Peripheral-physiological and neural correlates of flow experience while playing video games: A comprehensive review

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The flow state is defined by intense involvement in an activity with high degrees of concentration and focused attention, and accompanied by a sense of pleasure. Video games are effective tools for inducing flow, and keeping players in this state is considered to be one of the central goals of game design. Many studies have focused on the underlying physiological and neural mechanisms of flow. Results are inconsistent when describing a unified mechanism underling this mental state. This paper provides a comprehensive review of the physiological and neural correlates of flow and offers an explanation of the relationship between the reported physiological and the neural markers of flow experience. Despite the heterogeneous results, it seems possible to establish associations between reported markers and cognitive and experiential aspects of flow, particularly regarding arousal, attention control, reward processing, automaticity, and self-referential processing.

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Abstract

The flow state is defined by intense involvement in an activity with high degrees of concentration and focused attention, and accompanied by a sense of pleasure. Video games are effective tools for inducing flow, and keeping players in this state is considered to be one of the central goals of game design. Many studies have focused on the underlying physiological and neural mechanisms of flow. Results are inconsistent when describing a unified mechanism underling this mental state. This paper provides a comprehensive review of the physiological and neural correlates of flow and offers an explanation of the relationship between the reported physiological and the neural markers of flow experience. Despite the heterogeneous results, it seems possible to establish associations between reported markers and cognitive and experiential aspects of flow, particularly regarding arousal, attention control, reward processing, automaticity, and self-referential processing.

Introduction

What makes everyday experiences genuinely satisfying? Why do we seek activities that make us happy? Csikszentmihalyi (1975) introduced the concept of “flow” or “being in the zone” as an optimal state in which complete absorption in an activity is reached and is accompanied by a sense of enjoyment stemming from intrinsic motivation for that activity. During this state, termed processing fluency, i.e. the ease with which information is processed, actions seem to happen effortlessly, fluently, and almost automatically. According to this theory, the clearest sign of flow is the merging of action and awareness in a way that “a person in flow is aware of his actions but not of the awareness itself” (Csikszentmihalyi, 1975, pp 38).Paradigmatic examples of flow-inducing activities include the artist who is completely immersed in the activity of creating a work of art or playing an instrument and the athlete or game player who follows clear goals and perceives a match between demands and skills. The following factors enable the flow experience, which in combination create a deep sense of enjoyment (Csikszentmihalyi, 1975, 1990; Jackson & Eklund, 2004): 1) The balance between the level of skill and the challenges of the task, 2) clear goals of the activity, 3) clear immediate feedback of action results, 4) merging of action and awareness, 5) high concentration, 6) sense of control over the activity, 7) loss of self-awareness, 8) loss of the sense of time, and 9) autotelic experience.

Among the nine key dimensions of flow, the first three (balance between skills and challenges, clear goals and immediate feedback) are antecedents or preconditions for flow, and the remaining six items as components or characteristics of this subjective state. Optimal skill-challenge balance is considered the main antecedent which facilitates entering in to the flow state (Csikszentmihalyi & Csikszentmihalyi, 1992; Engeser & Rheinberg, 2008; Fong, Zaleski, & Leach, 2015; Keller & Blomann, 2008). Whenever the challenge level of the activity outweighs the skill level of the person performing it, the person will become frustrated and anxious. In contrast, if the challenge level is lower than the skill level, the person will become bored (the flow channel model; Csikszentmihalyi, 1975, 1990). Although skill-challenge balance is a perquisite for the flow experience, one should consider that it does not guarantee entering into the flow state. Fong et al. (2015) showed that additional variables such as age, cultural characteristics, domain of application (leisure or work/education contexts), and methodology (how the skill-challenge balance has been evaluated) may distinctively influence the relationship between flow and skill-challenge balance. Engeser & Rheinberg (2008) showed that in important activities flow was still high even when the demand was low. The moderating impact of personality characteristics, such as action-state orientation, was investigated and it was revealed that individuals with a strong habitual action orientation are more sensitive to modulations of the skill-challenge balance (Keller & Bless, 2008). The likelihood of the ensuing flow experience can also be altered by personality factors. A study by Ullén and colleagues reported a negative correlation between flow proneness (understood as the individual propensity to experience flow) and neuroticism (Ullén et al., 2012). De Manzano et al. (2013) suggested that lower trait impulsivity could facilitate the propensity to experience flow. Flow and performance also seem to be closely related (Csikszentmihalyi, Abuhamdeh, & Nakamura, 2005; Engeser & Rheinberg, 2008; Jin, 2012; Keller & Bless, 2008; Landhäußer & Keller, 2012). High performance levels are typically expected during the experience of flow, since frustration and boredom would lead to diminished concentration and consequently to a poor performance. It is still unclear whether flow influences performance or vice versa (De Kock, 2014; Landhäußer & Keller, 2012). Engeser and Rheinberg (2008) found that the flow experience led to improved performance in participants who played the game *Pac-Man* at three difficulty levels, while Jin (2012) reported that successful performance resulted in a greater flow experience in participants who played the games *Call of Duty: world at war* and *Trauma Center: New Blood*.

The concept of flow was initially investigated using the Experience Sampling Method (ESM) in naturalistic contexts (Csikszentmihalyi & Csikszentmihalyi, 1992). This method involves signaling participants at random moments throughout the day and asking them questions about the nature and quality of their experience (Csikszentmihalyi & Larson, 1983). Later studies optimized the ESM and designed new questionnaires to evaluate the flow experience. Some of these are the Flow State Scale (FSS, Jackson & Marsh, 1996) specific for the context of sports, the Flow Short Scale (FKS, Rheinberg & Vollmeyer, 2003) developed for different fields of activity, the flow subscale of the game experience questionnaire (GEQ, IJsselsteijn, De Kort, Poels, Jurgelionis, & Bellotti, 2007) designed for evaluation of the subjective gaming experience, the virtual-course flow measure (Shin, 2006) developed for the context of online learning, the flow state scale for occupational tasks (Yoshida et al., 2013), and the work related flow inventory (WOLF, Bakker, 2008) specific aimed at measuring the flow of employees. However, assessment of the flow experience with these retrospective questionnaires interrupts the ongoing activity and probably disrupts the flow experience. Utilizing these self-reported post-task questionnaires cannot provide information about characteristics of this experience like mean duration or depth of flow either. Hence, it is very important to find non-disruptive objective measures to evaluate the flow experience continuously. One way to assess this experience without interrupting it is to find neural and electrophysiological correlates of this state, which in turn might help to better understand the underlying physiological mechanisms.

Considering the easy establishment of game-based, flow-inducing paradigms in the laboratory, video games are one of the best tools to elicit this experience. Games offer challenging tasks that require training skills and provide clear goals, as well as immediate feedback (Alvarez Igarzábal, 2019; Salen & Zimmerman, 2003). An important driver of enjoyment in games comes from *effectance motivation*, a term coined by Nacke (2012), which is the feeling of empowerment in players when they see the impact of their actions. This feeling of empowerment can be experienced when the game's challenge matches the player's skills and goals and immediate feedback is provided. Inducing flow states under controlled laboratory conditions has been considered difficult. The most popular experimental approach used for inducing flow is manipulating the difficulty level of games to achieve the necessary skill-challenge balance. This can be achieved either through the dynamic matching of the game's difficulty level to the player's skill level (Keller & Bless, 2008; Rheinberg & Vollmeyer, 2003) or by pre-testing the participants' skills to individually assign appropriate matching challenge levels in the game (Moller, Csikszentmihalyi, Nakamura, & Deci, 2007). This can in turn help to contrast three experimental conditions of easy, optimal, and overwhelming. Using a self-selected level of difficulty (autonomy) is also suggested to be an important determinant of flow (De Sampaio Barros et al., 2018; Moller, Meier, & Wall, 2010). Immersion – another mental state explored in some studies – was described as the gradual process of transporting the player's mind into the virtual world which is linked to factors like graphics, sound and gameplay (Nacke & Lindley, 2008, 2010). Despite similarities, immersion presents subtle structural differences from flow (Michailidis, Balaguer-Ballester, & He, 2018) and will not be explored in this review. Rheinberg and Vollmeyer (2003) evaluated the impact of modulating the task difficulty on flow experience in two different video games: *Roboguard* and *Pac-Man*. The highest level of flow was reported following those trials when the game's difficulty was set to a medium level (flow) rather than to a low (boredom) or high (anxiety) level. For the sake of consistency, given that different studies label conditions in different ways, in the following we will refer to the overwhelming and easy conditions as the "anxiety" and "boredom" respectively, and to the optimal condition as "flow."

The flow state is an experiential feature of altered states of consciousness which can lead to a diminished sense of self and time (Wittmann 2015, 2018). Video games specifically making time fly in a pleasant way which is one of the main aspects of the flow experience (Bisson, Tobin, & Grondin, 2012; Tobin, Bisson, & Grondin, 2010). Distortions in the notions of the self and time have been reported in many patient groups with psychiatric disorders (Khoshnoud, Shamsi, Nazari, & Makeig, 2017; Vogel et al., 2019; Vogel, Krämer, Schoofs, Kupke, & Vogeley, 2018). The sense of self and time is overly represented in individuals with anxiety and depression, who are stuck with themselves in time, feeling states that are the complete opposite of flow (Liknaitzky, 2017). Inducing flow states in these individuals could potentially lower symptoms of anxiety and depression. A study with the video game *Boson X* reported that playing it for six weeks reduced self-rumination and enhanced cognitive capacities in individuals with depression (Kühn, Berna, Lüdtke, Gallinat, & Moritz, 2018). The induction of flow states has been shown to alter the sense of time (Sinnett, Jäger, Singer, & Antonini Philippe, 2020). By measuring flow levels and temporal processing ability (through a temporal order judgment task, TOJ), Sinnett and colleagues identified that the higher the subjective flow experience of the sport or music performance, the better the participant performed in the post- performance TOJ task compared to the pre-performance TOJ task. Considering the beneficial nature of flow on psychiatric symptoms, creating a flow experience might be a helpful remedy in clinical psychology[1].

