The relation of flow-experience and physiological arousal under stress — Can u shape it? ☆

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HIGHLIGHTS

- We investigated psychophysiological processes of flow-experience under stress.
- Flow showed an inverted u-shaped relation with HPA-axis activation.
- Flow showed an inverted u-shaped relation with indices of sympathetic arousal.
- Parasympathetic activation was linearly and positively related to flow.
- Possibly a co-activation of both branches of the ANS facilitates task-related flow.

ABSTRACT

In this study, we investigate the relationship between stress and flow-experience with the help of psychophysiological arousal indicators. Whereas recent studies suggest a positive relation between flow and physiological arousal, so far nothing is known on the relation between flow and high arousal in response to a salient stressor. We here suggest that the relation of flow with sympathetic arousal and hypothalamic–pituitary–adrenal (HPA) axis activation follows an inverted u-curve rather than a linear function: moderate physiological arousal should facilitate flow-experience, whereas excessive physiological arousal should hinder flow. In order to experimentally stimulate high physiological arousal, we exposed 22 healthy male participants to a modified version of the Trier Social Stress Test. Then, participants had to perform a complex computer task for 60 minutes and to rate their flow-experience on the Flow Short-Scale directly after task completion. During the experiment, cortisol samples were taken every 15 minutes, and heart rate variability measures were assessed by continuous electrocardiography. We found an inverted u-shaped relationship of flow-experience with indices of sympathetic arousal and cortisol, whereas parasympathetic indices of heart rate control during stress were linearly and positively correlated with flow-experience. Our results suggest that moderate sympathetic arousal and HPA-axis activation and possibly a co-activation of both branches of the autonomic nervous system characterize task-related flow-experience.

Introduction

Flow-experience is a pleasant state of absorption of a person during an optimally challenging activity. During flow, the acting person shows undivided attention to a limited stimulus field, while time experience is typically distorted and self-referential thoughts are faded out of the mind (Csikszentmihalyi, 1975). This experiential state occurs when skills of a person and demands of the activity are in balance, and both above average (Csikszentmihalyi & LeFevre, 1989; Rheinberg, 2008).

The first studies on the physiology of flow were published in the last few years, e.g., from Kivikangas (2006), Nacke and Lindley (2009), De Manzano and colleagues (De Manzano, Theorell, Harmat, & Ullén, 2010) and Keller and colleagues (2011), who – apart from Kivikangas –

found flow-experience to be associated with increased physiological activation on our bodies' two stress-systems: the fast reacting sympathetic nervous system (De Manzano et al., 2010; Nacke & Lindley, 2009) and the slow reacting hypothalamic–pituitary–adrenal (HPA) axis (Keller et al., 2011). Can we conclude that flow is from a physiological view point a state of stress (Keller, Bless, Blomann and Kleinbohl, 2011)?

Flow-experience has been described in the context of stress before: Csikszentmihalyi (e.g., Csikszentmihalyi, 1975) often refers to rock climbing – a high-risk sport – when investigating flow, and Rheinberg and colleagues (Rheinberg, Vollmeyer, & Engeser, 2003) found the highest flow values (compared to their earlier studies) in a study on graffiti spraying (Rheinberg & Manig, 2003) — an activity that is often performed illegally with a risk of being caught by authorities. Weimar (2005) explicitly investigated flow in relation to stress: In his cross-sectional study with teachers, he found support that flow can be experienced in situations that are stress-relevant according to the transactional stress model (e.g., Lazarus & Folkman, 1984). The transactional stress model states that an individual will experience stress, if – as a result of a subjective appraisal – a situation or task is rated as personally relevant and if the demands of a situation or task exceed the skills and coping resources of the individual. A stress-relevant situation can be appraised as a threat, a loss or a challenge. In contrast to threat and loss, challenge is followed by pleasurable emotions (Lazarus & Folkman, 1984). Csikszentmihalyi (1990) drew a link between flow and challenge, stating that stress could be transformed into flow when it is interpreted as challenge (see also: Ohse, 1997; Peifer, 2012; Weimar, 2005). Correspondingly, Lazarus and colleagues (Lazarus, Kanner, & Folkman, 1980) described flow as a very functional experience during challenging activities that helps to sustain coping when required.

Taken together, there is empirical and theoretical evidence that a certain amount of stress (more precisely: challenge) and the requirement to cope are linked to flow-experiences. Accordingly, studies found heightened physiological arousal on the two stress systems during flow. Does that imply a positive and linear relationship between physiological arousal and flow-experience?

