity scores smaller than zero, and these participants were evenly divided across conditions, $\chi^2(2) = 1.83$, $p = .401$. A repeated-measures GLM on the TCI showed a significant interaction between condition and task minute, $F(10, 180) = 1.98$, $p = .038$. As can be seen in Fig. 4, for the underload and overload condition, the pattern of results is generally the same as for the total sample: throughout the task, there is a relative shift from relative threat to challenge in the underload condition, and a relative shift from challenge to threat in the overload condition. However, for the fit condition we found a consistent relative tendency towards challenge throughout the task.[2]

6.3. *Performance*

A ONEWAY analysis of variance with condition (Underload, Fit, Overload) as factor and number of lines completed in Tetris as dependent variable yielded a significant effect, $F(2, 150) = 7.04$, $p = .001$. Participants in the fit condition ($M = 14.50$; $SD = 5.00$) completed more lines than participants in the underload condition ($M = 10.84$; $SD = 3.00$), $p = .001$, and participants in the overload condition, ($M = 11.75$; $SD = 6.60$), $p = .022$. In all three conditions, self-reported flow was significantly correlated with performance ($0.354 < rs > 0.390$; $0.004 < ps < 0.013$). Importantly, however, controlling for performance in the analysis on flow and CV reactivity yielded virtually identical results than those reported above. That is, when including performance as a covariate, the effect of condition on the flow state scale remained significant, *F*

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[2] A similar internal analysis of flow and performance showed generally the same results as for the total sample: On flow there was a significant effect of condition, $F(2, 95) = 34.18$, $p < .001$, indicating that participants in the overload condition reported less flow ($M = 3.67$, $SD = 0.60$) than participants in the fit ($M = 4.57$, $SD = 0.76$) and underload conditions ($M = 4.91$, $SD = 0.58$); on performance there was also a significant effect of condition, $F(2, 95) = 4.35$, $p = .016$, indicating that participants in the fit condition ($M = 15.10$, $SD = 4.82$) performed better than participants in the underload ($M = 11.31$, $SD = 2.28$) and overload ($M = 12.41$, $SD = 6.88$) conditions.

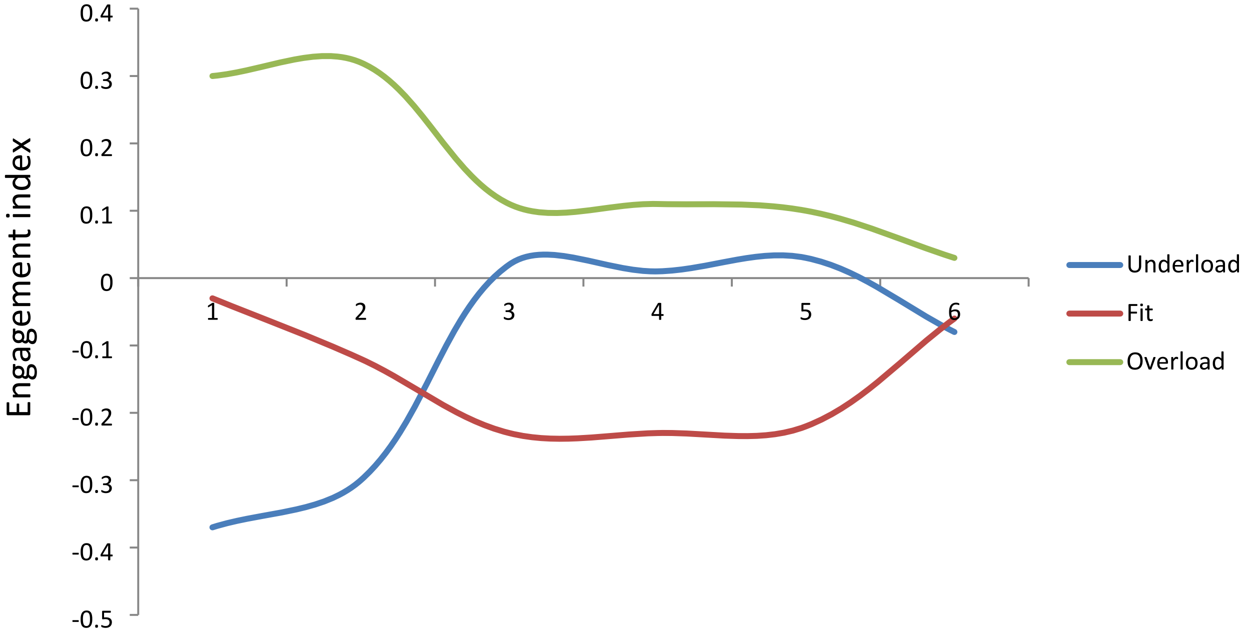

Fig. 2. Engagement index as a function of condition.

