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The Psychophysiology of Flow During Piano Playing

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Expert performance is commonly accompanied by a subjective state of optimal experience called *flow*. Previous research has shown positive correlations between flow and quality of performance and suggests that flow may function as a reward signal that promotes practice. Here, piano playing was used as a flow-inducing behavior in order to analyze the relationship between subjective flow reports and psychophysiological measures. Professional classical pianists were asked to play a musical piece and then rate state flow. The performance was repeated five times in order to induce a variation in flow, keeping other factors constant, while recording the arterial pulse pressure waveform, respiration, head movements, and activity from the corrugator supercilii and zygomaticus major facial muscles. A significant relation was found between flow and heart period, blood pressure, heart rate variability, activity of the zygomaticus major muscle, and respiratory depth. These findings are discussed in relation to current models of emotion, attention, and expertise, and flow is proposed to be a state of effortless attention, which arises through an interaction between positive affect and high attention.

Keywords: flow, emotion, attention, psychophysiology, music

The concept of being in *flow* originates from studies on what motivates people to devote more time to certain activities (e.g., sports and music) than would be expected based solely on associated external rewards. The common denominator across individuals and settings appears to be the intrinsically rewarding experiences people have when deeply involved in such activities. These experiences have been dubbed *flow experiences* (Csikszentmihalyi, 1997). Qualitative research based on verbal reports of subjective flow has identified nine elements that define the experience (Csikszentmihalyi, 1990): (i) Challenge-skill balance – Task difficulty must be equal to person's ability, or feelings of anxiety/boredom will emerge; (ii) Action-awareness merging – Actions feel automatic and little or no attentional resources are required for executing action sequences; (iii) Clear goals; (iv) Unambiguous feedback; (v) High concentration; (vi) Sense of control; (vii) Loss of self-consciousness – Self-reflective thoughts and fear of social evaluation are absent; (viii) Transformation of time – Time may seem to move faster or slower than usual; and (ix) Autotelic experience – An induced state of positive affect, which can make a task intrinsically rewarding, that is, performing the task becomes a goal in itself. When operationalizing flow, these elements are generally transformed into dimensions that load equally on a composite flow score (Jackson & Eklund, 2004). It is important to note that flow is thus not usually regarded as an all-or-nothing peak experience; rather, degree of flow is a continuous variable that can be used to characterize the experiential quality of any everyday activity (Csikszentmihalyi & Csikszentmihalyi, 1992).

Findings from a wide range of domains, including chess playing, writing, sports, and visual arts, show a positive correlation between flow state measures and objective measures of quality of performance (Csikszentmihalyi & Csikszentmihalyi, 1992). In addition, flow has been suggested to function as a reward signal to promote practice (Csikszentmihalyi, 1997). Yet, other studies have found positive correlations between flow and quality of life (Csikszentmihalyi, 1990), giving reason for investigations of relations between flow and health. These observations motivate a scientific investigation of the biological basis of flow. This article, in which we investigate the link between flow and physiology, is intended as a first exploration on this quest, as there is to our knowledge no previous literature on the subject, apart from one unpublished master's thesis (Kivikangas, 2006), in which subjective *flow* reports were compared to facial EMG and skin conductance. Before introducing the empirical work, however, it is first necessary to discuss three related psychological constructs, namely *emotion*, *attention,* and *expertise*.

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Flow is by definition associated with feelings of enjoyment and positive affect, since a strong autotelic experience can even make external rewards appear redundant (Csikszentmihalyi, 1997). Furthermore, the state is experienced when deeply and actively involved in a task, performing at the peak of ability under high levels of concentration, which for most tasks indicates a state of heightened arousal. The link between flow on one hand and affect and arousal on the other means that the flow experience carries certain emotional content. Several elements of the flow experience are correspondingly found to be dependent on emotional state: Challenge appraisals and task engagement both vary as a function of affect (Maier, Waldstein, & Synowski, 2003); emotional stimuli can modulate attentional processes/concentration (Brosch, Sander, Pourtois, & Scherer, 2008; Jefferies, Smilek, Eich, & Enns, 2008; Sheth & Pham, 2008); perceived personal control is related to greater self-reported coping ability prior to a task and lower self-reported stressfulness following that task (Weinstein & Quigley, 2006); pleasant emotions are generally found to reduce self-conscious awareness (Roy, Peretz, & Rainville, 2008); sense of time is altered such that highly arousing stimuli with positive valence are perceived as having shorter duration and are reproduced at a faster tempo than negative, low arousing stimuli (Droit-Volet & Meck, 2007; Noulhiane, Mella, Samson, Ragot, & Pouthas, 2007). Based on these observations, it is reasonable to elaborate on flow, making reference to a model of human emotions. Here, we chose to frame the discussion using the two-dimensional affective space of valence and arousal (Lang, 1995), illustrated in Figure 1. Because flow is not an on-off state but may vary along a continuum, we discuss emotional (and later psychophysiological) correlates of flow within a dimensional range, rather than discrete emotional states for which flow may occur. The states in Figure 1 should thus be taken as examples of emotions at certain levels of each dimension. The valence dimension reflects engagement of neural structures and pathways in either the appetitive or aversive motivation systems, whereas the arousal dimension reflects variations in activation (metabolic and neural). A flow state is thus associated with the upper right quadrant of the affective space; that is, it is paired with an emotional state characterized by moderate to high levels of both dimensions (henceforth referred to as *joyous*). It is interesting to note that the dimensions of valence and arousal are commonly found to organize not only subjective but also somatophysiological responses, as will be described further down. Hence, by locating flow in the affective space, it is possible to formulate a hypothesis about how psychophysiological measures of emotion can be used to describe the flow experience.