Since flow is an enjoyable mental state, keeping the player in a flow state is considered to be one of the most important goals for game designers (Chen, 2006; Salen & Zimmerman, 2003; Schell, 2008). To address this, game designers and researchers attempt to maintain the player's flow state through affect-based, dynamic difficulty-adjustment (DDA) techniques (Afergan et al., 2014; Liu, Agrawal, Sarkar, & Chen, 2009; Park, Sim, & Lee, 2014). Finding neural and electrophysiological indicators of this optimal mental state, which are objective and can be measured without interrupting the experience, could enhance the dynamic difficulty adjustment. Apart from these internal correlates, another promising approach would be the application of techniques that indirectly measure the extent to which subjects experience flow by assessing their levels of attention engagement. Here we provide an overview of all findings concerning the physiological and neural correlates of the flow experience. To our knowledge, this is the first review that combines physiological and neural correlates of flow in the context of video games. Harris et al. (2017) conducted a review on neurocognitive mechanisms of flow with more emphasis on sports as well as the role of attention suggesting attentional changes as the fundamental mechanism for creation of flow state. However, in their review, the rule of physiological arousal was not discussed in detail. In a recent systematic review conducted by Knierim et al. (2018), only peripheral nervous system indicators of flow were explored in a broad range of tasks identifying increased level of arousal as a central approach to the physiological measurement of flow. We believe that this paper makes a key contribution to the field of flow in the context of video games by considering reflections of flow in the central and peripheral nervous systems and integrating key physiological and neural mechanisms of the flow experience. Based on the results of the reviewed studies, we make suggestions on how to disentangle the internal phenomenon of flow from the external characteristics of the task.

Survey methodology

In this review, relevant academic articles were located in the Web of science and PubMed databases using search term: [(flow OR absorption) AND (physiological OR electrophysiological

[1] This is the approach in the EU-funded project VIRTUALTIMES - Exploring and modifying the sense of time in virtual environments with the principal investigators Kai Vogeley (Cologne), Anne Giersch (Strasbourg), Marc Erich Latoschik, Jean-Luc Lugrin (Würzburg), Giulio Jacucci, Niklas Ravaja (Helsinki), and Xavier Palomer, Xavier Oromi (Barcelona).

OR neurophysiology OR brain activity OR neural activity) AND (game OR video game OR gameplay)]. This search provided a total of 215 citations. After removing duplicates, the set of 55 articles comprising of peer reviewed, empirical studies with the focus of physiological and neural phenomenon of flow experience during playing video games without a-priori, publication date restriction have been selected. By scanning the references listed in the body of literature found in the initial search, additional 18 studies were identified. In a further attempt by applying the inclusion criteria to the full text of manuscripts, 35 articles including research with exergames or multiplayer games are excluded, as they introduce other confounding factors. Overall the set of 38 articles included in the review were presented in two sections: peripheral-physiological and neural correlates of flow.

Peripheral-physiological correlates of flow

Before introducing the empirical work, however, it is first necessary to discuss the theoretical background of peripheral-physiological correlates of flow. During the flow state, feelings of enjoyment along with high levels of concentration and focused attention are indicative of the involvement of the emotional and attentional systems of the brain. Based on this line of thought, several hypotheses have been proposed, which we will discuss in the following sections. First, the experimental approach by Kivikangas, (2006) defined the flow experience as a state of positive valence and heightened arousal. Later, de Manzano and colleagues described the physiology of flow as a combination of positive valence, heightened arousal, and effortless attention that arises through the interaction between positive affect and focused attention (de Manzano, Theorell, Harmat, & Ullén, 2010; Ullén, de Manzano, Theorell, & Harmat, 2010). According to this hypothesis, flow is associated with parasympathetic modulation of the sympathetic branch of the autonomic nervous system (ANS). Ullén et al. (2010) argued that this co-activation of the sympathetic nervous system (SNS) and the parasympathetic nervous system (PNS) acts as a physiological coping mechanism for high demands of attention and can distinguish between states of effortful and effortless attention. In contrast to effortless attention, typical of the flow experience, some researchers postulated that a high degree of involvement along with the challenging nature of the task might result in greater mental effort (Keller, Bless, Blomann, & Kleinböhl, 2011). Finally, by combining the stress-model with the flow-model, Peifer et al. (2014) argued that the experience of flow induces a certain amount of stress (more precisely, challenge) accompanied by heightened physiological arousal as indicated by increased activation of the SNS (fast reacting) and the hypothalamic–pituitary–adrenal (HPA) axis (slow reacting). They suggested an inverted U-shaped relationship between flow experience and physiological arousal, with a moderate arousal level during flow and lower and higher levels of arousal for the boredom and anxiety conditions, respectively. Reported negative effects of exogenous cortisol dosage on experienced flow supports their recent proposition of an inverted u-shaped relationship between cortisol and flow (Peifer, Schächinger, Engeser, & Antoni, 2015). Empirical studies in this field (see Table 1) are presented in the following section. However, inconsistent results during flow state show that the relationship between flow experience, arousal, and mental effort is highly dependent on the task.

** INSERT TABLE 1 HERE **

Positive valence and heightened physiological arousal

One of the first studies that investigated correlations between valence, arousal, and flow was conducted by Kivikangas (2006). The study assessed the participants' facial electromyographic (EMG) activity as an index of emotional valence (Lang, Greenwald, Bradley, & Hamm, 1993; Larsen, Berntson, Poehlmann, Ito, & Cacioppo, 2008) and electrodermal activity (EDA) as a sensitive measure of arousal (Boucsein, 2012) while they played the science-fiction computer game *Halo: Combat Evolved*. The activity of corrugator supercilii muscle (CS, "frowning muscle"), an index of negative valence, was negatively associated with the flow scores assessed by the FSS questionnaire, showing decreased negative valence during the experience of flow. No significant effects for the zygomaticus major (ZM, "smiling muscle") and orbicularis oculi (OO, "eyelid muscle") muscle activities- indices of positive valence – nor for EDA were found.

Chanel et al. (2008) employed physiological measures including cardiovascular activity and EDA to determine the three emotional states of boredom, flow, and anxiety, by modulating the difficulty of the game *Tetris*. Cardiovascular activity is reflective of ANS activity, with heart rate (HR) being stimulated by SNS and inhibited by PNS activity (Shaffer & Ginsberg, 2017). The behavioral results demonstrated that participants felt the highest positive valence and had a medium arousal level in the flow condition in contrast to the boredom and the anxiety conditions. Electrophysiological measures showed heightened arousal level as difficulty of the game increased identified by increase in EDA, as well as increase in HR (increased SNS activity). Utilizing a modified version of the first-person shooter (FPS) game *Half-Life 2* with specifically-designed levels, Nacke and Lindley (2008) assessed immersion along with boredom and flow by addressing their correlations with objective electrophysiological measures. The significantly highest mean ZM muscle activity and EDA values resulted during the flow game level. However, the flow experience was not evaluated by any questionnaire and it is not clear whether participants experienced flow in the flow condition of the game. In a correlational study employing three FPS games, no significant correlation was reported between EDA activity and flow scores assessed by the flow dimension of the GEQ, while HR was reported to negatively correlate with flow (Drachen, Nacke, Yannakakis, & Pedersen, 2010).

Bian et al. (2016) presented a physiological evaluation model for the state of flow in the virtual reality (VR) game *Air Bombardment*. In contrast to the findings of the study by Nacke and Lindley, (2008), the authors reported no correlations between ZM activity and flow scores as assessed by the FKS questionnaire (Bian et al., 2016). Using a mental arithmetic task, a study by Ulrich and colleagues found an inverse U-shaped pattern for EDA with significantly greater values during the flow condition than during the boredom and anxiety conditions, highlighting higher arousal levels during the experience of flow (Ulrich, Keller, & Grön, 2016). EDA was also assessed during playing *Blocmania 3D* game with three difficulty levels corresponding to boredom, flow, and anxiety (Tian et al., 2017). Difficulty manipulation was assessed with the FSS questionnaire and the highest flow state which was reported during the flow condition of the game was associated with moderate EDA activity, which reflects moderate sympathetic arousal. In a single case-study, Moreno et al.(2020) reported that a flow-like state in an expert gamer during playing the puzzle game *Portal,* coincided with increased EDA. It should be considered that in their study physiological assessment was conducted not during the moments of flow but when individuals were goal-oriented during gameplay.