Table 3
Cardiovascular indices of challenge and threat (cardiac output, total peripheral resistance, threat-challenge index).

Task minute	1 *M* (*SD*)	2 *M* (*SD*)	3 *M* (*SD*)	4 *M* (*SD*)	5 *M* (*SD*)	6 *M* (*SD*)
Cardiac Output						
Underload	0.05	−0.01	0.01	−0.01	0.01	−0.01
	(0.25)	(0.22)	(0.20)	(0.21)	(0.23)	(0.24)
Fit	0.15	0.08	0.06	0.01	0.00	0.03
	(0.43)	(0.38)	(0.38)	(0.29)	(0.30)	(0.36)
Overload	0.11	0.09	0.04	0.01	0.00	0.00
	(0.28)	(0.29)	(0.27)	(0.25)	(0.24)	(0.25)
Total Peripheral Resistance						
Underload	45	178	111	165	131	154
	(456)	(494)	(423)	(441)	(476)	(409)
Fit	−5	122	191	223	230	206
	(548)	(568)	(502)	(546)	(624)	(647)
Overload	−52	−4	100	110	114	160
	(479)	(504)	(447)	(519)	(586)	(630)
Threat-Challenge Index						
Underload	−0.26	−0.35	−0.04	−0.05	0.04	−0.02
	(1.53)	(1.48)	(1.43)	(1.50)	(1.57)	(1.40)
Fit	0.17	0.05	−0.05	−0.08	−0.15	0.04
	(2.16)	(2.12)	(2.16)	(2.00)	(2.04)	(2.15)
Overload	0.11	0.32	0.09	0.12	0.10	−0.01
	(1.64)	(1.77)	(1.73)	(1.81)	(1.80)	(1.81)

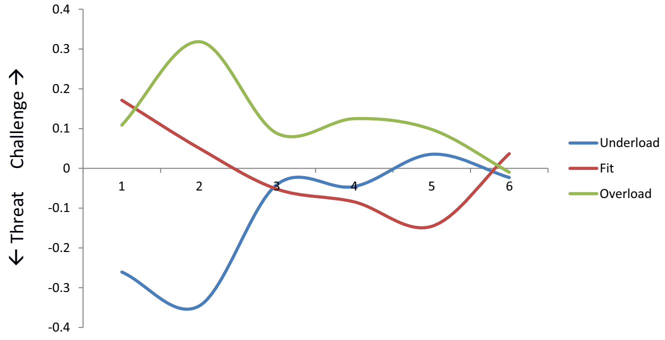

Fig. 3. Threat-challenge index as a function of condition.

(2, 149) = 45.79, $p < .001$, while the interaction between condition and task minute remained significant for the engagement index, $F(10, 272) = 2.45$, $p = .008$, and marginally-significant for the TCI, $F(10, 266) = 1.71$, $p = .071$.

7. Discussion

Identifying the motivational mechanisms underlying human behavior is one of the central themes in psychology and psychophysiology. With the current study we aimed to bridge two important approaches to motivation: Flow theory (Csikszentmihalyi, 1975; Engeser and Schiepe-Tiska, 2021; Nakamura and Csikszentmihalyi, 2009) and the biopsychosocial model of challenge and threat (BPS-CT; Blascovich, 2008; Blascovich and Mendes, 2010; Blascovich and Tomaka, 1996; Mendes and Park, 2014; Seery, 2011; Wormwood et al., 2019). Both perspectives are based on the idea that an optimal motivational state (flow, challenge) is grounded in a balance between task demands and personal and contextual resources: When demands outweigh resources, the person becomes threatened; when resources greatly outweigh demands, the person becomes bored; when resources approach or meet demands, the person becomes challenged, and ready to enter a state of flow. Both flow and challenge have similar and important consequences in terms of positive well-being and performance (Bakker et al., 2011; Behnke and Kaczmarek, 2018; Blascovich, 2008; Derks and Scheepers, 2018; Hase et al., 2018; Hase et al., 2020; Nakamura and Csikszentmihalyi, 2009; Engeser and Schiepe-Tiska, 2021; Ilies et al., 2017).