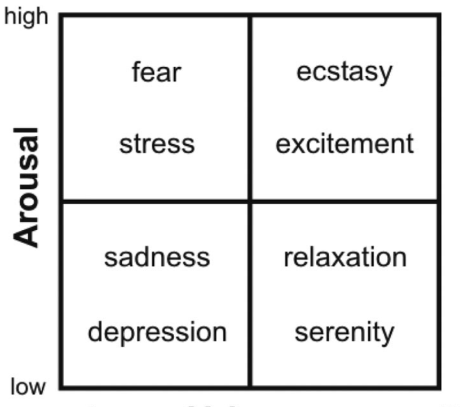

Figure 1. The affective space, defined by the dimensions valence and arousal, based on Lang (1995).

Attention is a central component of human cognition and a prerequisite for being able to maintain goals and execute goal oriented action (for a review, see Raz & Buhle, 2006). Focused yet effortless attention seems to be a contradiction in terms. Nevertheless, a flow state is characterized by a subjective experience of heightened, unforced concentration. One can speculate that this occurs as a result of an interaction between positive valence and attention, as positive valence can distract away from negative and even painful stimuli (Roy et al., 2008); that is, a task of great attentional load may be experienced as less effortful in a state of positive affect. Similar theoretical models have been used in psychophysiological stress research (Lundberg & Frankenhaeuser, 1980). This transient neglect could be explained by that brain systems respond differently to a stimulus depending on whether attention is focused on sensory- or affect-related properties, for example, intensity or pleasantness (Grabenhorst & Rolls, 2008).

Expertise, implemented as stored long-term representations in the brain, will guide planning and expectations (Ericsson & Lehmann, 1996) and even influence sensory processing to attend to task-relevant cues (Summerfield, Lepsien, Gitelman, Mesulam, & Nobre, 2006). Thus, expertise is likely to facilitate sustained attention, reduce distractibility, and promote many, if not all elements of flow. This also implies that the relation between expertise and flow might depend on whether task difficulty is predetermined or set by the performer. If difficulty is fixed, a certain optimal level of expertise is necessary for challenge-skill balance; if it is variable, higher levels of expertise (paired with greater challenge) should increase the probability for flow. This, however, remains to be tested empirically.

This article introduces the notion that flow is the subjective experience of an interaction between positive valence and high attention during performance of a nontrivial task whose difficulty is on par with the skill level of the subject, which is facilitated by a certain level of expertise. If this is indeed the case, we would expect to see the same physiological response to flow as predicted by these cognitive states, thus enabling us to deduce a hypothesis about flow and physiology. It is well recognized that mental and emotional activity can alter function within the autonomic nervous system. The next two sections will focus on how emotion and attention, in particular, manifest themselves in three of the more common physiological measures: cardiovascular function, respiration and electromyography (EMG), which were used in the empirical study on flow during piano playing, described later in this article. Unfortunately, previous research on how expertise may modulate physiological measures is largely lacking and is therefore left out of the following discussion.

When in flow, awareness is limited to the performed task, which implies a high degree of selective attention. *Mental effort* is a term commonly used within psychophysiology to study aspects of selective attention and attentional load. It is not known how mental effort relates to the effortless attention experienced when in flow (Bruya, in press), but both states are nonetheless defined by high levels of concentration. The literature on mental effort might therefore give a clue about the physiology of flow, as well as providing the theoretical means for testing *how* they potentially differ.

Mental effort is related to changes in cardiovascular state, respiration, and EMG: Facial muscle activity increases in the corrugator supercilii (CS); that is, the "frown-muscle" (Cohen, Davidson, Senulis, Saron, & Weisman, 1992; Waterink & van Boxtel, 1994); respiration is typically fast and shallow with an increased minute volume (Backs & Seljos, 1994; Veltman & Gaillard, 1998; Wientjes, 1992); cardiovascular measures generally show increased heart rate/decreased heart period (HP) and increased systolic blood pressure (systolic BP), together with a decreased variability in these measures (HRV and BPV, respectively; Berntson, Cacioppo, & Quigley, 1993; Middleton, Sharma, Agouzoul, Sahakian, & Robbins, 1999; Porges & Byrne, 1992; Richter, Friedrich, & Gendolla, 2008; Veltman & Gaillard, 1996, 1998). These observations unanimously point to an increased activation of the sympathetic branch of the autonomic nervous system. However, it should be noted that during working memory- and attention-demanding tasks, better performance is associated with relatively greater—that is, less suppressed – HRV related to vagal influence, that is, the parasympathetic component of the HRV spectrum (the high-frequency component, often termed respiratory sinus arrhythmia or RSA; Hansen, Johnsen, & Thayer, 2003).

Ekman, Levenson, and Friesen (1983) showed that the autonomic nervous system generates emotion-specific activity. However, the specific relationship between experienced emotion and different physiological measures have been found to vary across experimental settings (Mauss & Robinson, 2009). Although it is not clear to what extent this can be attributed to methodological issues, it makes it difficult to associate a certain emotion with a corresponding physiological response and generalize this across contexts. In the study featured later in this article, participants experienced emotion during musical performance. Unfortunately, there are very few studies on emotion-related changes in physiology in this particular context (Nakahara, Furuya, Obata, Masuko, & Kinoshita, 2009). Therefore, we choose to also reference studies from neighboring contexts, primarily music listening, in order to suggest a relationship between emotional aspects of flow and physiology.