Co-activation of sympathetic and parasympathetic nervous system

Findings regarding the relation between the flow state and ANS are mixed, as both sympathetic and parasympathetic activities have been shown to correlate with flow, both in combination and alone. De Manzano et al. (2010) argued that the flow state experienced while playing piano is linked to increased parasympathetic modulation of sympathetic activity. Their study showed that the flow reports of the players (as assessed by the FSS questionnaire) correlated with a decreased heart period (HP, increased SNS activity), decreased heart rate variability (HRV, fluctuations in the time intervals of adjacent heartbeats and an index of parasympathetic activity (Laborde, Mosley, & Thayer, 2017)) , an increased LF/HF ratio (low frequency HRV/high frequency HRV, reflecting autonomic balance between SNS and PNS), and larger respiratory depth (RD, increased PNS activity) (de Manzano et al., 2010). Chanel et al. (2011), in contrast, reported less low frequency heart rate variability (LF-HRV) power during the experience of flow compared to boredom and anxiety while playing *Tetris*. In a computerized knowledge task, with the three levels of boredom, flow, and anxiety, Keller et al. (2011) reported lower HRV during the flow condition as compared to boredom and anxiety, indicating lower parasympathetic activity. A more detailed assessment of cardiovascular and respiratory responses was performed by Harmat et al. (2015) during trials of *Tetris* gameplay in three conditions: boredom, flow, and anxiety. The flow condition was characterized by the highest levels of flow measured by the FSS questionnaire, positive affect, and effortless attention. More flow was associated with larger respiratory depth (reflecting increased parasympathetic activity) and lower LF-HRV (reflecting both sympathetic and parasympathetic influences). Given the lack of a significant relation between HF-HRV (high-frequency HRV, a direct measure of parasympathetic activation) and flow, their results could not clearly support the hypothesis that the flow state is linked to activation of sympathetic, as well as to the parasympathetic nervous system (Harmat et al., 2015). Tian and colleagues (2017) also reported moderate HR and HRV along with increased RD during the flow condition of playing the game, suggesting increased parasympathetic modulation of sympathetic activity during flow experience. In a FPS game called *Unreal Tournament 2004*, lower HF-HRV was reported in players playing the game during the flow condition compared to boredom and anxiety conditions (Kozhevnikov, Li, Wong, Obana, & Amihai, 2018). Given the lack of significant change in the LF-HRV values, authors argued that this pattern of reduction in parasympathetic activity is critical for reaching flow. Nonetheless, the flow experience was not assessed directly in their investigation and it is not clear whether subjects felt higher flow while playing the game during the flow condition as compared to the other two conditions.

It is important to note that both HRV and HF-HRV are considered as sensitive indices of parasympathetic activity (Laborde et al., 2017; Malik et al., 1996; Shaffer & Ginsberg, 2017) which is reported to be causally involved in flow experience (Colzato, Wolters, & Peifer, 2018). Nonetheless, the interpretation of LF-HRV is controversial, since it is considered as a marker of sympathetic modulation (Kamath MV, 1993), and both sympathetic and vagal influences (Laborde et al., 2017; Malik et al., 1996; Shaffer & Ginsberg, 2017). A comprehensive literature review conducted by Reyes del Paso et al. (2013) challenged this interpretation that the LF and LF/HF ratio reflect sympathetic activity and autonomic balance, respectively, and suggested that the LF component of HRV is mainly determined by the parasympathetic system.

Effortless or effortful attention

According to Ullén et al. (2010), the co-activation of SNS and PNS results from the interaction between positive affect and high attention, which leads to a state of effortless attention. Nevertheless, the flow experience is characterized by heightened concentration and high degree of attention. Specific patterns of activity like increased heart rate, decreased HRV, shallow respiration, and increased facial EMG activity are signs of mental effort (Aasman, Mulder, & Mulder, 1987; Backs & Seljos, 1994; Veltman & Gaillard, 1998; Waterink & van Boxtel, 1994), which are distinctive from the observed results in studies concerned with flow. In contrast to the idea of effortless attention, Keller et al. (2011) linked reduced HRV to increased mental effort during the experience of flow in a computerized knowledge task. During simulation-based training on the use of *enterprise resource planning software* with the three levels of boredom, flow, and anxiety, Léger et al. (2014) reported less mental effort during the flow situation. According to their results, participants who exhibited smaller variations in the EDA level (i.e. being more emotionally stable), lower HR, and higher HRV (indicative of less mental effort) were reported to be more likely to experience a cognitively absorbed state. Similarly, Peifer et al. (2014) reported a positive linear relationship between HRV values (HF-HRV) and flow experience in a computer task (Cabin Air Management System simulation). The participants' stress level was manipulated via the Trier Social Stress Test (TSST) before they performed the task. After the task, their flow experience was evaluated with the FKS questionnaire. Flow was associated to increased HF-HRV and a decrease in mental effort. These results contradicted the findings by Keller and colleagues (Keller et al., 2011), who found a negative relationship between flow and parasympathetic activity. Apart from the small number of participants in Keller's study, these differences showed that during a difficult level of a computerized knowledge task or game, participants are not likely to perceive as much stress and threat as they might experience during the TSST, which is designed to create considerable social anxiety.

Keller's study did not evaluate the correlation between physiological measures and the experienced level of flow. Instead, the flow experience corresponded to the skill-challenge balance condition.

Harris et al. (2016) explored whether concentration during flow is related to objective indices of effortful attention processing in a simulated car-racing task with the three standard levels of difficulty, namely boredom, flow, and anxiety. The FKS questionnaire was used for experimental manipulation check. The authors reported significantly higher flow scores for the flow condition of the game. The observed higher mental effort (lower HRV) and more focused attention (more focused eye gaze) along with less self-reported subjective effort in the flow condition than in the anxiety condition suggested that the experience of flow is based on an efficient, but effortful, engagement of attention. The link between attention and flow was examined by De Sampaio Barros et al. (2018) to see whether flow mobilizes attentional resources while playing two video games, *Tetris* and *Pong*. In this case, the authors added an "autonomy" condition to the traditional boredom, flow, and anxiety. The authors argued that this capacity to determine the difficulty level is an important factor for experiencing flow. However, the flow scores measured by the FKS questionnaire in the flow (pre-selected) and autonomy (self-selected) conditions were similar, albeit greater than in the boredom and anxiety conditions. HR significantly increased with task difficulty, and HRV was lower during the autonomy level than during the other conditions for both games, suggesting higher mental effort during autonomy.

Inverted U-shaped relationship between flow and activity of the stress system

A number of studies on the physiology of flow found associations between flow and physiological activation of the stress system. Keller and colleagues (2011) reported that a state of flow while playing a game involves high levels of tension reflected by higher salivary cortisol levels (increased HPA-axis activation). In the second experiment, the authors utilized *Tetris* in three conditions of boredom, flow, and anxiety to see whether strong involvement during the flow experience is associated with increased salivary cortisol levels in the participants. Higher cortisol levels were reported for the flow and anxiety conditions. By combining the stress-model with the flow-model, Peifer et al. (2014) suggested an inverted U-shaped curve between LF-HRV and cortisol level on one hand; and the flow experience assessed by FKS questionnaire on the other hand revealing moderate LF-HRV and cortisol levels in flow and low and high LF-HRV and cortisol values during boredom and anxiety, respectively.

The functional association between HRV factors (LF-HRV and HF-HRV) and flow (measured by the FKS questionnaire) was also assessed during a driving-simulation game (Tozman, Magdas, MacDougall, & Vollmeyer, 2015). The task used was a driving simulator chosen from the sporting-race, video-game package *Rfactor* with three fixed levels of difficulty representing boredom, flow, and anxiety. An increase in task difficulty caused a decrease in the HF-HRV and LF-HRV components. In contrast to the findings by Peifer et al. (2014), which showed an inverted U-shaped relation between flow and HRV measures, there was a negative linear connection between LF-HRV and flow when the conditions for flow were met (flow condition) and an inverted U-shaped relation between LF-HRV and HF-HRV, on the one hand, and flow, on the other hand, when demands exceeded the skill level (anxiety condition) (Tozman et al., 2015). In a VR game, Bian et al. (2016) reported similar results to the previous studies showing that increased HR, HRV, and respiratory rate (RR), as well as shorter inter-beat intervals (IBI), predict an increase in flow score assesses by the FKS questionnaire. An inverted U-shaped function between LF-HRV and HF-HRV, on the one hand, and flow on the other hand, was also reported, highlighting moderate LF-and HF-HRV levels for high flow scores and both low and high values of LF- and HF-HRV for low-flow scores. The authors stated that the physiological aspects of flow in VR games might be particularly affected by the VR environment (Bian et al., 2016).

Neural correlates of flow states

There is still considerable conceptual ambiguity concerning the possible brain mechanisms involved in the flow experience. Here we are going to discuss the main hypotheses established in the literature. Given the effortlessness and automatic characteristics of flow, Dietrich (2004) argued that such an optimal performance state is controlled through an implicit rather than an explicit information-processing system in the brain. The explicit system, which is associated with higher-order cognitive functions, is rule-based, can be verbalized, is connected to conscious awareness, and is supported by frontal-lobe activation. In contrast, the implicit system is skill-based, cannot be verbalized, is inaccessible to conscious awareness, and is supported primarily by the basal ganglia. Dietrich proposed that inhibition of the explicit system and transient hypofrontality is a necessary prerequisite for the experience of flow (Dietrich, 2004). The synchronization theory of flow proposed by Weber et al. (2009) specifies neuropsychological processes of the flow experience considering that it is characterized by intense concentration and an autotelic activity. This theory is based on Posner's tripartite theory of attention involving executive, alerting, and orienting networks (Posner, Inhoff, Friedrich, & Cohen, 1987). Accordingly, the optimal and gratifying experience of flow results from synchronized activity of the attentional and reward networks under the balanced skill-challenge condition (Weber et al., 2009).

Csikszentmihalyi (1975) described the flow experience as “self-forgetfulness” or “loss of self-consciousness,” highlighting the fact that, when the demands of the activity require the allocation of all attentional resources, attention is directed away from the self. Loss of self-awareness, as one of the important components of flow, sheds light on another interesting line of research that investigated default mode networks (DMN) activity during the flow experience (Sadlo, 2016). The activity of the DMN has been linked to self-referential thinking, and therefore declines in task-focused and goal-directed actions (Goldberg, Harel, & Malach, 2006; Raichle et al., 2001). During moments of flow, the activity of DMN decreases, highlighting less self-referential processing (Peifer, 2012; Sadlo, 2016). Table 2 presents a set of articles exploring brain activation during the flow experience.