When we compare the transactional stress-model with the flow-model, both models make use of a comparison between demands of the situation and skills of the person. If demands exceed skills, Lazarus calls this state stress, while Csikszentmihalyi calls it anxiety (compare Fig. 1A). Beyond stress, the flow-model describes other experiential states depending on different demand-skill-ratios: boredom and relaxation occur if skills exceed demands; and flow occurs when skills and demands are in balance (Csikszentmihalyi, 1975; Csikszentmihalyi & LeFevre, 1989). From a physiological point of view, anxiety and stress are characterized by high physiological arousal, as indicated by increased sympathetic nervous system and HPA-axis activation; boredom and relaxation are characterized by low physiological arousal, respectively. As flow-experience in the flow-model is located between
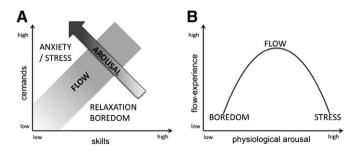
boredom and anxiety, we expect – from a physiological perspective – flow-experience to occur between high arousal (characteristic for anxiety) and low arousal (characteristic for boredom), at a state of moderate activation of the sympathetic nervous system and the HPA-axis (Fig. 1A). This means that the highest flow-values should be measured during moderate sympathetic nervous system or HPA-axis activation, whereas low flow-values will occur in both in a state of low (boredom) as well as in a state of high (stress) physiological arousal. As illustrated in Fig. 1B, we conclude that the relation of flow-experience with arousal on the two stress systems describes an inverted u-function. In detail, we expect an inverted u-shaped relationship between flow-experience and sympathetic activation (Hypothesis 1) and between flow-experience and HPA-axis-activation (Hypothesis 2).

Also De Manzano et al. (2010) suggested that an inverted u-shaped relationship between arousal and flow is intuitively plausible, despite finding a linear relationship between arousal and flow in their study, when participants played their favorite piano piece. They speculated that flow-experience might be related to arousal in a similar way as performance and point to the Yerkes-Dodson Law (Yerkes & Dodson, 1908), which states the relationship between arousal and performance follows an inverted u-curve.

In spite of strong theoretical arguments for the postulated inverted u-shaped relationship of flow-experience with physiological arousal, this relationship has not been tested until now. The research existing so far on the psychophysiology of flow found support for a positive relation between flow and arousal. However, these findings do not contradict the proposed inverted u-shaped relationship: none of these studies tested (and did not intend to test) physiological arousal on a stress level and were, consequently, only able to test the left side of the proposed u-curve, representing a positive relationship between flow and arousal. All past studies on physiological aspects of flow have taken place in a safe laboratory context, either playing a computer game (Keller et al., 2011; Kivikangas, 2006; Nacke & Lindley, 2009) or playing a favorite piece of music on the piano (De Manzano et al., 2010). Both – even when computer games are played at a high demand level – will most likely not be appraised as so personally relevant to perceive threat or loss and will not lead to high arousal and stress in a physiological and psychological sense. Furthermore, none of these previous studies tested quadratic relationships. The major aim of this study is, thus, to assess the relation between flow and physiological arousal *under stressful conditions*, in order to test the predicted inverted u-shaped relationship. In contrast to previous studies on the physiology of flow, we apply a special design feature to make sure our participants experience a significant amount of stress: we manipulate the participants' stress-level with a well-established stress protocol before the start of the actual experiment and use the transfer of arousal to test our predictions (compare Schachter, 1964, 1970; Schwarz & Clore, 1983; Schwarz, 2011; Zillmann, 1971; cf. the Methods section for a more detailed explication of this approach).

While we expect an inverted u-shaped relation between flow and sympathetic activation, the expected relation between flow and parasympathetic activation (= vagal tone) is less clear: The parasympathetic nervous system is the counter player of the sympathetic nervous system and down regulates physiological arousal (Porges, 1995). Both players can be active at the same time and influence arousal measures independently (Berntson, Cacioppo, & Quigley, 1991). The interaction pattern of sympathetic and parasympathetic activation can be reciprocal, positively related (coactivation or coinhibition) or uncoupled (Berntson et al., 1991). The different possibilities of sympathetic and parasympathetic interaction provide a higher flexibility and precision of the autonomic response in order to meet anticipated or realized environmental challenges (Berntson et al., 1991; Thayer & Lane, 2000). De Manzano et al. (2010) found indication that flow-experience might be associated with increased parasympathetic modulation of sympathetic activity. This speaks for a coactivation of the autonomic branches during flow and, in terms of parasympathetic activation, for a positive relation to

Fig. 1. Physiological arousal during flow-experience between stress and relaxation. A. The flow-channel model adapted from Csikszentmihalyi (1975) and Rheinberg (2008): physiological arousal increases continuously from a low arousal state of boredom or relaxation to a high arousal state of anxiety/stress leading to the suggestion that flow-experience comes along with moderate physiological arousal. B. The relationship of flow-experience and physiological arousal as described in Panel A. can be drawn as an inverted u-curve.

flow. However, Keller and colleagues (2011) found parasympathetic activation to be decreased during the skills–demands compatibility condition (designed to induce flow) of a computerized knowledge task compared to a boredom condition. On trend level significance, parasympathetic activation was even decreased compared to a high difficulty condition (Keller et al., 2011). As evidence so far is insufficient to draw a clear hypothesis, we use an exploratory approach to investigate the relationship of parasympathetic activation and flow-experience (Hypothesis 3).