In the above quoted study by Ekman, Levenson, and Friesen (1983), as well as in other studies since (e.g., Ravaja, Saari, Laarni, & Kallinen, 2006; Witvliet & Vrana, 1995), EMG has been successfully employed to differentiate between emotional states. Two commonly probed muscles in this context are the CS, mentioned previously, and the zygomaticus major (ZM), that is, the "smile-muscle." Positive affect and negative affect have reciprocal effects on activity over CS, such that negative effect will increase and positive affect will decrease activation. Activity in the ZM increases with positive affect (Larsen, Norris, & Cacioppo, 2003). In relation to music listening, happy music has been found to increase ZM activity (Lundqvist, Carlsson, Hilmersson, & Juslin, 2009). Activity in these muscles is also affected by arousal: CS activity is, thus, highest during negatively valent low-arousal states, while ZM activity is greatest during positive, high-arousal, joyous states (Witvliet & Vrana, 1995). In the previously mentioned master's thesis by Kivikangas (2006), CS activity was found—as the only significant correlate—to be inversely related to reported *flow* during playing of computer games. Regarding respiratory measures, excited and aroused states are typically associated with rapid deep breathing with a high inspiratory flow rate (Wientjes, 1992). Blood & Zatorre (2001) found respiratory depth to be increased during the experience of pleasurable "chills" while listening to music. Other studies on music listening have, however, failed to replicate this result (Etzel, Johnsen, Dickerson, Tranel & Adolphs, 2006; Gomez & Danauser, 2004, 2007; Krumhansl, 1997), possibly because the induced experience was less intense. These studies instead show time domain related measures—such as respiratory rate—to be more sensitive. It could be that in the musical context, joyous experiences are related to increased ventilation, which may be associated to changes in *either* rate or depth or both simultaneously. Cardiovascular measures, too, demonstrate emotion-specific autonomic activation: High-arousal is, from a physiological perspective, typically associated with decreased HP and increased systolic BP (Ekman et al., 1983; Schwartz, Weinberger, & Singer, 1981; Sinha, Lovallo, & Parsons, 1992; Witvliet & Vrana, 1995). Again, comparably higher task related RSA has been associated with better performance, here in terms of improved self-regulation of cognitive and emotional processes (Butler, Wilhelm, & Gross, 2006; Porges, 1992; Segerstrom & Nes, 2007; Thayer & Lane, 2000). For some contexts, however, including music listening, cardiovascular measures are less sensitive when it comes to differentiating between different emotions (e.g., Etzel et al., 2006; Krumhansl, 1997). In the one study that already exists on relations between cardiac activity and emotional state during musical perception and performance in pianists, expressive perception and performance of music produced higher heart rate than nonexpressive conditions. There was a stronger emotion-induced sympathetic facilitation and decreased RSA during musical performance than during perception. Additionally, heart rate for the expressive performance commonly peaked during the period of the reported highest pleasant feeling.

From the literature reviewed in previous sections, it can be concluded that high attention and joyous states have both compatible (e.g., sympaticus activation) and incompatible physiological correlates (e.g., respiratory depth), which allows us to formulate a hypothesis about the *unique* physiology of flow: First, an increase in flow should be associated with: (i) decreased heart period; (ii) increased cardiac output (decreased HP and increased BP); and (iii) increased respiratory rate, which signify both increased attention and arousal. Second, flow could be associated with an (iv) increased respiratory depth; (v) increased activity in the ZM; and (vi) decreased activity in the CS and (vii) increased RSA. This second set of effects are usually not seen during a state of cognitive and physical load but could if present reflect the positive affect, effortless attention, and coping typically experienced during flow.

In this experiment, playing a musical instrument (piano) was chosen as experimental task. Flow is not uncommon during musical experience (Csikszentmihalyi & Csikszentmihalyi, 1992) and playing an instrument, in particular, is a task with interesting properties in relation to the elements of flow. The performer is generally free to choose a piece that matches his or her skill level and goals; feedback is instantaneous and continuous; a smooth performance critically depends on a certain degree of action-awareness merging, attention/concentration, and control; the focused mindset can shut out self-reflective thoughts; the sense of time is sometimes distorted; and a successful performance is highly enjoyable. This suggests that piano playing is an example of what could be called a *flow-inducing* task; that is, a task that not only satisfies all basic requirements for enabling a high level of flow but induces a state of mind characterized by high concentration and high valence/arousal, which promotes optimal experience. Playing an instrument might thus be particularly well suited as an experimental task to study flow. In order to minimize variability in other variables that could influence physiology, variations in flow and physiology were studied while the same, well-learned musical piece was played repeatedly across five trials. In particular, this controls for essentially all sensorimotor processing and physical effort. Flow was measured after each trial using self-reports and then compared to physiological measures obtained during each trial.

Methods

Participants

Since expertise will, at least theoretically, increase the probability for achieving flow during piano playing, a group of experts was chosen to perform the experimental task: Twenty-one professionally active classical pianists, including three students from the Royal Academy of Music in Stockholm, were recruited from the Stockholm region, (18 male; $M = 41 \pm 11$ years old) and volunteered to participate in the study. This can be regarded as a representative sample of the target population. In total, 33 individuals were contacted, which represents the majority of active solo concert pianists within the Stockholm region. Eight could not find the time to participate; four did not want to participate. All experimental procedures were ethically approved by the Karolinska Hospital Ethical Committee (Dnr: 2007/83–/32), undertaken with the understanding and written consent of each participant, and conformed to "The Code of Ethics of the World Medical Association" (Declaration of Helsinki).

Experimental Task

Participants were asked to select and bring a piece for piano (either a complete piece or a complete movement of a larger cycle) of their own preference, which they could play well, enjoyed playing, and that would correspond to a 3–7 min performance. This length of the piece was chosen for practical reasons: It would allow the performance of a complete piece or movement, while restricting the duration of each session to 1.5–2 hours in total. The nature of the experiment was made explicit during recruitment, with the intention to make participants choose music that would maximize the probability that at least some trials would be accompanied by a high level of flow.

Measures and Instruments

Musical instrument. The participants played a conventional upright piano (Yamaha, Silent piano). This piano carries an extra device that records keystrokes and generates a MIDI-signal. The MIDI signal was recorded but not used in the subsequent analysis.