** INSERT TABLE 2 HERE **

Transient Hypofrontality

The transient hypofrontality hypothesis proposed by Dietrich (2004) was addressed by a few studies. Applying brain imaging techniques in a blocks of mental arithmetic task with the three levels of task difficulty of boredom, flow, and anxiety, Ulrich et al. (2014, 2016) reported a relative decrease in the activity of the medial prefrontal cortex (MPFC). However, other studies failed to further support this idea. In a functional near-infrared spectroscopy (fNIRS) study, Yoshida et al. (2014) explored the activity of the prefrontal cortex (PFC) during flow while playing a video game and failed to support the transient hypofrontality hypothesis. The task was performed under the two conditions of boredom and flow while playing *Tetris.* Flow score assessed with the flow state scale for occupational tasks (Yoshida et al., 2013), was higher in the flow than the boredom condition. Significantly higher activation of the left and right ventrolateral prefrontal cortex (VLPFC) was reported during the last 30 seconds of flow than throughout the entire flow condition, while the same trend was not seen during the boredom condition (Yoshida et al., 2014). Harmat et al. (2015) also failed to show an association between flow while playing a video game and decreased activity in frontal brain regions. None of their fNIRS analyses revealed associations between lower frontal cortical activation and flow, suggesting that the neural substrates of flow may vary depending on the task (Harmat et al., 2015). De Sampaio Barros et al. (2018) recorded the cerebral hemodynamics of 20 volunteers while they played *Tetris* and *Pong*. The flow and autonomy playing conditions not only led to higher activation in the lateral PFC, but also led to higher deactivation in the MPFC compared to the other conditions.

It seems that the neural signature of transient hypofrontality during flow is task dependent. In tasks which need sustained attention, a deactivation of prefrontal areas seems to be unlikely. Gold & Ciorciari (2019) investigated whether decreased excitability over the left dorsolateral prefrontal cortex (DLPFC) and increased excitability in the right parietal cortex during gameplay promotes an increased experience of flow measured by the FSS questionnaire. Transcranial direct-current stimulation (tDCS, a non-invasive electrical stimulation technique that modulates the activation of the cortical neurons under a probe electrode) was used to alter the excitability of the cortex. In the first experiment, they recruited trained gamers to play an FPS video game in two sessions using active and sham tDCS stimulation. The second experiment was conducted with untrained gamers playing *Tetris* in boredom, flow, and anxiety versions. Both trained FPS and untrained *Tetris* players experienced significantly higher levels of flow after the active stimulation compared to the sham condition. The authors argued that inhibiting the DLPFC and the disruption of explicit executive functions resulted in improved implicit information processing and a more intense flow experience (Gold & Ciorciari, 2019).

Synchronization of attentional and reward networks

One of the first studies to assess the neural correlates of enjoyment during video-game play by means of functional magnetic resonance imaging (fMRI) was conducted by Klasen and colleagues in 2008. The participants' brain activation was measured in relation to subjective experience, which was assessed by having participants think aloud while they watched a replay of their gameplay session with an FPS game (*Counter-Strike: Source*). Reported game pleasure was correlated with cerebro-thalamic motor-network and visual-network activity (Klasen, Zvyagintsev, Weber, Mathiak, & Mathiak, 2008). In a subsequent study, Klasen et al. (2012) focused on game events that contribute to the flow factors described by Csikszentmihalyi and corresponding fMRI data were analyzed while participants played an FPS video game called *Tactical Ops: Assault on Terror*. Somatosensory networks and motor areas were jointly activated during flow-contributing events (Klasen et al., 2012). Authors discussed that this sensorimotor activation reflects the stimulation of physical activity, suggesting deep involvement and immersion in the game. The activation patterns of individual flow factors included the reward system (putamen, caudate nucleus, and thalamus), error monitoring (anterior cingulate cortex; ACC), orbito-frontal cortex (OFC), temporal poles (TP), and motor system. Specifically, reward-system activation was detected during game events with a skill-challenge balance, i.e. during moments when the player was able to master the challenges of the game and had a rewarding experience. The involvement of the reward system along with motor areas in both studies was considered in line with the synchronization theory of Weber et al. (2009). Nonetheless, flow is a highly subjective phenomenon, and the second study did not examine the actual flow experience, but the situations with an enhanced probability of flow.

Ulrich et al.(2016, 2014) also found increased activity in the inferior frontal gyrus (IFG, an executive attention structure) along with the left putamen (a region involved in reward processing), the anterior insula, and posterior cortical regions in the flow condition of the mental arithmetic task. Yoshida et al. (2014) observed a higher activation of the right and left VLPFC during the flow condition of Tetris, which relates to reward and emotion processing in a state of flow. Considering the involvement of VLPFC in top-down attention (Raz & Buhle, 2006), one can interpret this as a co-activation of the attentional and reward networks during the flow experience(Weber, Huskey, & Craighead, 2016). The results of the study by De Sampaio Barros et al.(2018) showed a significant positive correlation between the self-reported measure of attention and the average neural activation in the frontoparietal regions. Higher activation in the lateral PFC was reported in the flow and autonomy playing conditions of *Tetris* and *Pong* compared to the other conditions. In a custom-designed car game, Ju and Wallraven (2019) assessed the neural correlates of the flow experience with the flow subscale of the GEQ. Besides a baseline driving condition with fixed structure, they designed three extra conditions in order to modulate difficulty with one parameter (speed, obstacle, or tokens). Although no significant differences in the flow subscale ratings were reported across conditions, the results of fMRI analysis showed positive correlations between the flow experience and brain activity in regions related to visual (dorsal and ventral visual pathway) and spatial execution (middle and superior temporal gyrus) as well as attentional processes (IFG, inferior and superior parietal lobule).

Self-referential processing

Relating existing theories of default mode networks to the feeling of selflessness during flow, Peifer (2012) argued that the down regulation of task-irrelevant processes during the experience of flow should lead to decreased activity in these resting state networks of the brain. First empirical evidence came from a magnetic resonance (MR)-based perfusion imaging study by Ulrich et al. (2014), who found that a relative decrease of activity in the MPFC(an important structure of self-referential processing), and the amygdala (AMY) accompany the experience of flow in a mental arithmetic task. The MPFC along with the precuneus, the amygdala, and the posterior cingulate cortex (PCC) constitute the DMN (Raichle et al., 2001). A flow index that was specifically computed to represent the individually experienced level of flow correlated negatively with activity in the MPFC (less self) and the AMY. The higher the subjective experience of flow, the greater the decrease in neural activity in the MPFC and AMY. The authors later explored the neural effects of flow experience at higher levels of temporal resolution using an fMRI block design with blocks of activation as short as 30 seconds (Ulrich et al., 2016). This study yielded similar results as their previous study, with the addition of an activation decrease in the PCC, which altogether were interpreted as deep concentration and less self-referential processing along with less emotional arousal (reflected by down-modulation of AMY) during the flow experience. In the flow and autonomy playing conditions of the study by De Sampaio Barros et al. (2018), a decreased activity in the MPFC was also reported highlighting less self-referential processing during the experience of flow. Ju and Wallraven (2019) found negative correlations between the flow experience and activity in the brain regions associated with the DMN in a car driving game. Authors argued that as player became more engaged in the game, the DMN as a task-negative network became more deactivated. Also, positive correlations between flow and activity in the insula in this study indicated less self-awareness during moments of flow (Ju & Wallraven, 2019).

Ulrich and colleagues further explored the role of the MPFC in mediating flow experience using tDCS technique to interfere with the MPFC's activation level by the modulation of cortical excitability (Ulrich et al., 2018). During the above-mentioned mental arithmetic task, current stimulation was applied over the frontal-central (Fpz) scalp position with three modulation types: anodal (increase neuronal excitability), cathodal (decrease neuronal excitability), and sham (baseline). Flow experience was assessed along with the implementation of (MR)-based perfusion imaging while participants performed the task at three difficulty levels (boredom, flow, and anxiety). There was no significant difference among stimulation types (sham, anodal, and cathodal tDCS) and the measured flow index across all subjects. After splitting the subjects into two groups based on the flow index in the sham condition (lower-flow and higher-flow), a significant increase in the flow index in the lower-flow group under anodal tDCS stimulation was reported. Correspondingly, anodal tDCS elicited a significantly stronger deactivation of the right AMY in this group compared to the higher-flow group (Ulrich et al., 2018).

Neural oscillations and flow

Nacke & Lindley (2010) proposed an affective ludology context referring to investigations of affective player-game interaction. To address this issue, some studies have explored how the information of electroencephalogram (EEG, assessment of cortical activity of the brain through electrodes placed on the scalp) signals can differentiate emotions from cognitive activity during gameplay. Specific neural oscillations in four frequency bands of EEG (delta, theta, alpha, and beta) were investigated as underlying neurophysiological mechanisms of the experience of flow (see Table 3). Nevertheless, studies were mostly explorative without specific background theory.

Some studies examined if verbal-analytic processing is reduced during flow, following the notion of peak performance and automaticity characteristics of the flow experience (specifically in motor responses in athletes) (Harris et al., 2017; Kramer, 2007; Wolf et al., 2015). Temporal alpha asymmetry has been shown to relate to peak performance, especially in athletes (Kerick, Douglass, & Hatfield, 2004). According to Vernon (2005), higher left temporal cortex alpha activity (decreased cortical activity in this region), which is associated with improved performance, represented reduced internal verbalizations and increased visual-spatial processing (which is associated with right-hemispheric activity). Among frequency bands, frontal theta activity (specifically frontal mid-line theta) was of particular interest. Frontal mid-line theta has been linked to cognitive control and concentration (Brandmeyer, Delorme, & Wahbeh, 2019; Cavanagh & Frank, 2014) and consequently may increase during the flow experience.