We can summarize the following hypotheses for this study:

Hypothesis 1. There is an inverted u-shaped relationship between flow-experience and sympathetic activation.

Hypothesis 2. There is an inverted u-shaped relationship between flow-experience and HPA-axis-activation.

Hypothesis 3. There is a relationship between flow-experience and parasympathetic activation.

Method

Sample

Participants were 22 healthy male subjects, with an age range of 20 to 34 years ($M = 24.95$; $SD = 2.70$). All participants were recruited from technical study programs of the University of Trier and the University of Applied Sciences Trier and they received 50 € (10 € per hour) gratuity for their participation.

Experimental task

As a task environment, we used the computer program *Cabin Air Management System* (CAMS) in the version *AutoCAMS 1.0* (Automation Enhanced Cabin Air Management System; Manzey et al., 2008). CAMS simulates a complex environment of a spacecraft's life support system. The game is described elsewhere in more detail (see Manzey et al., 2008; Sauer, Wastell, & Hockey, 2000).

Procedure

All participants took part in a 3.5 hours knowledge-based training with a maximum group size of eight. Participants were trained to understand the processes of CAMS in order to enable them to successfully operate the simulation program.

The experiment itself took place during the week following the training session within a range of 1 to 4 days between training and experiment. The experiment lasted approximately 1.5 hours and was always held in the afternoon to control for the circadian rhythm of cortisol release over a day.

Each participant began by filling in questionnaires with demographical information, followed by a 15 minutes baseline session of the CAMS task. After that, the social stress protocol was conducted before participants performed the CAMS task for 60 minutes. Finally, they filled in the Flow-Questionnaire to rate their experience during CAMS.

Stress

In order to increase physiological and psychological arousal, we applied a stress treatment before the start of the experiment: the Trier Social Stress Test (TSST, Kirschbaum, Pirke, & Hellhammer, 1993) is a valid, reliable and standardized instrument that produces significant physiological and psychological stress responses. The stress responses to the TSST still vary between participants: literature reveals a cortisol responder rate of about 70% (Kirschbaum et al., 1993; Kudielka & Kirschbaum, 2005).

The TSST simulates a realistic job interview in which two interviewers ask unpleasant questions while refusing to give any (positive or negative) nonverbal feedback, and the participants assume they are being videotaped. For a detailed description of the TSST see Kirschbaum et al. (1993). In our experiment, the second part of the original protocol (an arithmetic task) was substituted by the CAMS task, which started immediately after the job interview. Participants were told that CAMS would have predictive value for future job success and that it would be part of the assessment. In order to keep the stress present during the experiment, both investigators stayed in the room, one in front of the participant and one behind him to monitor the computer screen during task performance. Furthermore, participants were told that the videotaping would carry on throughout the whole session. At the very end of the experiment, all participants where debriefed and told that they had been part of an experiment on stress.

The manipulation check confirmed a significant cortisol response after the TSST ($F_{7;12} = 6.0$; $p < .01$). However, cortisol values dropped in the second half of the experiment compared to the first half, indicating that the stress level of the participants was significantly decreasing towards the end of the experiment ($F_{1;21} = 12.98$; $p < .01$).

Design

By inducing stress before the actual experiment, we applied a different design approach compared to earlier studies on the flow–arousal-relationship. Previous studies either have not manipulated arousal, but measured it during the activity (e.g., De Manzano et al., 2010) or have increased task difficulty in order to enhance stress (Keller et al., 2011). However, Keller and colleagues (2011) found no increase of arousal by means of higher task difficulty compared to the optimal fit condition. In our study, we aimed at increasing arousal above an optimal level, in order to be able to test the postulated inverted u-shaped relationship between flow-experience and arousal. In contrast to previous studies, we induced stress *beforehand* with the help of an established stress protocol and made use of the spillover-effect of arousal between tasks. The spillover-effect of arousal has repeatedly been demonstrated within research on the excitation transfer theory (Zillmann, 1971), the two-factor theory of emotions (Schachter, 1964, 1970), and the feelings-as-information theory (Schwarz, 2011; Schwarz & Clore, 1983). In order to ensure the transfer of arousal between tasks, we linked the TSST and CAMS as two parts of one personnel selection instrument. As a cover story, we told participants that the CAMS-task would be a reliable instrument to assess technical skills and to predict future job success.