Physiological measures. Because this experiment was designed to measure differences in state *flow*, it was considered important not to use invasive equipment. The chosen setup thus results from a trade-off between sensitivity and practical requirements. All physiological data were recorded at a sample rate of 1000Hz using an 8 channel/16 bit, PowerLab™ DAQ and prepared for statistical analysis using the Chart 5 Pro software (ADInstruments). All analyses were made offline.

Muscle tone of the CS and ZM muscles was recorded using Ag/AgCl surface electrodes (AMBU® Blue Sensor) attached to muscle sites on the left side of the face. The participant's skin was prepared with a low-alcohol detergent to minimize impedance. The raw EMG signal was amplified (ML135 Dual Bio Amp, ADInstruments) and filtered, using a notchfilter of 50Hz and bandpass filter removing frequencies below 20Hz and above 400Hz.

Head movements were recorded for two reasons: to allow for crosschecking in regard to potential movement artifacts in other physiological measures and to explore a potential association between head movement pattern and flow. Head movements were registered using a 3-axis accelerometer with a range of $\pm$ 19.6 m/s^2 and a sensitivity of 30.6 $mV/(m/s^2)$ (ACA302, Star Micronics America, Inc) fitted to a headband.

Thoracic respiration was measured using a piezo-electric respiratory belt transducer with an output range of 20–400 mV and a sensitivity of 4.5 ± 1 mV/mm (MLT1133, ADInstruments). The belt was attached around the chest below the nipple line (or below the breast for women).

Heart period and blood pressure measurements were based on arterial pulse pressure acquired with an IR plethysmograph (MLT1020EC, ADInstruments) attached to the right ear. Other methods are generally preferred when obtaining BP data (Shapiro et al., 1996), but studies have shown photoplethysmography to be an adequate instrument for measuring BP in cardiologically healthy subjects (Allen, 2007; Awad et al., 2001; Shelley, 2007). The full-width-at-half-maximum (FWHM) of the pulse pressure waveform shows strong correlations with invasive measures of BP and cardiac output (Awad et al., 2007; Awad et al., 2006), particularly when obtained from the ear, as this measurement site is relatively immune to vasoconstrictive challenges (Awad et al., 2001). In addition to HP and BP, we explored the possibility of acquiring HRV related measures using the plethysmograph. This has been accomplished in other settings (Lu et al., 2008; Middleton et al., 1999), but caution must be taken because the validity of these measures can decrease with an increased mental effort (Giardino, Lehrer, & Edelberg, 2002), which could be problematic given such a complex and demanding task as piano playing. HRV was primarily calculated to potentially strengthen the ability to interpret HP and BP. In order to minimize artifacts and confounding respiratory influence on cardiac measures, the plethysmographic waveform was band-pass filtered. Since the data would not be pooled across participants in the later statistical analysis, band-pass filters could be created and optimized for each individual separately: (i) A preliminary filter (0.5–3.5Hz) was first applied, then (ii) the minimum and maximum heart period for the individual across trials were obtained, based on which (iii) a new band-pass filter could be created. Steps two and three were iterated until a stable solution was reached, meaning that an optimized filter had been found based on the minimum and maximum heart period across trials for that participant.

Trial duration was measured to indicate speed of motor output; a variable that could potentially confound the relation between flow and physiology.

Flow questionnaire. The participants' level of flow was estimated using a subset of the Flow State Scale, which has been shown to be a reliable and valid measure of the flow construct (Jackson & Eklund, 2004). Items in this self-report questionnaire are formulated as propositions about the trial experience, with which the respondent will agree or disagree, answering on a Likert-scale. Nine items were selected from the original questionnaire to probe each dimension. Those items were chosen that according to the test manual (Jackson & Eklund, 2004) load most on each flow dimension respectively. Answers were given on a 9-step scale, from *strongly disagree* (1) to *strongly agree* (9).

Procedure

All experiments were carried out individually, during a single session, at the Swedish School of Sports and Health Sciences in Stockholm. The experimenter would begin the session with describing the procedure to the participant, who then gave informed consent. The participant was seated in front of the piano and prepared with the equipment for data acquisition. A warm-up period was given until the subject felt comfortable (typically 15–20 min), and appropriate technical adjustments had been made. The participant was then asked to perform the musical piece, during which the physiological data were recorded. After the trial, the experimenter would administer the flow-questions in randomized order and record the answers manually. The participants had 1–2 min to relax between trials while data were being stored and preparations for the subsequent trial were being made. This procedure was repeated over five trials to study variations in flow and their physiological correlates, keeping sensory input, motor output, emotional content of music, and other possibly confounding variables constant. It was therefore assumed that the direction of association between flow and physiological variables would be the same independent of the average emotional and physiological state, which could for instance depend on emotional tone in the chosen piece of music.

Data Analysis

All data were stored on disk after each trial and then analyzed off-line. One participant was excluded from analysis of physiological measurements due to technical problems during data collection. Other issues (e.g., facial hair in the case of ZM EMG, or a vigorous playing style, which gave recording artifacts) prevented the complete dataset to be used for every measurement (see Results section).