** INSERT TABLE 3 HERE **

Reduced verbal-analytic processing - In a car-driving game, Kramer (2007) studied neural correlates of peak performance (as associated with the state of flow) by exploring EEG signals' power information. Their results showed that a decrease in alpha power in the right temporal lobe prior to a game trial predicted better game performance reflected by an increase in visuo-spatial processing. Greater mean left-temporal alpha power ten seconds before a game trial resulted in improved performance. As in some other studies, the players' flow experience was not directly evaluated, but the high-performance intervals functioned as a proxy for the subjective states. Later, Wolf et al. (2015) linked states of highly-focused attention in athletes (one key component of flow experience) to reduced influence of verbal-analytical processes reflected by stronger relative left-temporal-cortex alpha power. In this study, 35 expert and amateur table-tennis players were asked to watch a 7-second-long video clip of a table-tennis player serving a ball and to imagine them reacting to it. A significant change towards lower T4–

T3 alpha power (stronger right-temporal cortical activity) at the beginning of the movement phase was reported in experts. This result, along with a positive correlation between T4-T3 alpha asymmetry and the flow score (measured by the FKS questionnaire) in the experts, was interpreted to reflect lower verbal analytic processing as associated with a higher degree of flow in expert table tennis players.

Delta and Theta frequency bands- Chanel et al. (2011) classified the three emotional states of boredom, flow, and anxiety induced by playing *Tetris* at three different challenge-skill levels. Their EEG results indicated distinct theta power in some electrodes between conditions. The investigation was a classification study, and there was no precise information about differences in theta power among conditions. In an exploratory EEG study, Nacke and colleagues probed the impact of different difficulty levels of a game on brainwave activity (Nacke et al., 2011). The authors did not use the methods of difficulty modulation for creating different levels of the gameplay. Based on specific level-design guidelines (LDGs), three gameplay conditions (boredom, immersion, and flow) of the game *Half-Life 2* were created. Theta and delta power were significantly higher in immersion than in flow and boredom. Since the immersion condition of the game required navigating through landmarks, the authors argued that high theta activity in this level might be attributed to its architectural complexity.

In another study, EEG correlates of the flow state induced by playing a ping-pong video game were investigated at two levels, slow as boring and fast as flow inducing (Metin et al., 2017). EEG-frequency power evaluations revealed a higher mean theta power during the flow condition for all regions of interest and a higher mean delta power in frontal, central, and parietal regions as compared to the non-flow condition. The regional theta and delta frequency bands correlated positively with the absorption, enjoyment, and intrinsic-motivation subscales of the Turkish version of the FKS flow questionnaire. Regarding the two playing levels, a higher theta band was not surprising, as theta activity has been linked to concentration, working memory, and sustained attention, and these cognitive components would be higher at a higher difficulties. Katahira et al. (2018) characterized the flow state by increased theta activity in the frontal areas. Employing a mental arithmetic task used in the previous study (Ulrich et al., 2014) with three difficulty level, theta activity in the frontal areas was reported higher during flow and anxiety condition of the task than in the boredom condition.

Alpha frequency band - Alpha power attenuation in the flow condition was reported as an indicator that the subject had entered a flow state (Berta, Bellotti, De Gloria, Pranantha, & Schatten, 2013). Using a four-electrode EEG (F7, F8, T5, and T6), they analyzed distinct user-states induced by a specifically designed plane battle video game with appropriate levels for boredom, flow, and anxiety. The main differences among the three conditions were reported in alpha and low-beta frequency-band powers with the lowest alpha and low-beta in the flow state. There was no information regarding the region of observed distinct frequency power bands among conditions. Self-assessed flow scores of the GEQ showed significantly different boredom and anxiety levels, but failed to distinguish the flow level. Léger et al. (2014) explored the relationship between EEG and flow in a simulation-based training session with the three difficulty levels of boredom, flow, and anxiety. Subjects with high alpha and low beta activity reported a higher cognitive absorption score. The authors argued that these results showed a more relaxed and less vigilant state in the learners.

Beta frequency band - Wang & Hsu (2014) explored the state of flow during a computer-based instruction paradigm utilizing EEG to see whether the attention score captured by the EEG signal is associated with the flow score assessed by the virtual-course flow measure. Participants completed three lessons of computer-based instructions pertaining to Excel operations with easy (boredom), medium (flow), and difficult (anxiety) content. The EEG attention value—derived from the beta wave of brain activity at Fp1 electrode—was reported to correlate with the flow dimensions of enjoyment, focused attention, involvement, and time distortion. However, the correlation coefficient was small, and the authors argued that the attention value cannot exactly represent the flow experience and is only one component. Léger et al. (2014) found low beta activity associated with a higher flow score, highlighting a less vigilant state in the learners. Utilizing an adapted version of the WOLF questionnaire, De Kock (2014) evaluated the flow experience of participants subjected to a continuous visuomotor computer game (*Need for Speed Carbon*). EEG signal activity at prefrontal, sensorimotor, parietal, and occipital regions was compared between low-flow/low-performance and high-flow/high-performance groups. The high-flow condition was associated with increased low-beta power in the sensorimotor cortex, as well as low-beta synchronization among all cortical connections. The shift in low-beta power in the sensorimotor area was connected to fluent and coordinated motion. Synchronized low-beta connections in all cortical regions in the high-flow condition indicated optimized transmission of neural information throughout the brain, ensuring smooth, accurate, and effortless motor execution (De Kock, 2014). Increased beta activity during flow-like states was also reported in a single-case study by Moreno et al. (2020) highlighting higher cognitive engagement during moments of flow.

Implementation of dual-task paradigms

Although the above-mentioned studies have provided neural signatures of the flow state, they all face a similar limitation. Their methodology cannot discern between internal flow and the external task conditions that facilitate the experience of flow. A skill-challenge balance is considered a prerequisite to inducing flow, but alone it does not guarantee that an individual will enter the flow state. It has been demonstrated that different factors, but especially the methodology, can affect the association of skill-challenge balance and flow (Fong et al., 2015). In some studies in which difficulty modulation was used for creating boredom, flow, and anxiety conditions, the adaptive playing condition was considered as flow without any post-manipulation check to see whether participants really experienced flow in their experimental set-up (e.g. Chanel et al., 2011). This fact led to the application of techniques that indirectly measure the extent to which subjects experience flow by assessing their levels of attention engagement. Based on the flow theory (Csikszentmihalyi & Csikszentmihalyi, 1992), focused attention during the experience of flow leads to complete absorption in an activity to the extent that one does not allocate attentional resources to irrelevant external stimuli. During boredom or anxiety, attentional disengagement from the task makes it more likely that an individual will pay attention to irrelevant stimuli. These considerations led to an interesting line of research using dual-task paradigms to indirectly measure electrophysiological correlates of the flow experience (see Table 4). Secondary-task reaction times were suggested as reliable and valid measures of available attentional resources (Weber, Alicea, Huskey, & Mathiak, 2018).

** INSERT TABLE 4 HERE **

Castellar and colleageus utilized an auditory oddball paradigm as a secondary task to investigate attention while subjects played a game as a primary task (Castellar et al., 2016). Participants were requested to play the game *Star Reaction* in boredom, flow, and anxiety conditions while simultaneously responding to a rare sound in the auditory oddball task. The larger the absorption in the primary task, the slower the reaction times and more errors registered in the detection of oddball sounds. Event-related potential (ERP) analysis showed that the maximal frontocentral negative deflection after the response onset was significantly delayed during the flow condition compared to the other two conditions in the correct-responses trials, reflecting delayed attention re-allocation to the primary task during flow. Significant midfrontal alpha power increase during the flow condition may well indicate the intrinsic rewarding nature of the flow experience (Castellar et al., 2016).

A study by Yun et al. (2017) extended the secondary-task idea by adding a passive random beeping sound while subjects played an FPS game (*Call of Duty : Modern Warfare 2*). Complete absorption in the game world was expected to lead to the neglect of the game-irrelevant sensory stimulation from the real world, which is reflected by the suppression of auditory evoked potentials (AEPs) of EEG signals elicited by random beeps. Due to the insufficient number of trials and background noise, the typically detected AEPs were not observable, and the authors instead analyzed event-related spectral perturbation (ERSP) suppression at low frequencies in the flow trials. A significant correlation was reported between the suppressed evoked potential derived from ERSP and the self-reported experience of flow. By utilizing source-localization algorithms, the activation of the ACC and temporal pole was reported during flow trials only in the beta-frequency range. Subjective flow ratings also positively correlated with activation in these regions, suggesting a link between the flow experience and high concentration, focused attention, and less self-referential processing (Yun et al., 2017). Auditory oddball sounds were also applied as a secondary task in a VR gaming context to explore attentional allocation during the experience of flow (Bombeke, Dongen, Durnez, & Anzolin, 2018). Participants played a shooter game *Counter-Strike: Global Offensive* under three conditions (boredom, flow, and anxiety) both in a 2D and a VR set-up while they were simultaneously asked to respond to the oddball sounds. Their results did not replicate the results of the previous study by Castellar et al. (2016) reporting higher reaction times and more errors in the flow condition. A smaller posterior mid-line P300 amplitude was reported (marginally significant) in VR compared to playing on 2D during the flow condition. The flow ratings measured with the Flow Questionnaire (FQ, Sherry et al.,(2006)) did not show significant differences among the different gaming conditions, and it is unclear whether participants really experienced boredom, flow, and anxiety in this set-up. Through the application of a secondary-task reaction time (STRT) procedure while playing the game *Asteroid Impact* at three levels of difficulty (boredom, flow, and anxiety), Huskey et al. (2018) reported the greatest intrinsic reward (measured by the autotelic experience subscale of the FSS questionnaire) and longer reaction times during the flow condition. Their results revealed that the flow condition elicited significantly greater activity in the areas related to cognitive control (DLPFC), orienting attention (superior parietal lobe; SPL), attentional alerting (dorsal anterior insula, dAI), and reward networks (putamen). These results correlate well with the synchronization theory of flow. The low-difficulty condition evoked activity in DMN structures which was absent in the high-difficulty condition (Huskey et al., 2018).