The results of the current study do indeed point to a relationship between self-reported flow and CV indices of relative challenge, although this relationship is relatively weak and methodological limitations call for caution before drawing more definitive conclusions. The condition where generally most flow was reported (underload) was also the condition where CV responses developed towards a relative state of challenge. Moreover, during the final stages of the task, just before flow was measured, relative challenge correlated positively to flow and performance in this particular condition.

Table 4
Correlations (p-values between brackets) between threat challenge index, flow state scale, and performance.

	TCI 1	TCI 2	TCI 3	TCI 4	TCI 5	TCI 6
Underload						
Flow State Scale	0.166 (0.266)	0.191 (0.199)	0.258 (0.080)	0.264 (0.073)	0.318* (0.030)	0.321* (0.028)
Performance	−0.033 (0.826)	0.080 (0.591)	0.146 (0.328)	0.258 (0.080)	0.361* (0.013)	0.378** (0.009)
Fit						
Flow State Scale	−0.012 (0.937)	−0.097 (0.526)	−0.086 (0.569)	0.014 (0.928)	−0.038 (0.803)	−0.021 (0.892)
Performance	0.180 (0.238)	0.141 (0.357)	0.102 (0.502)	0.216 (0.149)	0.149 (0.323)	0.100 (0.510)
Overload						
Flow State Scale	−0.033 (0.824)	−0.140 (0.341)	−0.088 (0.548)	−0.113 (0.441)	−0.080 (0.583)	−0.079 (0.591)
Performance	0.006 (0.967)	−0.092 (0.535)	−0.077 (0.598)	−0.042 (0.774)	−0.074 (0.615)	−0.048 (0.743)

* $p < .05$.
** $p < .01$.

Table 5
Correlations (p-values between brackets) between engagement index, flow state scale, and performance.

	Engagement Index 1	Engagement Index 2	Engagement Index 3	Engagement Index 4	Engagement Index 5	Engagement Index 6
Underload						
Flow State Scale	0.273 (0.060)	0.267 (0.066)	0.288* (0.047)	0.254 (0.081)	0.300* (0.038)	0.327* (0.023)
Performance	0.086 (0.559)	0.131 (0.373)	0.194 (0.187)	0.307* (0.034)	0.387** (0.007)	0.268 (0.066)
Fit						
Flow State Scale	0.036 (0.811)	−0.024 (0.873)	0.063 (0.675)	0.134 (0.374)	0.077 (0.612)	0.059 (0.698)
Performance	0.158 (0.295)	0.080 (0.597)	0.085 (0.573)	0.154 (0.307)	0.167 (0.266)	0.098 (0.516)
Overload						
Flow State Scale	0.140 (0.338)	0.041 (0.781)	0.120 (0.412)	0.057 (0.699)	0.020 (0.893)	0.059 (0.686)
Performance	0.230 (0.113)	0.162 (0.267)	0.240 (0.096)	0.262 (0.069)	0.211 (0.146)	0.215 (0.138)

* $p < .05$.
** $p < .01$.

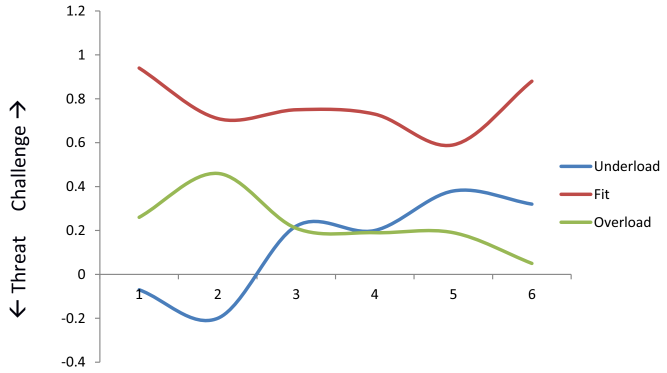

Fig. 4. Threat-challenge index as a function of condition, for participants showing task engagement (PEP < 0).