All measures were averaged over each trial for each participant. EMG was measured over the ZM and CS muscles as the root-mean-square (mV) of obtained activity. In the case of head movements, three measures were computed: movement amplitude (mV), based on the sum of amplitudes in three spatial dimensions; frequency (Hz), averaged over three spatial dimensions; and root-mean-square (mV), summed over three spatial dimensions. Three measures were obtained for respiration: respiratory rate (RR; bpm), respiratory depth (RD; V), and respiratory cycle duration (Rcycle; s). The Chart 5 HRV module was used to detect R-R intervals based on waveform peaks in the pulse signal and compute N-N intervals, upon which subsequent analysis was performed. Drop beats and N-N intervals deviating more than three standard deviations from the mean interval were excluded and replaced with values calculated by linear interpolation between adjacent normal N-N intervals, using a custom made script in MATLAB. Heart period (ms) was based on mean N-N across each trial. A spectral analysis, using a Fast Fourier transform (size 1024; Welch window; [1/2] overlap), was performed to divide the HRV power spectrum into two frequency bands and obtain power within each band: LF, 0.04–0.15 Hz (ms^2), and HF, 0.15–0.5 Hz (ms^2). Power was corrected for HP by dividing the square root of the power value with the mean N-N. HF was corrected for RR and RD as is commonly recommended (Berntson et al., 1997; Grossman & Taylor, 2007), by performing a multiple regression (within participant) to obtain the residual HF, which was then used as a measure of RSA. Total power and LF/HF ratio were also analyzed. The Chart 5 blood pressure module was used to attain measures of minimum (MinP), maximum (MaxP), and range (MaxP-MinP) of pulse wave amplitude (V). Full-width-half-maximum (FWHM; ms) was calculated through the use of a custom made script in MATLAB. A similar script was also used to remove and replace BP related values beyond three standard deviations from the mean with values based on linear interpolation between adjacent normal values. Trial duration (s) was measured as the time interval between the first and the last keystroke of the performance. Flow was operationalized as the average self-reported magnitude across the nine dimensions (*Flow9D*). Based on the theoretical background presented in the introduction, an additional measure was created (*Flow3D*) combining the average response on the dimensions Challenge-Skill Balance, Concentration, and Autotelic—the three dimensions that arguably corresponds most directly to (task) expertise, attention, and emotional experience, respectively.

Three important points had to be taken into consideration when choosing the proper test for statistical analysis: First, the baselines for rated flow and physiological response might differ between individuals, which means that it would be wrong to simply pool data across individuals. Instead, a second level analysis would be required, evaluating the association between flow and physiology first within and then between subjects. Second, the number of trials and sample size were fairly small. Third, even though responses on the flow state scale are based on a Likert-scale and such responses are by convention thought to fall on an interval scale, there are in this case no empirical observations that can confirm this, which means that it can only be correct to assume an ordinal scale. Together, these points rule out the use of a parametric test. The Page Test for Ordered Alternatives, however, does accommodate all these points by testing if the rank order of measures (Φ_1, $\Phi_2, \ldots, \Phi_k$) of a dependent variable matches the rank order of measures of an independent variable (Siegel & Castellan Jr., 1988). The null hypothesis can thus be stated as:

$$H_0\colon \Phi_1 = \Phi_2 = \ldots \Phi_k,$$

and the alternative hypothesis:

$$H_1\colon \Phi_1 \leq \Phi_2 \leq \ldots \Phi_k,$$

where the difference between at least two measurements is a strict inequality ($<$).

Hence, if the null hypothesis is rejected, there is an association between the two variables in the prespecified direction. This nonparametric test allows for a mixed effects analysis in which relative flow is first compared to physiology within participant across trials before checking if a potential relationship holds across participants; rank orders are pooled instead of raw data, thus avoiding the problem of individual baselines (Siegel & Castellan Jr., 1988). The statistical test and analysis were implemented and performed in the MATLAB environment. Rank orders for each subject were computed based on absolute physiological values during piano playing. This was considered preferable in relation to using change scores from periods before each trial because such baseline measurements would be dependent on the previous active condition, given the short intertrial period.

Results

Behavioral Data

Means and standard deviations (SDs) for the dimensions in the flow-questionnaire (based on means and SDs for each participant) are presented in Table 1. The flow response averaged across all flow dimensions is high with relatively little variation across trials; for example, the *B* dimension showed zero variation across 16 of the 21 participants. A majority of the participants gave verbal reports on that the dimensions *B* and *F* were difficult to estimate within the given context. However, the three-dimensional measure showed greater variation, indicating that attention and enjoyment varied across trials even though skill, difficulty, and task prerequisites were largely constant. Figure 2A and 2B illustrate how *Flow9D* and *Flow3D* vary from Trial 1 to Trial 5. According to *Flow9D*, the first trial produced significantly less flow than Trial 2, 3, and 5; *Flow3D* displays that the first trial was significantly lower on rated flow than all other trials.

Flow and Physiology

Using the Page test, the relative magnitude of *Flow9D* and *Flow3D* across trials were compared to the relative magnitude of corresponding physiological measures for each participant and then pooled across participants. Significant results (and strong trends) are presented in Table 2. Both *Flow9D* and *Flow3D* are significantly associated with more than one physiological measure. The following findings support the previously stated hypotheses: decreased heart period (*Flow9D*: $z_L = 1.90$, $p < .05$; *Flow3D*: $z_L = 2.75$, $p < .01$), increased activity in ZM (*Flow9D*: $z_L = 6.02$, $p < .001$; *Flow3D*: $z_L = 4.57$, $p < .001$), and increased respiratory depth (*Flow9D*: $z_L = 2.33$, $p < .01$; *Flow3D*: $z_L = 2.38$, $p < .01$). No effect was found for CS activity or respiratory rate. Contrary to the stated hypotheses, flow was associated with a reduction in RSA (*Flow9D*: $z_L = 2.35$, $p < .01$; *Flow3D*: $z_L = 1.65$, $p < .01$) and *Flow3D* indicated a reduction in cardiac output: decreased FWHM (*Flow3D*: $z_L = 2.25$, $p < .01$), decreased MaxP (*Flow3D*: $z_L = 2.48$, $p < .01$), increased MinP (*Flow3D*: $z_L = 2.48$, $p < .01$), and decreased MaxP-MinP (*Flow3D*: $z_L = 2.84$, $p < .01$). For illustrative purpose, means and standard errors of variables significantly associated with *Flow3D* are displayed in Figure 3. Trials are sorted according to the level of flow experienced (1 = *lowest* to 5 = *highest*).