Variables of the study

Self-report measures

Flow-experience was measured with the two subscales *absorption* and *fluency* of the Flow Short-Scale (Engeser & Rheinberg, 2008; Rheinberg, Vollmeyer and Engeser, 2003). The items are assessed on a seven-point Likert scale from 1 (I don't agree) to 7 (I agree). Absorption consists of four items (e.g., "I do not recognize that time is going by") and fluency is measured by six items (e.g., "I feel that everything is under control"). We found good to satisfactory reliabilities of absorption (Cronbach's $\alpha = .69$) and fluency (Cronbach's $\alpha = .86$). Participants answered the Flow Short-Scale immediately after they finished the experimental task and were instructed to refer to the CAMS task when filling in the questionnaire.

According to Rheinberg and Vollmeyer (2003), fluency occurs in situations in which demands are lower than or meet the skills of a person, thus falling right in or underneath the flow-channel, in the area of boredom or relaxation. Absorption, however, occurs only when demands and skills are in balance (Rheinberg & Vollmeyer, 2003) — thus, exclusively in the flow-channel and is the more representative indicator for flow. That is why we expect our hypotheses to apply for the

factor absorption, whereas for fluency no clear predictions are possible, as it occurs both in situations in which demands are lower than or meet the skills of a person.

Physiological variables

As the manipulation check had revealed that the participants' stress-level dropped during the experiment, we decided to split the measurement of the physiological variables into two parts: Whereas physiological measures during the first half of the experiment can be clearly related to the social stress procedure, they might be influenced by other factors during the second half, such as habituation, particular task demands, metabolism and diurnal patterns (in the case of cortisol). Therefore, we calculated two values for each physiological parameter, marked by '(t1)' for the first half of the experiment and '(t2)' for the second half.

In order to measure *sympathetic* and *parasympathetic activation*, we used particular measures of heart rate variability (HRV): through spectral analysis of the HRV, different frequency bands can be extracted (for details see Task Force of the European Society of Cardiology and the North American Society of Pacing and Electrophysiology, 1996). The *high frequency band of HRV* reflects central parasympathetic activity; the *low frequency band of HRV* is often taken as an indicator for sympathetic activity or sympathetic and parasympathetic activity, depending on the source (Task Force of the European Society of Cardiology and the North American Society of Pacing and Electrophysiology, 1996).

Parameters of *heart rate variability* (HRV) were calculated from raw electrocardiography (ECG). ECG electrodes (ECG Tyco Healthcare H34SG Ag/AgCl electrodes of 45 mm diameter) were attached following a standard lead II configuration. The software Dasylab V. 8.00.04 (National Instruments, Inc., 1000Hz, 16bit, ASCII Format) was used for data acquisition. The amplifier PARON EKG301 (PAR Electronic GmbH Berlin) was used, with a time constant of 1.5 seconds, a low pass filter of 500 Hz and an amplification of 5000 (A/D-transformer card: NI6033, National Instruments, Inc.).

After data acquisition, ECG raw data were imported to WinCPRS (Absolute Aliens Only, Tuku, Finland) to calculate HRV indicators used in this study. The spectral analysis of inter-beat-intervals was done with WinCPRS software using a FFT routine. The R–R interval time series was linearly interpolated and resampled with a sampling rate of 5 Hz, the resampled data was tapered using a Hanning window and the windowed data zero padded to the next power of 2. The FFT spectrum was smoothed using a sliding triangular weighting function in order to increase the number of freedoms, and thus improve the statistical relevance of the spectrum. The low frequency band (low frequency HRV (t1); low frequency HRV (t2)) was defined as 0.06 to 0.14 Hz, and the high frequency band (high frequency HRV (t1); high frequency HRV (t2)) as 0.15 to 0.5 Hz, as applied in previous studies (Schächinger et al., 2008; Suter, Huggenberger, Richter, Blumenthal, & Schächinger, 2009). One participant had to be excluded from ECG-analysis, as one electrode loosened during the CAMS-session and the recording was no longer analyzable. Final output measures yielded a skewness of <1 for all absolute band power values and the Kolmogorov–Smirnov test for normal distribution remained insignificant. Thus, absolute band power values were not logarithmically transformed before they were included into the statistical models.