In line with flow theory and research we found that participants in the fit condition outperformed participants in the underload and overload condition, and also reported higher flow than participants in the overload condition. However, different than expected, we found relatively high flow in the underload condition and on some of the dimensions the scores were even highest in this condition. Because we found meaningful differences between conditions in flow and CV reactivity, we could still test the relation between these constructs and found evidence that flow and challenge developed, and related to each other, under similar circumstances. Therefore, we cautiously conclude that the current study provides initial evidence for a relation between flow as described in flow theory and a CV state of relative challenge as described within the BPS-CT.

Despite the fact that the current study provides first insights into the relation between CV challenge and flow, the issue why these states developed in particular in the underload condition deserves further discussion. We identify three possible explanations. First, some participants in the underload condition may have used creative ways to make the task challenging, for example by waiting with moving the object until the last moment.

Second, participants were relatively inexperienced Tetris players. That is, 66 % indicated to have never played the game before while another 30 % indicated to play the game about only once a year. Thus, only a small minority of the participants was a bit more experienced in playing Tetris. As a result, quite some participants might have found the underload condition already quite challenging and enjoyable (i.e., finding out the basics of the game), also compared to other tasks they may typically encounter in psychological experiments. At the same time, the constantly changing demand level in the fit condition may have also induced a sense of uncertainty (which is one of the main demand factors in the BPS-CT; Blascovich and Tomaka, 1996); as a consequence, this may have also somewhat tempered scores on the TCI in the fit condition.

Finally, in the current study we used a somewhat shorter Tetris task (6 min) than in previous research employing this task (Keller and Bless, 2008: 8 min; Keller et al., 2011: 15 min). As a consequence, participants in the underload condition might not have been "bored" yet after only six minutes, while participants in the fit condition might not have been fully "in flow" yet. In line with the latter two explanations it indeed appeared that it was particularly in the underload (and not the fit-) condition where participants experienced a fit of skills and task demands (rather than overload). That is, when specifically examining the FSS item that most directly measures this state ("The challenge and my skills were at an equally high level."; see also Barthelmäs and Keller, 2021) we identified that 43 of the 51 cases (84 %) in the underload condition scored 4 or higher (on a 7-point scale) while in the fit condition 13 cases out of 51 (26 %) scored *lower* than 4, and in the overload condition 10 out of 51 cases (19 %) scored 4 or higher. Together this suggests that the manipulation was only partially successful, and that it were in fact the participants in the underload condition who experienced the strongest fit between task demands and personal resources. However, irrespective of what caused the relatively high flow in the underload condition, ultimately we do not see it as undermining the main aim we had with this work, namely relating the psychological state of flow to a physiological response pattern indicative of relative challenge.

A related issue that deserves further attention concerns the more general patterns of CV reactivity in the different conditions. That is, while participants in the underload condition started relatively threatened and became more challenged throughout the task, participants in the fit and overload condition showed the opposite pattern as they started relatively challenged, but their motivational state developed towards threat as they progressed on the task. Again, these patterns may be explained with reference to the fact that most participants were relatively inexperienced Tetris players. As a consequence, for those in fit- and overload conditions, the task may have seemed highly demanding (though exciting) at first. However, when the levels quickly became more difficult or even impossible, motivation developed in the direction of threat throughout the remainder of the task. By contrast, in the underload condition the trials went rather slow from the onset, also limiting the possibilities to try-out things, to practice, and thus make sense of the situation, all possibly leading to relative threat. However, after a while, the participants in the underload condition may have developed a strategy for optimal performance, and may have even discovered ways to make the task challenging. Although all these explanations remain speculative at this point, we again stress that the absence of replicating the standard pattern of flow as a function of task condition is not detrimental for our main aim, namely relating flow to CV indices of relative challenge.

Parallel to the development of challenge there was a tendency among participants in the underload condition to become more engaged throughout the task, and this again related to higher performance and flow. Importantly, however, the effects of condition and task-minute on the TCI remained stable when controlling for engagement, which suggests that engagement and challenge relate relatively independently to flow. It seems likely, however, that engagement, challenge, flow and performance influenced each other in an iterative fashion during the task (see also Hase et al., 2020), something we could not examine here directly because flow and performance were only assessed at the end of the task. Nevertheless, it is noteworthy that not all variance in challenge could be explained in terms of task engagement.

