

# 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 underlying 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.

1 **Peripheral-physiological and neural correlates of flow**  
2 **experience while playing video games: a**  
3 **comprehensive review**

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## 24 **Abstract**

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

## 36 **Introduction**

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

54 Among the nine key dimensions of flow, the first three (balance between skills and challenges,  
55 clear goals and immediate feedback) are antecedents or preconditions for flow, and the  
56 remaining six items as components or characteristics of this subjective state. Optimal skill-  
57 challenge balance is considered the main antecedent which facilitates entering in to the flow state  
58 (Csikszentmihalyi & Csikszentmihalyi, 1992; Engeser & Rheinberg, 2008; Fong, Zaleski, &  
59 Leach, 2015; Keller & Blomann, 2008). Whenever the challenge level of the activity outweighs  
60 the skill level of the person performing it, the person will become frustrated and anxious. In  
61 contrast, if the challenge level is lower than the skill level, the person will become bored (the

62 flow channel model; Csikszentmihalyi, 1975, 1990). Although skill-challenge balance is a  
63 **perquisite** for the flow experience, one should consider that it does not guarantee entering into  
64 the flow state. Fong et al. (2015) showed that additional variables such as age, cultural  
65 characteristics, domain of application (leisure or work/education contexts), and methodology  
66 (how the skill-challenge balance has been evaluated) may distinctively influence the relationship  
67 between flow and skill-challenge balance. Engeser & Rheinberg (2008) showed that in important  
68 activities flow was still high even when the demand was low. The moderating impact of  
69 personality characteristics, such as action-state orientation, was investigated and it was revealed  
70 that individuals with a strong habitual action orientation are more sensitive to modulations of the  
71 skill-challenge balance (Keller & Bless, 2008). The likelihood of the ensuing flow experience  
72 can also be altered by personality factors. A study by Ullén and colleagues reported a negative  
73 correlation between flow proneness (understood as the individual propensity to experience flow)  
74 and neuroticism (Ullén et al., 2012). De Manzano et al. (2013) suggested that lower trait  
75 impulsivity could facilitate the propensity to experience flow. Flow and performance also seem  
76 to be closely related (Csikszentmihalyi, Abuhamdeh, & Nakamura, 2005; Engeser & Rheinberg,  
77 2008; Jin, 2012; Keller & Bless, 2008; Landhäuser & Keller, 2012). High performance levels are  
78 typically expected during the experience of flow, since frustration and boredom would lead to  
79 diminished concentration and consequently to a poor performance. It is still unclear whether flow  
80 influences performance or vice versa (De Kock, 2014; Landhäuser & Keller, 2012). Engeser and  
81 Rheinberg (2008) found that the flow experience led to improved performance in participants  
82 who played the game *Pac-Man* at three difficulty levels, while Jin (2012) reported that  
83 successful performance resulted in a greater flow experience in participants who played the  
84 games *Call of Duty: world at war* and *Trauma Center: New Blood*.

85 The concept of flow was initially investigated using the Experience Sampling Method (ESM) in  
86 naturalistic contexts (Csikszentmihalyi & Csikszentmihalyi, 1992). This method involves  
87 signaling participants at random moments throughout the day and asking them questions about  
88 the nature and quality of their experience (Csikszentmihalyi & Larson, 1983). Later studies  
89 optimized the ESM and designed new questionnaires to evaluate the flow experience. Some of  
90 these are the Flow State Scale (FSS, Jackson & Marsh, 1996) specific for the context of sports,  
91 the Flow Short Scale (FSS, Rheinberg & Vollmeyer, 2003) developed for different fields of  
92 activity, the flow subscale of the game experience questionnaire (GEQ, IJsselsteijn, De Kort,  
93 Poels, Jurgelionis, & Bellotti, 2007) designed for evaluation of the subjective gaming experience,  
94 the virtual-course flow measure (Shin, 2006) developed for the context of online learning, the  
95 flow state scale for occupational tasks (Yoshida et al., 2013), and the work related flow inventory  
96 (WOLF, Bakker, 2008) **specific** aimed at measuring the flow of employees. However,  
97 assessment of the flow experience with these retrospective questionnaires interrupts the ongoing  
98 activity and probably disrupts the flow experience. Utilizing these self-reported post-task  
99 questionnaires cannot provide information about characteristics of this experience like mean  
100 duration or depth of flow either. Hence, it is very important to find non-disruptive objective  
101 measures to evaluate the flow experience continuously. One way to assess this experience