Discussion

We conducted a comprehensive review of the current literature on the underlying electrophysiological and neural mechanisms of the experience of flow. Although a number of physiological and neural measures could potentially be seen as markers of flow, it is difficult to relate them to a unified mechanism that underlies this mental state. Flow is a complex state that requires the involvement of distinct cognitive subfunctions, which in turn necessitates the activation of different physiological and neural systems. Here we tried to categorize some of these distinct physiological and cognitive subfunctions, which were addressed by most of the studies.

State of positive valence and heightened arousal

Activity in the smiling (ZM, positive association) and frowning muscles of the face (CS, negative association), and larger respiratory depth during flow states represent positive affect (de Manzano et al., 2010; Harmat et al., 2015; Kivikangas, 2006; Mauri, Cipresso, Balgera, Villamira, & Riva, 2011; Nacke & Lindley, 2008). The pattern of arousal modulation, however, is somewhat complex and varies in how studies used it to distinguish flow states from straining experiences such as stress. Peifer and colleagues (2014) proposed an inverted U-shaped function between flow experience and physiological arousal. If we consider the relationship between flow and performance (Csikszentmihalyi et al., 2005; Engeser & Rheinberg, 2008; Jin, 2012; Keller & Bless, 2008; Landhäußer & Keller, 2012), this pattern aligns well with the classic Yerkes-Dodson Law, which proposes an inverted U-shaped association between arousal and performance (Yerkes & Dodson, 1908). Nevertheless, findings concerning the sympathetic and parasympathetic reflections of arousal are heterogeneous, given that both linear (Chanel et al., 2011; de Manzano et al., 2010; De Sampaio Barros et al., 2018; Keller et al., 2011; Tian et al., 2017) and inverted U-shaped (Bian et al., 2016; Peifer et al., 2014; Tozman et al., 2015) associations have been reported. On the other hand, EDA—a robust indicator of sympathetic arousal (Critchley & Nagai, 2013) —has been shown to positively correlate with flow, reflecting heightened sympathetic arousal during the moments of flow (Léger et al., 2014; Moreno et al., 2020; Nacke & Lindley, 2010; Ulrich et al., 2016).

One possible explanation of obtaining a linear function between arousal and flow experience is that playing a game in a laboratory setting, even at a higher level of difficulty, might not be perceived as a threat and thus fails to elicit high arousal levels at high levels of difficulty. Building upon the biopsychosocial model of challenge and threat, Tozman and Peifer (2016) suggest using framing techniques in order to manipulate challenge appraisal in the game and create threat during gameplay. The question is how framing context affects flow experience, given that external impositions such as threat, negative feedback, and deadline might negatively influence intrinsic motivation and consequently the flow experience (Di Domenico & Ryan, 2017). Studies investigating the relationship between flow and salivary cortisol levels (Keller et al., 2011; Peifer et al., 2015, 2014) also suggested that this relationship is moderated by the type of intervention, personal characteristics, and interaction of both (Brom et al., 2014). It is also possible that the internal motivation for gameplay was adversely affected by the experimental setup, as players participated in the experiment not for the pleasure of the game, but for the specific context. Being in an artificial experimental situation and receiving external rewards (e.g., the monetary compensation for participation in the study) may suppress arousal. It is worth to mention that the LF-HRV which was considered as a marker of sympathetic activity in the study by Peifer and colleagues (2014), was determined mainly by the parasympathetic system's activity (Reyes del Paso et al., 2013). Future studies should consider more robust indicators of sympathetic arousal for the evaluation of relationship between flow and physiological arousal. The pre-ejection period of cardiovascular activity was suggested as a reliable indicator which could clarify this inconsistency (Tozman & Peifer, 2016). In general, one can suggest that the simultaneous presence of heightened arousal and positive valence can distinguish flow from the experiences of boredom and anxiety.

Joyous state of focused attention

Flow as a state of complete concentration during a skill-challenge balance condition also necessitates a high degree of attention that is understood to be effortless. Both flow and mental effort increase with the increased task difficulty (Tozman & Peifer, 2016), but the specific pattern of ANS activity observed during the flow experience (e.g. decreased heart period with deep respiration) is different from the pattern associated with mental effort (e.g. decreased heart period, lower HRV along with fast and shallow respiration). Studies that found lower HRV in the flow condition explained this phenomenon in the light of higher mental effort during the experience of flow (De Sampaio Barros et al., 2018; Harris et al., 2016; Keller et al., 2011) and, in contrast, studies with observed higher HRV suggested lower mental effort (Bian et al., 2016; Peifer et al., 2014). The inconsistencies of findings regarding mental effort and flow experience could be partly traced back to the imprecise measures used for assessing mental effort. Although HRV has been found to be a sensitive measure of mental effort (Aasman et al., 1987; Backs & Seljos, 1994; Waterink & van Boxtel, 1994), Veltman and Gaillard (1998) argued the opposite, as it can be affected by respiratory activity. For instance, during moments with more respiration, differences in mental effort measured by HRV might be overestimated. It is therefore necessary to test more precise measures of the cardiovascular control system's suppression as a result of mental effort. Blood glucose and pupil dilation were suggested as sensitive measures for exploring mental effort (Saproo, Shih, Jangraw, & Sajda, 2016; Tozman & Peifer, 2016) which has not been investigated in the concept of flow.

Harris et al. (2016) demonstrated that felt and objective attentional effort might dissociate from each other. Focused eye gaze (increased attention) as well as lower HRV (higher mental effort) reported during the flow condition did not match the lower effort scores obtained through self report (Harris et al., 2016). Ullén et al. (2010) suggested that this may occur as a result of an interaction between positive valence and focused attention. In a state of positive affect, a task with great attentional load might be experienced as less effortful. Observed co-activation of the sympathetic (reflected by decreased HP) and parasympathetic systems (reflected by deep respiration) align well with this suggestion. Considering the role of the PFC in attention and concentration, the experience of flow was displayed to associate with increased activity in this integrative frontal area of the cortex (Klasen et al., 2012; Ulrich et al., 2016, 2014; Yoshida et al., 2014). Frontal midline theta activation has been linked to concentration, working memory, and sustained attention (Cavanagh & Frank, 2014). High theta activity reported during flow (Katahira et al., 2018; Metin et al., 2017; Nacke et al., 2011) might therefore reflect focused attention. We argue that the flow state is accompanied by an efficient attentional effort and that the coupled activity of the sympathetic and parasympathetic nervous systems can be used to distinguish this joyous state of focused attention from the pure effortful mental experience.

Synchronized activation of attentional and reward networks

Flow is considered to be a state with focused attention which is intrinsically rewarding, as the flow-inducing task is performed for its own sake. Some studies support the synchronization theory of flow (Weber et al., 2009) by showing the joint activation of frontoparietal attention networks (e.g. IFG and inferior parietal lobe) and reward networks (e.g. putamen, thalamus) during the flow experience (Castellar et al., 2016; De Sampaio Barros et al., 2018; Huskey et al., 2018; Ju & Wallraven, 2019; Klasen et al., 2012; Ulrich et al., 2016, 2014; Yoshida et al., 2014). A positive correlation between dopaminergic receptor availability in the striatum and putamen and flow proneness supports this theory and shows that the experience of flow is intrinsically rewarding (de Manzano et al., 2013).

Automaticity

Concerning the neural mechanisms underlying the experience of flow, inhibition of the explicit system and the transient hypofrontality theory (Dietrich, 2004) received partial empirical support (Gold & Ciorciari, 2019; Ulrich et al., 2016, 2014). Other studies failed to find transient hypofrontality during the state of flow (Harmat et al., 2015; Yoshida et al., 2014). Fluent, smooth and effortless motor performance were related to increased low-beta power in the sensorimotor cortex, as well as low-beta synchronization among all cortical connections (De Kock 2014). We suggest that this hypothesis might be an oversimplification of the flow state or only related to specific situations. During tasks with high demands of executive control, a decoupling of actions from conscious effort and controlled attention is unlikely to happen. It has been suggested that the decrease in frontal functions is more likely to occur when the action becomes more automatic (Harris et al., 2017). This means that transient hypofrontality might happen after prolonged exercise.

Loss of self-awareness

A promising consistent outcome of neural research on flow experience is the deactivation of the DMN, specifically the MPFC, which indicates less self-referential processing during the flow experience (De Sampaio Barros et al., 2018; Ju & Wallraven, 2019; Sadlo, 2016; Ulrich et al., 2016, 2014, 2018). It has been stated that during the performance of cognitively demanding task, the activity of the central executive network and salience network increases whereas the DMN's activity declines (Sridharan, Levitin, & Menon, 2008). Activity in the DMN is reported to be associated with a relaxed mind, mind-wandering, and self-referential thinking, which is reduced in task-focused and goal-directed actions (Goldberg, Harel, & Malach, 2006; Raichle et al., 2001). Reduced activity was found in the DMN during focused sensory perception (Goldberg et al., 2006), which reflects the loss of self during the activity. Activation of DMN regions was also reported during a boredom-induction task, suggesting a relation between mind wandering and DMN activity (Danckert & Merrifield, 2018). Several studies discussed the role of MPFC and its relative decreased activity in self-referential processing (Goldberg et al., 2006; Gusnard, Akbudak, Shulman, & Raichle, 2001; Raichle et al., 2001). This is strongly related to Csikszentmihalyi's (1990) dimension of loss of self-awareness in flow theory. High concentration and focused attention demanded by the task at hand restrict resource allocation for task-irrelevant demands like body and self-awareness. Sridharan et al. (2008) stated that the saliency network, including the VLPFC and the anterior insula (AI), is involved in shifts between the DMN and cognitive executive networks acting as an outflow hub at the junction of both networks. This notion is further confirmed by the positive correlation between the flow experience and the activity increase reported in the insular cortex, especially in the anterior insula (Huskey et al., 2018; Ju & Wallraven, 2019; Ulrich et al., 2016). Consequently, higher activity in the anterior insula might show disengagement of the task-irrelevant DMN regions during the experience of flow. On the other hand, activity in anterior and posterior parts of the insula was linked to time perception (Wittmann, Simmons, Aron, & Paulus, 2010) and the anterior regions were shown to associate with the experience of bodily self-awareness (Craig, 2009). A study by Berkovich-Ohana et al. (2013) reported that timelessness in a meditation practice is accompanied by higher theta activation in the right insula. Further investigations should interrogate the rule of the anterior insula in the experience of flow.