As measure for HPA-axis-activation, we assessed its end-product cortisol. *Cortisol* was measured with saliva samples, using Salivette (Sarsted, Germany) collection devices, and analyzed by an immunoassay (Biochemical Laboratory at the University of Trier, Germany). Samples were collected every 15 minutes during the experiment: the first two samples after TSST were aggregated to cortisol (t1), the second three samples to cortisol (t2). One outlier in the variable cortisol (t2) was detected and excluded from further analysis, as it was located more than three standard deviations from the mean. However, results showed the same pattern with or without this outlier.

Statistical analysis

To test the hypothesized inverted u-shaped relationship between physiological arousal indicators (independent variables) and flow-experience (dependent variable), we regressed flow on the physiological variables using the curve fit procedure by SPPS. This procedure equals hierarchical regression analyses putting the linear model in the first ($Y = b_0 + b_1 t$) and the quadratic model ($Y = b_0 + b_1 t + b_2 t$) in the second block (with Y = dependent variable, b_0 = constant, b_n = regression coefficient and t = independent variable) (compare Abraham & Ledolter, 1983; Montgomery & Peck, 1982). In case both models were significant, we performed post-hoc comparisons by generating and visually analyzing scatterplots of the residual and the fit values of the concerning models, as proposed by Abraham and Ledolter (1983).

Results

Table 1 shows means, standard deviations and intercorrelations of all variables in this study.

Hypothesis 1: sympathetic activation and flow-experience

To investigate Hypothesis 1, we tested the relationship between low frequency HRV as a marker of sympathetic activity and flow-experience. The quadratic model of flow-experience regressed on low frequency HRV (t1, t2) was significant for absorption in the first ($R^2 = .40$; $p < .01$) and also in the second ($R^2 = .23$; $p < .05$) half of the experiment. The quadratic model of fluency regressed on low frequency HRV (t1) was significant for the first half of the experiment ($R^2 = .29$; $p < .05$), but not for the second half. Taken together, and given that low frequency HRV is an indicator of sympathetic activation, our results support Hypothesis 1: lower and higher levels of low frequency HRV (t1, t2) were associated with lower levels of flow whereas moderate levels of low frequency HRV were associated with higher levels of flow. This

Table 1
Means, standard deviations and intercorrelations of flow-experience and physiological arousal indicators.

Variable	M	SD	1	2	3	4	5	6	7
1. Absorption	4.78	1.07	–						
2. Fluency	4.45	1.15	.73**	–					
3. Low frequency HRV (t1) [ms²]	745.31	323.42	.48*	.48*	–				
4. High frequency HRV (t1) [ms²]	397.05	233.12	.52*	.33	.30	–			
5. Cortisol (t1) [nmol/l]	6.18	3.05	.37†	.15	.43†	.24	–		
6. Low frequency HRV (t2) [ms²]	868.43	401.35	.25	.21	.64**	.10	.54*	–	
7. High frequency HRV (t2) [ms²]	432.72	246.07	.44*	.14	.16	.87**	.28	.24	–
8. Cortisol (t2) [nmol/l]	4.2	1.98	.37	−.04	.15	.18	.69**	.22	.35

Note. Absorption = subscale absorption of the Flow Short Scale; fluency = subscale fluency of the Flow-Short Scale; HRV = heart rate variability; (t1) = in the first half of the experiment, after the stress induction; (t2) = in the second half of the experiment.
† $p < .10$ (two-tailed).
* $p < .05$ (two-tailed).
** $p < .01$ (two-tailed).

finding applies to the flow-scale absorption for both halves of the experiment; for fluency it applies only for the first half.

Hypothesis 2: HPA-axis activation and flow-experience

Regarding Hypothesis 2, we found evidence for the postulated quadratic relationship between cortisol and flow-experience: In the first half of the experiment, we found the quadratic regression model of absorption regressed on cortisol (t1) to be significant ($R^2 = .21$; $p < .05$), which supports Hypothesis 2: lower and higher levels of cortisol (t1) were associated with lower levels of flow whereas moderate levels of cortisol (t1) were associated with higher levels of flow. In the second half of the experiment, we found no significant relationship between cortisol (t2) and flow. Fluency showed no significant relationship to cortisol (t1, t2) in the first and the second half of the experiment.

Hypothesis 3: parasympathetic activation and flow-experience

The linear regression model of absorption regressed on high frequency HRV (t1, t2) was significant for the first half of the experiment ($R^2 = .23$; $p < .05$), and also in the second half of the experiment ($R^2 = .15$; $p < .05$): higher absorption-values corresponded to higher high frequency HRV-values (t1, t2). The quadratic regression model of absorption on high frequency HRF (t1, t2) was not significant. Our findings support a positive relationship of parasympathetic activation with flow-experience as measured through the flow-scale absorption. We found no relationship between fluency and high frequency HRV (t1, t2).

Table 2 shows the detailed results of the linear and quadratic regression models of all physiological parameters with flow-experience. Fig. 2 shows three representative scatterplots and fitted curves illustrating our findings.