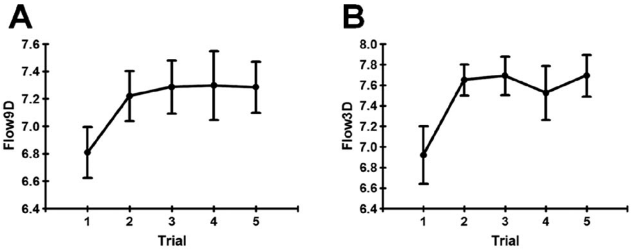

Figure 2. A. *Flow9D* – means and standard errors across Trials 1–5. B. *Flow3D* – means and standard errors across Trials 1–5.

Discussion

Flow and Physiology

EMG, cardiovascular, and respiratory measures were all significantly associated with self-reported flow. Both flow measures show increased flow to be related to decreased HP and RSA, increased LF/HF ratio, total power, and RD. This suggests that during a physically and cognitively demanding task, an increased activation of the sympathetic branch of the autonomic nervous system in combination with deep breathing and activation of the ZM might potentially be used as an indicator of effortless attention and flow.

The three dimensional flow-measure appeared more sensitive to blood pressure related measures than was the full flow composite score, in which these effects were likely attenuated by flow dimensions not displaying much variation (see Table 1). Decreased cardiac output together with a decreased heart period can be observed during rapid shallow breathing (tachypnea), but in this case RD increases, which normally leads to an increase in cardiac output. This seemingly strange result could possibly be explained by how respiration interacts with the experimental task: Respiratory rate has more degrees of freedom than respiratory depth to vary independently of metabolic and other factors, along dimensions that are associated with psychological and behavioral influences (Wientjes, Grossman, & Gaillard, 1998). The respiration cycle has accordingly been shown to be influenced by musical

Table 1
Mean and Standard Deviation for Each Flow Dimension, Flow9D, and Flow3D

N = 21	*B*	*M*	*G*	*F*	*Cc*	*Ct*	*Cs*	*T*	*A*	*Flow9D*	*Flow3D*
M	8.10	7.28	7.38	7.90	6.97	7.13	7.89	6.10	6.78	7.28	7.28
SD	0.18	1.01	0.78	0.65	1.22	1.01	0.72	1.13	1.18	0.33	1.44

Note. *B* = Challenge-skill balance; *M* = Action-awareness merging; *G* = Goals; *F* = Feedback; *Cc* = Concentration; *Ct* = Control; *Cs* = Consciousness; *T* = Time; *A* = Autotelic; *Flow9D* = a composite score of the nine dimensions; *Flow3D* = a composite score of dimensions *B; Cc* and *A*.

Table 2
Page Test Results: Physiological Measures vs. Flow Measures

		z_L	
Variable	*N*	*Flow9D*	*Flow3D*
EMG ZM	15	6.02^{***}	4.57^{***}
EMG CS	17	0.82	0.24
HP	19	1.90^{a*}	2.75^{a**}
FWHM	19	1.17^{a}	2.25^{a**}
MinP	19	1.58^{+}	2.89^{**}
MaxP	19	0.94^{a}	2.48^{a**}
MaxP-MinP	19	1.17^{a}	2.84^{a**}
RSA	17	2.35^{a**}	1.65^{a*}
LF/HF	19	1.67^{*}	1.79^{*}
Total power	19	2.32^{**}	2.29^{**}
RD	18	2.33^{**}	2.38^{**}
RR	18	0.33^{a}	1.34
Rcycle	18	0.38	0.82
Head Amp	14	0.69	1.07
Head Fq	14	0.59	0.37
Head RMS	14	0.27^{a}	0.86
Trial duration	21	0.70	0.26

Note. *N* = number of participants; z_L = page test statistic; EMG ZM = zygomaticus major activation; EMG CS = corrugator supercilii; H*p* = heart period; FWHM = full-width-half-maximum of the arterial pulse pressure waveform; MinP = minimum estimated blood pressure; MaxP = maximum estimated blood pressure; MaxP-MinP = estimated pulse pressure; RSA = respiratory sinus arrhythmia; LF/HF = low frequency heart rate variability/high frequency heart rate variability; Total power = total heart rate variability; RD = respiratory depth; RR = respiratory rate; Rcycle = respiratory cycle duration; Head Amp = head movement amplitude; Head Fq = head movement frequency; Head RMS = head movement root-mean-square.
$^{+}$ Trend at $p \leq .06$; $^{*}p \leq .05$; $^{**}p \leq .01$; $^{***}p \leq .001$.
^{a} Signifies an inverse relationship between flow measure and physiological measure.

tempo (Gomez & Danuser, 2007), and this effect appears to be particularly prominent in musicians (Bernardi, Porta, & Sleight, 2006) This provides a plausible explanation for why RD and *not* RR or Rcycle differed at different levels of flow or concentration. Deep breathing increases the efficiency of oxygenation: During inhalation, the oxygen in the lungs has maximum access to deoxygenated blood; during exhalation, which has a longer duration than during shallow breathing, the HR decreases and the heart is allowed to relax. Consequently, it may be that while respiratory rate was entrained to the musical performance, respiratory depth was increased to meet metabolic demands, without necessarily producing an increase in cardiac output. However, this does not explain why RSA changes were not in the expected direction. It could be that the parasympathetic effect on RSA was overridden by the arousal/sympathetic stimulation. Still, without the deep breathing, the decrease in RSA would have been even more pronounced and the magnitude of change between trials ranked according to experienced flow is actually very small (see Figure 2). This indicates that flow might in fact be associated with an increased parasympathetic modulation of sympathetic activity. Nonreciprocal coactivation of the sympathetic and parasympathetic systems has been observed in relation to critical events that induce high workload and require active coping (Backs, Lenneman, & Sicard, 1999). Berntson, Cacioppo, and Quigley (1991) suggested that coactivation provides precise control of both the response direction and magnitude, as well as fine tuning of target organ function. It might therefore be interesting to consider flow as a feedback reward signal, which signifies optimal coping. This would also explain why flow is associated with high performance levels. It is interesting to note that a concomitant increase in parasympathetic tone to counter sympathetic activation has also been found to occur during attention demanding meditative states that are characterized by a combination of restfulness and heightened concentration (see, e.g., Ditto, Eclache & Goldman, 2006; Kubota et al., 2001).