Relatedly, although we found (under particular circumstances) reliable relationships between CV patterns of relative challenge, self-reported flow, and performance, these relationships were relatively small. However, at least some of these findings are in keeping with a meta-analysis on the relationship between CV markers of challenge and performance outcomes, which also found a reliable—but small—relationship ($r = 0.10$; Behnke and Kaczmarek, 2018). The somewhat modest relationships between CV markers of challenge, performance and flow may be partly due to methodological factors like different measurement systems underlying physiological, self-report, and behavioral measures. Another, related reason might be that we measured flow just once, and retrospectively, while CV responses were continuously measured.

However, in addition to these more methodological reasons, there may also be more conceptual and theoretical reasons for why one should probably not expect extremely strong correlations between CV makers of challenge and psychological measures of flow. First, even though a similar appraisal (balanced demands and resources) underlies both challenge and flow, task appraisal only forms the basis of the more extensive and rich phenomenology of flow, involving many other facets (e.g., lowered self-awareness, distortion of time experience). Thus, while situations eliciting flow are likely to also elicit challenge, when measuring the flow experience in a broader sense, as we have done in the current work, not all facets may relate to the same extent to physiological indices of challenge.

Relatedly, as indicated above, one of the main reasons behind the development of the BPS-CT was to create a model and technique that would allow for explaining and measuring more unconscious forms of motivation, based on the notion that people may not always have conscious access to their motivational states (Blascovich and Mendes, 2000). This is a second reason for why one would probably not expect a very strong overlap between the more implicitly measured CV markers of relative challenge and conscious reflections on the extent to which one is in flow. That is, a task may be challenging in a more subtle, unconscious way, and thus in the absence of a more overwhelming, full-blown subjective flow experience.

Third, despite the resemblance of the appraisals of challenge and flow, a closer consideration of flow theory and the BPS-CT reveals that the respective appraisal patterns underlying flow and challenge are not entirely identical. That is, while flow requires a (perfect) balance between demands and resources, challenge can also arise when resources approach, or even slightly exceed demands. Thus, there may be situations where one is already challenged, but not fully in flow (yet).

Finally, as indicated in the introduction, the BPS-CT specifically applies to situations that elicit sympathetic arousal. This was also apparent when selecting the data of only the participants who showed clear signs of sympathetic arousal: These participants displayed the CV response pattern that might be expected on the basis of the BPS-CT, i.e., a consistent relative tendency towards challenge in the fit condition. Importantly, however, it has been noted that flow may also emerge during situations eliciting parasympathetic arousal (Harmat et al., 2015; Jaque et al., 2020; Khoshnoud et al., 2020; de Manzano et al., 2010). This is yet another reason for why we would probably not expect a perfect overlap between challenge and flow. Indeed, when only selecting participants who showed clear task engagement, the pattern on flow in the different conditions was similar as when also including participants not clearly showing engagement (see Footnote 2). This is again suggestive of that the state of flow is less dependent on sympathetic arousal than the CV state of challenge is, according to the BPS-CT.

7.1. Theoretical and methodological implications

Despite the reservations outlined above, we found that at least under particular circumstances relative challenge and flow co-occurred and related to each other. This finding extends previous work on flow and challenge in different ways. As described in the introduction, traditionally, work on flow has mainly focused on its subjective state, and has mainly employed self-report measures to examine this state. Based on the conceptual and theoretical overlap of the appraisal component of flow and challenge, the current work made a first step in identifying a potentially relevant physiological dimension of flow. Moreover, the application of physiological measures provides several additional advantages, including the possibility to measure motivational states objectively and unconsciously, which is relevant because people may not always be willing or able to report on the motivational state they are in (Blascovich and Mendes, 2000). Moreover, an additional advantage of the current physiological approach is the possibility to measure indices of motivation continuously, which is especially relevant in relation to a phenomenon of flow for which a sense of continuity is a defining aspect that is, nonetheless, hard to capture directly using self-report measures. Thus, despite the reservations and the need for additional research on this topic, we think that the challenge CV pattern described by the BPS-CT forms a relevant physiological dimension of flow, at least under certain conditions.