Discussion

In Hypothesis 1, we postulated an inverted u-shaped relationship between sympathetic arousal and flow-experience. Indeed, we found the low frequency component of HRV to show the expected quadratic relationship with the flow-subscale absorption for the first and the second halves of the experiment, and in the first half of the experiment, also for the subscale fluency. Given that low frequency HRV reflects sympathetic cardiac control (e.g. Schächinger, Weinbacher, Kiss, Ritz, & Langewitz, 2001), this result confirms Hypothesis 1. However, some studies suggest that low frequency HRV is additionally influenced by parasympathetic mechanisms (compare Task Force of the European Society of Cardiology and the North American Society of Pacing and Electrophysiology, 1996). When looking at parasympathetic activation — measured through high

frequency HRV, we found a linear and positive relationship with flow. Accordingly, if low frequency HRV would be dominated by parasympathetic influence, one would expect a positive linear relationship between low frequency HRV and flow — however, it showed the inverted u-shaped relation to flow. This means that the decrease of low frequency HRV in the right side of the inverted u-curve cannot be explained by parasympathetic influence, but by a dominating sympathetic influence after the turning point of the curve — which again supports Hypothesis 1. Still, the relation between flow-experience and sympathetic activation should be corroborated in future studies that include measures exclusively indicating sympathetic activity.

In Hypothesis 2, we suggested an inverted u-shaped relation between flow-experience and HPA-axis activation as measured by cortisol levels. We found the proposed quadratic relation of cortisol with flow-experience for the subscale absorption in the first half of the experiment, shortly after the TSST, supporting Hypothesis 2. High absorption was found at moderately elevated levels of cortisol, whereas further increases in cortisol were related to lower absorption, resulting in an inverted u-shaped relationship between absorption and cortisol. Hypothesis 2 could not be supported for the second half of the experiment. This could be explained by the finding that cortisol levels decreased significantly in the second compared to the first half of the experiment indicating that participants were not sufficiently stressed anymore.

The finding that moderately elevated cortisol levels in a potentially stressful situation were associated with absorption is consistent with cortisol effects reported in the literature: Cortisol increases the auditory stimulus detection-threshold, which aids shielding task-irrelevant stimuli from attention and, therefore, aids focused attention (Fehm-Wolfsdorf & Nagel, 1996; Fehm-Wolfsdorf et al., 1993), a key element of absorption. Cortisol secretion enhances blood-glucose levels and provides additional energy resources to the individual in order to meet elevated energy demands during stress (Benedict et al., 2009; Cryer, 2007; Peters et al., 2004; Sapolsky, Romero, & Munck, 2000). This mechanism facilitates sustained attention, another key element of absorption and flow-experiences. Furthermore, elevated cortisol was linked to improved self-reported concentration and decreased tiredness — again typical for flow-experience (Born, Hitzler, Pietrowsky, Pauschinger, & Fehm, 1988).

Integrating our findings for Hypotheses 1 and 2, we could confirm from a physiological point of view that flow-experience is characterized by a moderate level of arousal, as reflected through sympathetic and HPA-axis-activation. High arousal, as well as low arousal, is associated with low flow-values. In accordance with Weimar (2005), we found that flow can be well experienced in stress-relevant situations, and in line with De Manzano et al. (2010) and Keller and colleagues (2011) that a moderate level of arousal is associated with flow. In addition, we found that above a moderate level, more arousal is associated with lower flow. Using the terminology of the transactional stress model (e.g., Lazarus & Folkman, 1984) and in line with Csikszentmihalyi (1990), we propose that situational demands that are appraised as challenging – and not yet as threatening – can lead to flow-experience. Conclusively, flow is associated with moderate forms of arousal that are experienced as challenging and reminds of moderate and positive forms of stress, such as the concept of Eustress (Selye, 1983).

Concerning our exploratory hypothesis on parasympathetic processes during flow, we found a linear positive relationship of absorption with the high frequency component of HRV in the first and second halves of the experiment. The literature is consistent that higher levels of high frequency HRV represent increased parasympathetic activation. When participants experienced flow under stressful conditions, they were more likely to show increased parasympathetic activation. Thus, our results contradict findings of Keller and colleagues, who found a negative relationship between flow and parasympathetic activation. A possible reason for the differing results could be that Keller and colleagues

Table 2

Adjusted R^2 indicating explanation of variance of the linear and quadratic regression models for flow-experience regressed on physiological parameters.