Flow was, as predicted, associated with ZM activity, but no effect was found for CS. The latter null-result could be due to the fact that flow was generally rated high, which means that there was little negative affect that could be reflected in CS activity.

Experimental Design and Operationalization of Flow

The integrity and interpretation of the results greatly depend on how potential confounds were controlled, such as flow-unrelated physiological response to physical and mental effort and emotional content of music (Gomez & Danuser, 2004, 2007). Through the use of a design by which the same musical piece was played and then repeated, sensorimotor processing and physical output were essentially identical throughout each session. This notion is supported by the fact that neither the duration of the trial nor head movements showed a significant difference across trials, in relation to flow, or to any other physiological variable. It is important to note that no attempt was made to identify *why* flow varied across trials. The flow state scale (Jackson & Eklund, 2004) was designed to measure dimensions relevant to flow across different tasks and contexts. In other words, the dimensions are higher order/intermediate constructs that capture how various more specific contextual factors affect flow. In the current experiment, several factors, such as habituation to experimental equipment, fatigue, and possibly quite a number of other variables not directly measured by the flow state items, could still have affected how these items were answered (e.g., why concentration shifted from trial to trial). In other words, it is possible that such factors had an effect on physiology independently of flow, but it is also likely that these variables affected physiology through their effects on flow. There was no possibility to disentangle such relationships in this first study on flow physiology.

The nine-dimensional operationalization of flow did not show much variance during the experiment. Only a small subset of the questions in the original flow-state questionnaire was used, but adding more questions to each dimension is not likely to have produced different results since correlations between different items tapping the same flow dimension in this test are extremely high (Jackson & Eklund, 2004). A more plausible explanation is that *Flow9D* is less sensitive in situations where the task properties cause magnitude of one or more dimensions to remain constant. Here, participants were told to bring a piece of music that they knew well and enjoyed playing and then reproduce it five times. This paradigm gives little variation in elements depending more on variability in external conditions, such as Feedback. This observation could be important with regard to future studies: The constituents of flow are a mix of different types of preconditions, some that are directly affected by task requirements, others that appear more dependent on cognitive and physiological factors

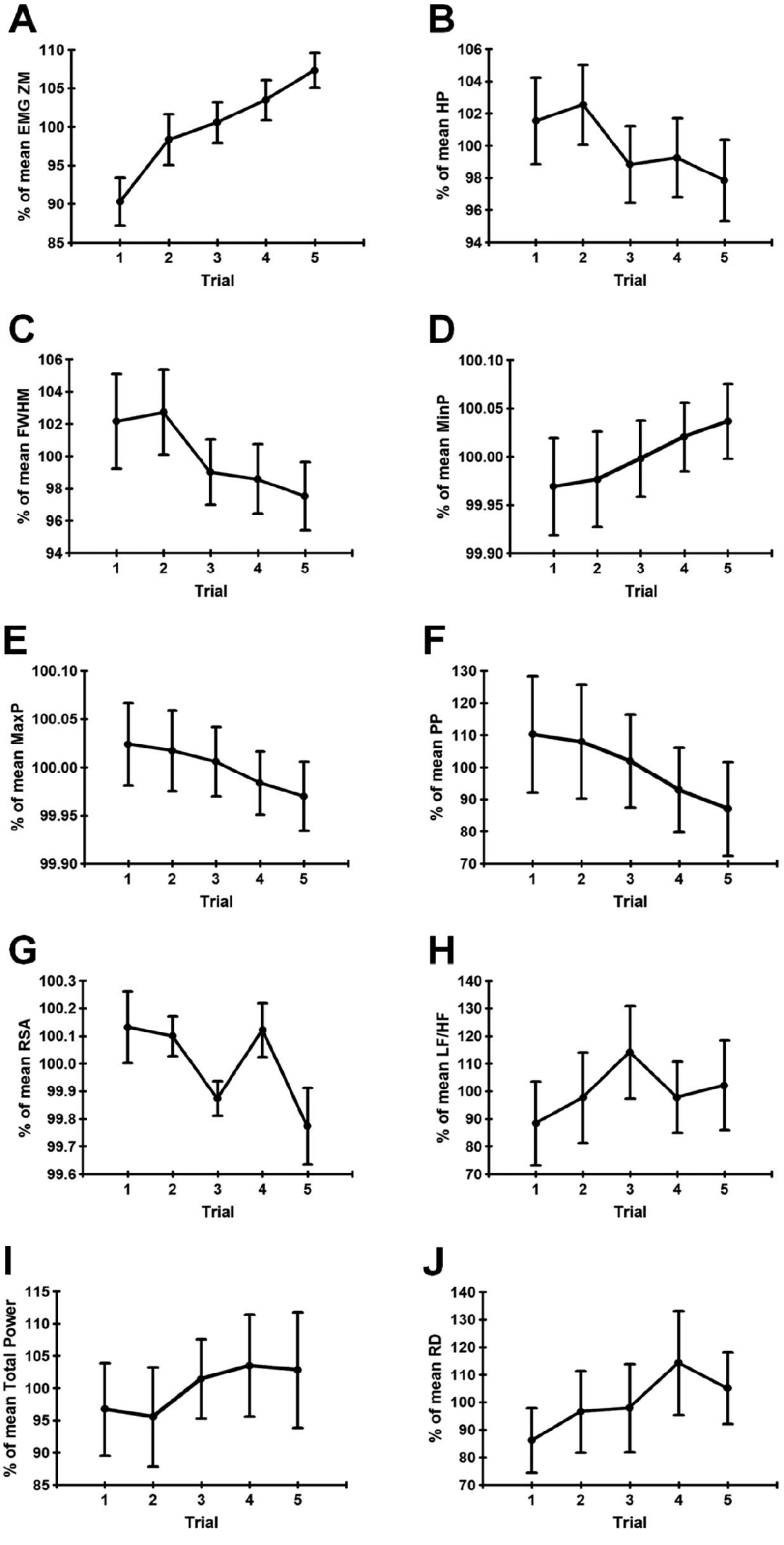

Figure 3. A–J. Physiological measures–means and standard errors across trials, sorted according to the level of flow experienced during each trial.