Another important issue here is that lower self-referential information processing is associated with decreased neural activity in the amygdala during flow (Ulrich et al., 2016, 2014, 2018). Given the amygdala's mediating role in emotion perception (Morris et al., 1996), the reduced activity in AMY reflected a decreased emotional arousal associated with the experience of flow. One might speculate that lowered self-awareness reduces the threat response and increase positive emotions (Sadlo, 2016; Ulrich et al., 2016). Reduced awareness of the self is also reported to contribute to improved performance in athletics (Harris et al., 2017). The close relationship between flow experiences and performance (Engeser & Rheinberg, 2008; Jin, 2012; Landhäußer & Keller, 2012) suggests that reduced self-awareness and, consequently, reduced DMN activity is one of the underlying key features of the flow experience.

Task dependency

Some of the inconsistencies in results can be explained by different experimental designs used in different research approaches. While some used continuous playing and correlational analysis, others preferred a difficulty-modulation approach, where they designed three levels of the game corresponding to the boredom, flow, and anxiety categories of the flow model. The way the skill-challenge balance is operationalized in these studies directly influences flow. More frequently, studies used global flow scales like the FSS or the FKS questionnaires to measure the level of flow in participants. Few studies just applied some individual items or subscales of these surveys to assess the subjective experience (Keller et al., 2011; Ulrich et al., 2016, 2014), and some others did not employ any measure for the evaluation of flow and considered the skill-challenge balance condition as a flow state without further checking of the manipulation (e.g. Chanel et al., 2011; Nacke & Lindley, 2008; Nacke et al., 2011). In a meta-analytic study, Fong et al. (2015) reported that the correlation between flow and optimal balance is higher when a global flow scale and one of its subscales of challenge-skill fit was used for operationalizing a skill-challenge fit. The length of the experimental blocks, ranging from 30 seconds to 12 minutes, is another limitation, which leads to strong variations in the strength of the flow experience. It has been stated that participants required a minimum of 25 minutes to get into the flow state (Bisson et al., 2012; Tobin et al., 2010; Yun et al., 2017). The next concern is that different paradigms or games require the involvement of different cognitive functions, which in turn affect the physiological and neural-activity outcome. Peifer (2012) argued that, as the physiological and cognitive demands of the flow-inducing activities are different, the neurophysiology of "optimal functioning" differs between them. First-person shooters, like *Half-Life 2* (HL2) or *Counter-Strike: Source* (CS:S), require more complex interactions than, for instance, *Tetris* or *Pong*.

Virtually anyone could pick up *Tetris* or *Pong* and play them right away, since the player only needs to use a few buttons. In FPSs, players typically control the character with a combination of mouse and keyboard that takes practice to use. Moreover, there are differences between the contents of the games used in the studies described above that would require players to use different cognitive functions while playing. FPSs are three-dimensional games in which navigation is crucial. At any given time, the player is only looking at a small portion of the total space, and challenges are often hidden from view until they are close to the player or in their line of sight. This category of games activates mental processes crucial for spatial navigation. In contrast, *Tetris* and *Pong* are two-dimensional and belong to the category of single-screen games, since all the relevant information is displayed simultaneously on the screen.

Remaining issues and future research considerations

It is important to note that most of the methodologies mentioned above cannot discriminate between internal states of flow and the external conditions that help induce a flow experience. Designing specific levels for the experiments (corresponding to boredom, flow, and anxiety) that are directly related to the amount of skill-challenge balance does not guarantee that people will enter a flow state. The subjective experience of flow was not directly assessed in some studies, and it is therefore not clear whether the participants were able to enter a full flow state or not. One could consider adding objective measures other than neural or physiological markers to isolate the state of flow. One type of objective measures was conceptually designed by applying a secondary reaction-time task to assess the level of attention engagement during gameplay (Bombeke et al., 2018; Castellar et al., 2016; Huskey et al., 2018; Yun et al., 2017). Longer reaction times and more errors in the secondary task were reported to correlate with the subjective experience of flow (Castellar et al., 2016; Huskey et al., 2018).

The associations between performance and arousal (Yerkes & Dodson, 1908) and flow and arousal (Peifer et al., 2014) suggest a close relationship between flow experience and performance. Nonetheless, the direction of this association has not yet been clearly investigated. It has been demonstrated that flow as a state of high concentration and a sense of control could actually motivate subjects to improve their performance (Engeser & Rheinberg, 2008; Jin, 2012; Landhäußer & Keller, 2012). While the association between flow and optimal performance has been described in academic activities, music, and sports (Landhäußer & Keller, 2012), there were few studies reporting a relationship in the gaming context (De Kock, 2014; Engeser & Rheinberg, 2008; Jin, 2012; Keller & Bless, 2008; Yun et al., 2017). Some studies failed to find an association between flow and optimal performance (Harris et al., 2016; Katahira et al., 2018; Ulrich et al., 2016, 2014) reporting medium levels of performance for the flow condition. It is noteworthy that the positive association was mostly reported in studies in which components of subjective flow were directly measured instead of assessing behavioral levels of challenge and skills (De Kock, 2014; Yun et al., 2017). More precisely, the causal relationship between flow and performance cannot be tested in typical cross-sectional experimental paradigms using difficulty manipulations. A longitudinal design is required to assess causality (Keller & Bless, 2008; Landhäußer & Keller, 2012). Considering this, performance might also be considered as an objective measure that, in combination with other measures (e.g. physiological and neural indices, subjective self-reports, and secondary reaction times), could precisely capture the actual emergence of flow. We argue that future studies should consider using objective measures beside subjective scales and self-reports to capture the actual emergence of flow.

Conclusions

This review provides an overview of physiological and neural findings during the flow experience and integrates the empirical results to explain the underlying mechanisms of this complex state. We sorted distinct physiological and cognitive subfunctions involved in the experience of flow. We conclude that flow is a positive mental state characterized by heightened arousal, focused attention, synchronized activity in the brain's attention and reward networks, and results in automatic action control with less self-referential processing. Combining objective measures with retrospective questionnaires seems essential to capture the actual emergence of flow. The important role of focused attention during moments of flow necessitates the employment of dual-task paradigms to disentangle internal flow phenomena from external situations inducing flow.

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Table 1(on next page)

Table1: Studies on peripheral-physiological correlates of the flow state

Table 1: Studies on peripheral-physiological correlates of the flow state

Ref.	N subjects	Age mean/ range	Sample	Experiment type	Design	Measure	Peripheral-physiological correlates of flow
Kivikangas (2006)	32(m)	17-34	Healthy students	FPS game: Halo: Combat Evolved	40 minutes gameplay	Facial EMG & EDA	Negative correlations between CS activity and flow
Chanel et al. (2008)	20 (7f)	27	Healthy participants	Game Tetris	5 minutes Boredom/ Flow/ Anxiety	EDA, BP, Res, & T	Increase in EDA & HR with increasing difficulty
Nacke & Lindley (2008)	25(m)	19-38	Healthy students	Game Half-Life 2	10 minutes Boredom/ Immersion/ Flow	Facial EMG & EDA	Highest ZM activity & EDA values for flow
Drachen et al. (2010)	16	—	—	FPS Games: Prey, Doom3, & Biochock	20 minutes gameplay	EDA, HR	Negative correlation between HR & flow subscale score
Chanel et al. (2011)	20(7f)	27	Healthy participants	Game Tetris	5 minutes Boredom/ Flow/ Anxiety	EDA, BP, Res, T, & EEG	Least LF-HRV during flow
Keller et al. (2011)	8(4f) 61(m)	—	Healthy students	Computerized knowledge task & game Tetris	Boredom/ Flow/ Anxiety	HRV & Cortisol	Lower HRV & higher cortisol during flow condition
Peifer et al. (2014)	22(m)	20-34	Healthy students	Cabin Air Management System software	60 minutes performance	ECG & Cortisol	Inverted U-shaped relationship of LFHRV & cortisol level with the flow experience & positive linear relationship between parasympathetic activation & flow
Leger et al. (2014)	36	—	Healthy students	Enterprise Resource Planning software	Boredom/ Flow/ Anxiety	ECG, EDA, & EEG	Smaller variation of EDA & lower HR & higher HRV for flow condition
Harmat et al. (2015)	77(40f	27	Healthy subjects	Game Tetris	6 minutes Boredom/ Flow/ Anxiety	fNIRS, ECG, & Res	Larger RD & lower LF-HRV during flow condition