	Absorption		Fluency	
	R^2_{linear}	$R^2_{quadratic}$	R^2_{linear}	$R^2_{quadratic}$
Low frequency HRV (t1)	.19[*]	.40[**]	.19[*]	.29[*]
High frequency HRV (t1)	.23[*]	.19[†]	.06	.06
Cortisol (t1)	.09[†]	.21[*]	−.03	−.04
Low frequency HRV (t2)	.01	.23[*]	−.01	−.05
High frequency HRV (t2)	.15[*]	.13	−.03	−.06
Cortisol (t2)	.09	.09	−.05	−.11

Note. Absorption = subscale absorption of the Flow Short Scale; fluency = subscale fluency of the Flow-Short Scale; HRV = heart rate variability; (t1) = in the first half of the experiment, after the stress induction; (t2) = in the second half of the experiment.
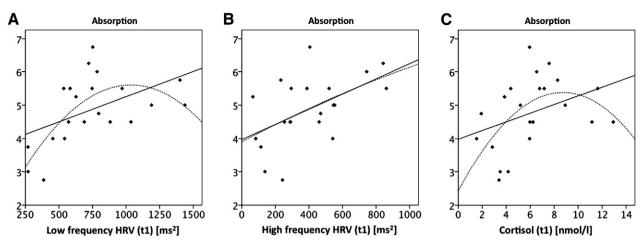
[†] $p < .10$.
[*] $p < .05$.
[**] $p < .01$.

Fig. 2. *Note.* ♦, observed values; —, linear relationship; ⋯, quadratic relationship; Absorption = subscale absorption of the Flow Short Scale; low frequency HRV = low frequency component of heart rate variability; high frequency HRV = high-frequency component of heart rate variability; (t1) = in the first half of the experiment, after the stress induction. A–C. Relationships of absorption with physiological variables. A. Absorption and low frequency HRV (t1). B. Absorption and high frequency HRV (t1). C. Absorption and cortisol (t1).

(2011) had related parasympathetic activation to an optimal fit condition and not to subjective flow ratings as it was done in our study. Furthermore, our findings support the theory of effortless attention (Bruya, 2010): Decreased parasympathetic activation was found to be a reliable indicator of enhanced cognitive workload (Bernardi et al., 2000). Thus, the association of flow with increased parasympathetic activation found in this study suggests a decrease of cognitive workload during flow, as described by Bruya (2010).

Integrating our findings on the relation between flow-experience and sympathetic and parasympathetic activation, we found high flow values at moderate sympathetic activation and at high parasympathetic activation. This finding fits the conclusion of De Manzano et al. (2010), who suggested that flow "might be associated with an increased parasympathetic modulation of sympathetic activity"(p. 307). Although the *interaction* of sympathetic and parasympathetic activation was not in the focus of this study, we did a post-hoc visual exploration of their relative pattern. On a descriptive level, we found the highest flow values, when high parasympathetic activation was combined with moderate sympathetic activation, which further supports the proposed relationship. Future studies should empirically test this interaction effect.

The combined activation of sympathetic and parasympathetic systems is associated with many desirable outcomes: this constellation was suggested to lead to better adaptation in demanding situations (Berntson et al., 1991) and was already observed during active coping with high workload (Backs, Lenneman, & Sicard, 1999) and during energy demanding states of physiological stress (Schächinger et al., 2004), with a compensating effect on heart rate. Furthermore, previous research found indication that the combined activation of sympathetic and parasympathetic branches buffers negative health effects of sympathetic activation alone (Kleiger, Miller, Bigger, & Moss, 1987; Liao et al., 1997) and is an indicator of high cardiac regulatory capacity, which was proposed to have health benefits (Berntson, Norman, Hawkley, & Cacioppo, 2008).

Thus, whereas a reciprocal pattern of increased sympathetic and decreased parasympathetic activation was found during states of stress, a coactivation of both branches is related to active coping with and the preparation for successful adaptation to challenging situations — a context in which flow is likely to appear (Csikszentmihalyi, 1990, Lazarus, Kanner and Folkman, 1980).

Strengths, limitations and future directions

To our knowledge, we were the first to test and find support for a u-shaped relationship of physiological arousal parameters and flow-

experience. To achieve the necessary high degree of stress and arousal, we used the TSST, a well-established instrument to induce stress. By doing this, our study expands the so far only limited knowledge on physiological processes during flow-experience.