The current work also has implications for work on the BPS-CT. Work in this field has focused on the contextual and dispositional determinants of challenge and threat, the role of cognitive appraisal in the emergence of these states, and their downstream consequences for performance and health (Blascovich, 2008; Behnke and Kaczmarek, 2018; Blascovich and Mendes, 2010; Blascovich and Tomaka, 1996; Derks and Scheepers, 2018; Hase et al., 2018; Hase et al., 2020; Mendes and Park, 2014; Seery, 2011; Wormwood et al., 2019). So far, however, little work has systematically focused on mapping the subjective experiences related to challenge and threat (cf. Mendes et al., 2008), which only seems to some extent obvious when considering that one of the main aims with the model was to provide *objective* (and implicit, unconscious) markers of challenge and threat. With the current work we make a first (small) step in documenting the subjective experiences associated with challenge, in the form of a flow experience.

The current work also confirms some of the basic principles of the BPS-CT. While recent research using this model has mostly applied the model to study diverse and more specific phenomena (e.g., inter-group interactions, negotiating), the current study revisits some of the seminal work on the basic principles of the model, in particular in relation to direct experimental inductions of the balance between demands and resources (e.g., Tomaka et al., 1997) and the key role of task engagement. That is, when only selecting the participants showing clear task engagement we found the strongest tendency towards challenge in the condition where demands met resources, precisely as the BPS-CT would predict.

Finally, the current study has also implications for the BPS-CT by showing the dynamics of task engagement during motivated performance, something that has received less attention in this model, also compared to other physiological approaches to motivation (Richter et al., 2016, cf. Seery et al., 2009). That is, in work on the BPS-CT, the significance of PEP and HR reactivity is typically just tested for as a general check on task engagement, before then examining differences in challenge and threat. The current study has illustrated how engagement developed as a function of both task condition and time, and that this was in this case strikingly similar to the development of challenge. Despite this similarity, engagement and challenge were also independent, in that the pattern on challenge remained stable after controlling for task engagement. Future research may more systematically examine how CV indices of engagement and challenge and threat mutually influence each other (Hase et al., 2020).

7.2. Limitations and suggestions for further research

A limitation of the current study is that we examined the relationship between flow and CV indices of relative challenge only in one particular task setting. In the current setting participants worked alone in a cubicle on a specific (gaming) task. Thus, to be able to draw more definitive conclusions about the challenge CV pattern as a physiological dimension of flow, it is important to test this relationship in a broader range of tasks, including more social tasks and in different domains (e.g., education, art).

Relatedly, we deliberately focused on a task that triggered sympathetic activation. Flow can be experienced in a wide range of situations, however, including situations where sympathetic activation is likely high (e.g., rock-climbing), situations where sympathetic activation may be more moderate (e.g., during more subtle cognitive tasks), or even low, as in the case of simple house-hold tasks that may elicit a state of “micro-flow” (Magyaródi and Oláh, 2015). Flow might also occur during situations eliciting high parasympathetic activation, like during emotional disclosure, or when empathizing with others (Graham, 2008; Mesurado and Richaud, 2017). Researchers have also argued that, at least under particular circumstances, flow might involve a mixture of both sympathetic and parasympathetic activation (de Manzano et al., 2010; Harmat et al., 2015; Khoshnoud et al., 2020). Future research could more systematically examine the role of sympathetic and parasympathetic (co-) activation in the emergence of flow during diverse activities. Importantly, this might also provide insights into the kind of tasks and situations where flow relates most strongly to challenge, following the BPS-CT.

7.3. Practical implications

The combination of physiological and self-report measures of flow may find its application in situations where it is necessary to measure the development and perseverance of motivation in an online and continuous fashion, for example in the context of game development. Game developers may want to design games in such a way that they create an almost continuous state of flow or challenge. The combination of physiological and self-report measures may be particularly functional in this context, as developers likely want to assess motivation in an online and continuous way, but at the same time also relate this to the subjective experience of e.g., enjoyment and flow. In this sense, the combination of physiological and self-report measures—which both have their strengths and limitations—will be most informative for creating games that elicit a more or less continuous state of challenge and engagement, as well as subjectively experienced flow.

7.4. Conclusion

Despite all factors that potentially temper the relation between CV markers of challenge and self-reported flow, we think that the BPS-CT remains a relevant model to capture the physiology of flow in a wide variety of situations, including sports, work, and educational settings. Thus, all in all we consider the current investigation as an important first step in bridging these two important motivational models.

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