Table 1: Studies on peripheral-physiological correlates of the flow state

Ref.	N subjects	Age mean/ range	Sample	Experiment type	Design	Measure	Peripheral-physiological correlates of flow
Tozman et al. (2015)	18(6f)	19	Healthy students	Sporting race game package Rfactor	6 minutes Boredom/ Flow/ Anxiety	ECG	Negative linear relationship between LF-HRV & flow in flow condition & Inverted U-shaped relation between LF-HRV / HF-HRV & flow in anxiety condition
Bian et al. (2016)	36(16f)	20-27	Healthy adults	VR game: Air Bombardment	6 minutes gameplay	ECG, Res, & Facial EMG	Inverted U-shaped relationship between LFHRV & HFHRV & flow
Harris et al. (2016)	33(10f)	20	Healthy students	Simulated car racing game	Boredom/ Flow/ Anxiety	ECG & eye gaze position	Lower SD of horizontal gaze position & Lower HF-HRV in flow condition
Ulrich et al. (2016)	23(m)	24	Healthy students	Mental arithmetic task	30 seconds Boredom/ Flow/ Anxiety	fMRI & EDA	Greater EDA during flow
Tian et al. (2017)	40(27f)	17-24	Healthy students	Game Blocmania 3D	6 minutes Boredom/ Flow/ Anxiety	ECG, Res, & EDA	Faster respiratory rate, increased RD, moderate HR, moderate HRV, & moderate EDA
De Sampaio Barros et al. (2018)	20 (7f)	26	Healthy adults	Games Tetris & Pong	3 minutes Boredom/ Flow/ Anxiety / Autonomy	ECG, Res, & NIRS	Lower HRV during autonomy condition
Kozhevnikov et al. (2018)	56(17f)	__	Healthy students	Game Unreal Tournament 2004	30 minutes Boredom/ Flow/ Anxiety	ECG	Lower HF-HRV during playing at flow condition
Moreno et al. (2020)	1	27	Expert gamer	Game Portal	45 minutes gameplay	EDA, EEG	Increased EDA during moments of goal attainment

ECG = electrocardiography; EEG = electroencephalography; EMG = electromyography; EDA = electrodermal activity; BP = blood pressure; T = temperature; HR= heart rate; HP= heart period; ZM = zygomaticus major; CS = corrugator supercilii; HRV = heart rate variability; LF-HRV = low frequency heart rate variability ; HF-HRV = high frequency heart rate variability; Res = respiration; RD = respiratory depth; fNIRS = functional near-infrared spectroscopy; NIRS = near-infrared spectroscopy; fMRI = functional magnetic resonance imaging; FPS = first person shooter; SD = standard deviation; m = male; f = female

Table 2(on next page)

Table 2: Studies on neural correlates of the flow state: brain imaging investigations

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Table 2: Studies on neural correlates of the flow state: brain imaging investigations

Ref.	N subjects	Age mean/ range	Sample	Experiment type	Design	Measure	Neural correlates of flow
Klasen et al. (2008)	18	—	—	FPS game: Counter Strike	12 minutes gameplay	fMRI	Correlation between game pleasure & cerebro-thalamic motor & visual network activity
Klasen et al. (2012)	13(m)	18-26	Healthy students	FPS game : Tactical Ops: Assault on Terror	12 minutes gameplay	fMRI	Activation of somatosensory networks & motor areas during situations with enhanced probability of flow
Ulrich et al. (2014)	27(m)	23	Healthy students	Mental arithmetic task	184 seconds Boredom/ Flow/ Anxiety	Perfusion MRI	Increased activity in the left IFG, left putamen, & posterior cortical regions as well as decrease in MPFC and AMY during flow
Yoshida et al. (2014)	20(10f)	21–25	Healthy students	Game Tetris	4 minutes Boredom & Flow	fNIRS	Higher activation in VLPFC during flow condition
Harmat et al. (2015)	77(40f)	27	Healthy subjects	Game Tetris	6 minutes Boredom/ Flow/ Anxiety	fNIRS, ECG, & Res	No association between frontal cortical oxygenation & flow
Ulrich et al. (2016)	23(m)	24	Healthy students	Mental arithmetic task	30 seconds Boredom/ Flow/ Anxiety	fMRI & EDA	Increased activity in the left IFG, left putamen, & posterior cortical regions as well as decrease in MPFC, PCC and AMY during flow
De Sampaio Barros et al. (2018)	20 (7f)	26	Healthy adults	Games Tetris & Pong	3 minutes Boredom/ Flow/ Anxiety/ Autonomy	ECG, Res, & NIRS	Higher activation in lateral PFC & deactivation in MPFC in Autonomy condition
Ulrich et al., (2018)	22(m)	24.9	Healthy students	Mental arithmetic task	170 seconds Boredom/ Flow/ Anxiety	Perfusion MRI & tDCS	Increase in the flow index of lower-flow group under anodal midfrontal tDCS stimulation & stronger deactivation of AMY

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Table 2: Studies on neural correlates of the flow state: brain imaging investigations

Ref.	N subjects	Age mean/ range	Sample	Experiment type	Design	Measure	Neural correlates of flow
Gold & Ciorciari (2019)	11(m) 21(11f)	29-31	Trained & untrained gamers	FPS game: Counter Strike: Global Offensive or Battlefield 4 & game Tetris	20 minutes & 3 minutes Boredom/ Flow/ Anxiety	tDCS	Higher level of flow after the active tDCS over DLPFC & right parietal cortex
Ju & Wallravan (2019)	31(m)	24.8	Healthy students	Car driving game	3 minutes blocks of gameplay	fMRI	Positive correlations between the flow experience and brain activity in regions related to visual and spatial execution as well as attentional processes & negative correlations with the DMN's activity

fMRI = functional magnetic resonance imaging; MRI = magnetic resonance imaging; fNIRS = functional near-infrared spectroscopy; NIRS = near-infrared spectroscopy; ECG = electrocardiography; EDA = electrodermal activity; tDCS = transcranial direct-current stimulation; FPS = first person shooter; Res = respiration; IFG = inferior frontal gyrus; PFC = prefrontal cortex; MPFC = medial prefrontal cortex; AMY= amygdala; VLPFC = ventrolateral prefrontal cortex; DLPFC = dorsolateral prefrontal cortex; PCC = posterior cingulate cortex; DMN = default mode m = male; f = female

Table 3(on next page)

Table 3: Studies on neural correlates of the flow state: neural oscillation investigations

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Table 3: Studies on neural correlates of the flow state: neural oscillation investigations

Ref.	N subjects	Age mean/ range	Sample	Experiment type	Design	Measure	Neural correlates of flow
Kramer et al. (2007)	10 (5f)	18-24	Healthy students	Driving video game	Playing trials	EDA & EEG	Greater left temporal alpha predicted performance level
Chanel et al. (2011)	20(7f)	27	Healthy subjects	Game Tetris	5 minutes Boredom/ Flow/ Anxiety	EDA, BP, Res, T, & EEG	Distinct theta & beta power between conditions
Nacke et al. (2011)	25(m)	19-38	Healthy students	Game Half-Life 2	10 minutes Boredom/ Immersion/ Flow	EEG	Higher theta & delta power in immersion
Berta et al. (2013)	22 (5f)	26.3	Healthy students	Plane battle game	4 minutes Boredom/ Flow/ Anxiety	EEG	Lowest mean alpha & low-beta in the flow state
Wang & Hsu (2014)	20(10f)	19-27	Healthy students	Computer-based instruction	7-9 minutes Boredom/ Flow/ Anxiety	EEG	EEG attention value was related to overall flow and flow dimensions
De Kock (2014)	20(m)	16-45	Healthy subjects	Game: Need for Speed – Carbon	Low flow-performance/ High flow-performance	EEG	Increased low-beta power in the sensorimotor cortex as well as low-beta synchronization between all cortical connections for high-flow
Leger et al. (2014)	36	__	Healthy students	Enterprise Resource Planning software	Boredom/ Flow/ Anxiety	ECG, EDA & EEG	Higher alpha & lower beta during medium content
Wolf et al. (2015)	35 (9f)	<36	Table-tennis players	Motor imagery paradigm	7 seconds video clips	EEG	Positive correlation between T4-T3 alpha asymmetry & flow score in the experts

Table 3: Studies on neural correlates of the flow state: neural oscillation investigations

Ref.	**N** subjects	**Age** mean/ range	**Sample**	**Experiment type**	**Design**	**Measure**	**Neural correlates of flow**
Metin et al. (2017)	20(7f)	20-35	Healthy subjects	Ping-pong game	2 minutes Boredom/ Flow	EEG	Greater theta & delta power during flow condition
Katahira et al. (2018)	16(6f)	21.9	Healthy students	Mental arithmetic task	184 seconds Boredom/ Flow/ Anxiety	EEG	Increased theta activity in the frontal areas, moderate alpha activities in the frontal & central areas.
Moreno et al. (2020)	1	27	Expert gamer	Game Portal	45 minutes gameplay	EDA, EEG	Increased beta activity during moments of goal attainment

ECG = electrocardiography; EEG = electroencephalography; EDA = electrodermal activity; Res = respiration; BP = blood pressure; T = temperature; SD = standard deviation; m = male; f = female

Table 4(on next page)

Table 4: Studies on neural correlates of the flow state: dual-task paradigms

Table 4: Studies on neural correlates of the flow state: dual-task paradigms

Ref.	**N** subjects	**Age** mean/ range	**Sample**	**Experiment type**	**Design**	**Measure**	**Neural correlates of flow**
Castellar et al. (2016)	18(9f)	28.5	Healthy subjects	Game Star reaction & Auditory oddball detection	Boredom/ Flow/ Anxiety	EEG	Delayed maximal frontocentral negative deflection after the response onset during flow
Yun et al. (2017)	29(5f)	23.5	Healthy subjects	FPS game: Call of Duty & Random beeping sound	30 minutes Low challenge/ High challenge	EEG	Suppressed evoked potential derived from ERSP during self-reported experience of flow
Bombeke et al. (2018)	18(3f)	25	Healthy students	FPS game Counter-Strike: Global offensive & Auditory oddball detection	8 minutes Boredom/ Flow/ Anxiety	EEG	Mid-line P300 amplitude smaller in VR compared to playing in 2D during flow condition
Huskey et al. (2018)	18(m)	__	Healthy students	Game Asteroid Impact & Secondary reaction time	2 minutes Boredom/ Flow/ Anxiety	fMRI	Higher activity in DLPFC, SPL, DAI, & putamen during flow condition

EEG = electroencephalography; fMRI = functional magnetic resonance imaging; ERSP = event-related spectral perturbation; VR = virtual reality; DLPFC = dorsolateral prefrontal cortex; SPL= superior parietal lobe; DAI = dorsal anterior insula; m = male; f = female