Referring to the two-factor theory of emotions (Schachter, 1964, 1970), the feelings-as-information theory (Schwarz, 2011; Schwarz & Clore, 1983), and the excitation transfer theory (Zillmann, 1971), we made use of the effect of arousal transfer between subsequent experiences. Zillmann, Johnson, and Day (1974) found that this effect only applies if the increased arousal can be (mis)attributed to the actual experience. In our case it seems that the arousal induced during the TSST spilled over to participants' experience during the CAMS-task as expressed in the systematically varying flow-ratings of the participants. To ensure that the stress could be attributed to CAMS, we linked the TSST and CAMS as two parts of one personnel selection instrument. However, future research will be needed to further understand how phenomenological experiences across successive related – or even unrelated – tasks influence one another. It would be informative to test if an explicit link between the stressor and the task is necessary to influence flow-experience. If not, this would open broader options for interventions to facilitate flow: For example, moderate physical activity combined with deep breathing could enhance sympathetic and parasympathetic nervous system-activity in order to reach the flow-typical physiological pattern (Peifer, 2012). Future studies could investigate whether such interventions potentially facilitate flow-experiences.

Another strength of this study is that we identified physiological parameters that show a relationship to flow-experience. The identification of a flow-typical physiological pattern is of particular relevance for future flow-research and interventions: till the present, flow is only measureable via self-report questionnaires, which are retrospective by nature, meaning that one must always interrupt the experience in order to assess flow. With the help of physiological measures, participants' flow could be measured while they are in flow, without the need to interrupt them. This will enable research for a deeper understanding of the phenomenon as well as enabling the development of adaptive interventions to facilitate flow-experience (Peifer, 2012).

Our study provides evidence for a positive relation between flow and parasympathetic activation. Previous research has shown that increased parasympathetic activation positively influences positive emotions and other indicators of wellbeing (Kok & Fredrickson, 2010). Also flow has already been linked with short-term and long-term positive affect and subjective wellbeing (for an overview see Landhäußer & Keller, 2012). Thus, parasympathetic activation might act as a mediator in the flow-wellbeing relationship. Similarly, and in accordance with the

broaden-and-build-theory of positive emotions (Fredrickson, 1998, 2001), it was found that the relationship between parasympathetic activation and positive emotions is reciprocal, leading to so-called "upward spirals of the heart" and increased habitual vagal tone (Kok & Fredrickson, 2010). Accordingly, regular flow-experiences might have the potential to increase the habitual vagal tone and – consequently – wellbeing and trait positive emotions. However, the proposed mediational relation needs empirical support by future research.

Although we found a positive relation between flow-experience and parasympathetic activation under stress, we cannot exclude that too much parasympathetic activation could be negatively related to flow, resulting in a possible inverted u-shaped relationship. Our design was not created to test this hypothesis: since we had increased arousal with a stress treatment we could not expect to find sufficiently high relaxation. Still, future studies should consider such a relationship.

We would like to address the differing results for the two flow subscales absorption and fluency in our study: as expected, we found the hypothesized effects between flow and the physiological variables primarily for absorption, fluency showed its only significant relationship with low frequency HRV. According to Rheinberg and Vollmeyer (2003), absorption is exclusively experienced at an optimal demand level, but is both low at times when skills exceed demands and also when demands exceed skills. Thus, it represents an exclusive cognitive state that is characteristic for the flow-channel, and does not occur during boredom or stress. In contrast, fluency can already appear at times when skills exceed demands and is, thus, not exclusive to flow. Therefore, the structure of our findings is in line with the description of the flow subscales by Rheinberg and Vollmeyer (2003).

One limitation of this study concerns the homogeneity of our sample: we included only male student participants of technical study programs. In future studies, this should clearly be extended in terms of gender and proficiency in order to generalize findings.

One more limitation refers to our data analyses: We had planned to conduct the analyses without the split into two test halves t1 and t2. But the manipulation check of the stress treatment uncovered that cortisol decreased significantly in the second part of the experiment. Therefore, we decided to conduct the split. The results for the variables indicating sympathetic and parasympathetic activation showed the same pattern in the first and second halves of the experiment, although the relation between sympathetic activation and flow was weaker in the second half. With regard to the HPA-axis activation indicator cortisol, we found the expected relationship with flow only in the first half of the experiment. As the flow-assessment refers to the whole hour of the experiment and not exclusively to the first part, one might have expected that self-reported flow would show a stronger relation to the most recent part of the experiment than to the first half. Possibly due to a primacy-effect, participants could better memorize their experience from the first part of the study (Asch, 1946). Alternatively, it is possible that a certain physiological pattern supports particularly the initiation of flow-experience. Factors contributing to the initiation might differ from those contributing to the sustainment of flow. This could be another topic for future investigation.

Conclusion

Returning to our starting question: How is flow associated with a physiological state of stress? Our results support the hypothesized inverted u-shaped relation between flow-experience and sympathetic and HPA-axis activation. On a continuum between low and high arousal, we found flow to most likely occur at a moderate arousal level. Flow was further characterized by increased parasympathetic activation, suggesting a coactivation of both branches of the autonomic nervous system to characterize task-related flow-experience.

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