102 without interrupting it is to find neural and electrophysiological correlates of this state, which in  
103 turn might help to better understand the underlying physiological mechanisms.

104 Considering the easy establishment of game-based, flow-inducing paradigms in the laboratory,  
105 video games are one of the best tools to elicit this experience. Games offer challenging tasks that  
106 require training skills and provide clear goals, as well as immediate feedback (Alvarez Igarzábal,  
107 2019; Salen & Zimmerman, 2003). An important driver of enjoyment in games comes from  
108 *effectance motivation*, a term coined by Nacke (2012), which is the feeling of empowerment in  
109 players when they see the impact of their actions. This feeling of empowerment can be  
110 experienced when the game's challenge matches the player's skills and goals and immediate  
111 feedback is provided. Inducing flow states under controlled laboratory conditions has been  
112 considered difficult. The most popular experimental approach used for inducing flow is  
113 manipulating the difficulty level of games to achieve the necessary skill-challenge balance. This  
114 can be achieved either through the dynamic matching of the game's difficulty level to the  
115 player's skill level (Keller & Bless, 2008; Rheinberg & Vollmeyer, 2003) or by pre-testing the  
116 participants' skills to individually assign appropriate matching challenge levels in the game  
117 (Moller, Csikszentmihalyi, Nakamura, & Deci, 2007). This can in turn help to contrast three  
118 experimental conditions of easy, optimal, and overwhelming. Using a self-selected level of  
119 difficulty (autonomy) is also suggested to be an important determinant of flow (De Sampaio  
120 Barros et al., 2018; Moller, Meier, & Wall, 2010). Immersion – another mental state explored in  
121 some studies – was described as the gradual process of transporting the player's mind into the  
122 virtual world which is linked to factors like graphics, sound and gameplay (Nacke & Lindley,  
123 2008, 2010). Despite similarities, immersion presents subtle structural differences from flow  
124 (Michailidis, Balaguer-Ballester, & He, 2018) and will not be explored in this review. Rheinberg  
125 and Vollmeyer (2003) evaluated the impact of modulating the task difficulty on flow experience  
126 in two different video games: *Roboguard* and *Pac-Man*. The highest level of flow was reported  
127 following those trials when the game's difficulty was set to a medium level (flow) rather than to  
128 a low (boredom) or high (anxiety) level. For the sake of consistency, given that different studies  
129 label conditions in different ways, in the following we will refer to the overwhelming and easy  
130 conditions as the “anxiety” and “boredom” respectively, and to the optimal condition as “flow.”

131 The flow state is an experiential feature of altered states of consciousness which can lead to a  
132 diminished sense of self and time (Wittmann 2015, 2018). Video games specifically making time  
133 fly in a pleasant way which is one of the main aspects of the flow experience (Bisson, Tobin, &  
134 Grondin, 2012; Tobin, Bisson, & Grondin, 2010). Distortions in the notions of the self and time  
135 have been reported in many patient groups with psychiatric disorders (Khoshnoud, Shamsi,  
136 Nazari, & Makeig, 2017; Vogel et al., 2019; Vogel, Krämer, Schoofs, Kupke, & Vogeley, 2018).  
137 The sense of self and time is overly represented in individuals with anxiety and depression, who  
138 are stuck with themselves in time, feeling states that are the complete opposite of flow  
139 (Liknaitzky, 2017). Inducing flow states in these individuals could potentially lower symptoms  
140 of anxiety and depression. A study with the video game *Boson X* reported that playing it for six