and/or other elements, some that are highly intercorrelated, and others that are not (Jackson & Eklund, 2004). It can, for instance, be discussed if, for example, Feedback should be regarded as part of the actual flow *experience* or rather as a perceived external prerequisite for attaining it. Suffice to say, some of the dimensions will presumably correspond more directly to biological processes than others.

In this article, we forward the hypothesis that flow is experienced during task performance as a result of an interaction between emotional and attentional systems, that is, both cognitive and physiological processes, enabled by a certain level of expertise. In line with this proposal, the two dimensions displaying the greatest variance during the experiment, when skill and task were held constant, were Concentration and Autotelic, which arguably are the dimensions corresponding most directly to attention and emotional state. The three dimensional flow measure, made up of Challenge-skill balance, Concentration, and Autotelic, did well in matching the outcome of *Flow9D* and even proved more sensitive to BP measures than did the full composite measure. Hence, when it comes to finding biological correlates of the flow experience, it might be fruitful to refine the operationalization of flow by identifying and separating factors, on the one hand relating to neurophysiological entities and on the other relating to environmental entities creating context and prerequisites for the previous. This was, however, considered to be beyond the scope of this study. Moreover, investigating individual flow dimensions in relation to physiological variables would have increased the risk of statistical error.

Limitations

This first study on flow and physiology shows results that motivate further investigations on the subject. There are, however, limitations that may have had an effect on the outcome of this particular experiment.

Though constituting a greater part of the target population, the number of participants was relatively modest, and in addition, technical difficulties prevented the full sample to be used in all analyses. A greater number of participants could possibly have increased the chance of finding BP correlates with the *Flow9D* measure, but this could only have been achieved by relaxing the inclusion criteria regarding piano expertise.

There was a restriction of range in the self-reports, which means that the observed physiological response was associated with an increase from high to even higher flow. This is not surprising given the experimental design and the measures taken to control possible confounds. It was a correct prediction that the first trial be associated with the least reported magnitude of flow; however, after the first trial flow increased significantly and remained high; that is, five trials were not enough to induce boredom. An additional note is that considering the amount of practice and repetitive training this particular group of experts typically endure (Bengtsson et al., 2005; Krampe & Ericsson, 1996), increasing the amount of trials might not be a practical way of inducing a greater variation in flow.

Plethysmography is less than optimal for BP and HRV measurements in general and during physically active states in particular, which means that related results must be viewed with some caution. The method was chosen primarily to assess heart period, for which it proved successful. Though plethysmography has been used successfully for both BP and HRV measurements (see Methods section) and there is no immediate reason to question the results presented in this article, subsequent studies might revert to more traditional measures of cardiovascular function in order to obtain more sensitive measurements (Berntson et al., 1997; Shapiro et al., 1996).

Only thoracic respiration was measured. Ideally, two respiratory belts should be used in order to also assess abdominal breathing (Wientjes, 1992). Still, the one respiratory belt was sufficient to observe a significant effect in relation to increased flow.

It would have been interesting to assess emotional experience of the pianists in terms of valence and arousal in order to investigate how flow varied along these dimensions and thus support the theoretical claim made in the introduction that flow be linked to joyous states. The generally high level of the *A* dimension nonetheless indicates that the participants agreed to some extent that the active conditions were "extremely rewarding" (quotation from the corresponding questionnaire item). The association between psychophysiological measures and flow clearly confirms that the experience is linked to an increase in arousal, at least in the context of piano playing.

Future Directions

Intuitively, too little or too much arousal in relation to task difficulty should decrease flow. One might speculate that this is reflected in the Challenge-skill balance dimension, and that arousal, thus, is related to optimal performance and flow as predicted by an inverted U-shaped relationship, as according to the (much debated) Yerkes-Dodson law (Hanoch & Vitouch, 2004). A detailed description of the link between subjective flow, objective measures of performance and arousal is absolutely necessary to the understanding of flow and its biological correlates.

Mentioned only in brief during the introduction is the fact that flow is linked to perceived quality of life, which is turn is positively related to measures of general health (Csikszentmihalyi, 1990). Given that this article demonstrates flow to have physiological effects, it should be possible to investigate the biological basis of this association: Flow is characterized by positive affect, the feeling of control, active coping, and, often, physical activation. All these concepts have all been found to relate positively to health (for a review see Pressman & Cohen, 2005). The mechanisms underlying these effects are still not entirely clear, but several studies have shown mood states and physical activity to be associated with immune function, mediated in part by the autonomic nervous system (McCraty, Atkinson, Rein, & Watkins, 1996; McCraty, Atkinson, Tiller, Rein, & Watkins, 1995). An interesting hypothesis is that a flow-inducing task could promote such positive effects by improving mood, perhaps irrespective of affective trait. Desirable events have been shown to yield positive effects with regard to immune function by decreasing negative mood (Stone, Marco, Cruise, Cox, & Neale, 1996). A positive mood will also help an individual to believe in his or her ability to carry out health-promoting behaviors (Salovey, Rothman, Detweiler, & Steward, 2000). Flow-inducing tasks could thus be very important in relation to therapy and (re-)habilitation, which deserves to be investigated.

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