141 weeks reduced self-rumination and enhanced cognitive capacities in individuals with depression  
142 (Kühn, Berna, Lüdtke, Gallinat, & Moritz, 2018). The induction of flow states has been shown to  
143 alter the sense of time (Sinnott, Jäger, Singer, & Antonini Philippe, 2020). By measuring flow  
144 levels and temporal processing ability (through a temporal order judgment task, TOJ), Sinnott  
145 and colleagues identified that the higher the subjective flow experience of the sport or music  
146 performance, the better the participant performed in the post-performance TOJ task compared to  
147 the pre-performance TOJ task. Considering the beneficial nature of flow on psychiatric  
148 symptoms, creating a flow experience might be a helpful remedy in clinical psychology<sup>1</sup>.

149 Since flow is an enjoyable mental state, keeping the player in a flow state is considered to be one  
150 of the most important goals for game designers (Chen, 2006; Salen & Zimmerman, 2003;  
151 Schell, 2008). To address this, game designers and researchers attempt to maintain the player's  
152 flow state through affect-based, dynamic difficulty-adjustment (DDA) techniques (Afergan et al.,  
153 2014; Liu, Agrawal, Sarkar, & Chen, 2009; Park, Sim, & Lee, 2014). Finding neural and  
154 electrophysiological indicators of this optimal mental state, which are objective and can be  
155 measured without interrupting the experience, could enhance the dynamic difficulty adjustment.  
156 Apart from these internal correlates, another promising approach would be the application of  
157 techniques that indirectly measure the extent to which subjects experience flow by assessing  
158 their levels of attention engagement. Here we provide an overview of all findings concerning the  
159 physiological and neural correlates of the flow experience. To our knowledge, this is the first  
160 review that combines physiological and neural correlates of flow in the context of video games.  
161 Harris et al. (2017) conducted a review on neurocognitive mechanisms of flow with more  
162 emphasis on sports as well as the role of attention suggesting attentional changes as the  
163 fundamental mechanism for creation of flow state. However, in their review, the **rule of**  
164 physiological arousal was not discussed in detail. In a recent systematic review conducted by  
165 Knierim et al. (2018), only peripheral nervous system indicators of flow were explored in a  
166 broad range of tasks identifying increased level of arousal as a central approach to the  
167 physiological measurement of flow. We believe that this paper makes a key contribution to the  
168 field of flow in the context of video games by considering reflections of flow in the central and  
169 peripheral nervous systems and integrating key physiological and neural mechanisms of the flow  
170 experience. Based on the results of the reviewed studies, we make suggestions on how to  
171 disentangle the internal phenomenon of flow from the external characteristics of the task.

## 172 **Survey methodology**

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

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<sup>1</sup> 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 Lugin (Würzburg), Giulio Jacucci, Niklas Ravaja (Helsinki), and Xavier Palomer, Xavier Oromi (Barcelona).

175 OR neurophysiology OR brain activity OR neural activity) AND (game OR video game OR  
176 gameplay)]. This search provided a total of 215 citations. After removing duplicates, the set of  
177 55 articles comprising of peer reviewed, empirical studies with the focus of physiological and  
178 neural phenomenon of flow experience during playing video games without a-priori, publication  
179 date restriction have been selected. By scanning the references listed in the body of literature  
180 found in the initial search, additional 18 studies were identified. In a further attempt by applying  
181 the inclusion criteria to the full text of manuscripts, 35 articles including research with  
182 exergames or multiplayer games are excluded, as they introduce other confounding factors.  
183 Overall the set of 38 articles included in the review were presented in two sections: peripheral-  
184 physiological and neural correlates of flow.

### 185 **Peripheral-physiological correlates of flow**

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



213 inconsistent results during flow state show that the relationship between flow experience,  
214 arousal, and mental effort is highly dependent on the task.

215 \*\* INSERT TABLE 1 HERE \*\*

## 216 **Positive valence and heightened physiological arousal**

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

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

244 Bian et al. (2016) presented a physiological evaluation model for the state of flow in the virtual  
245 reality (VR) game *Air Bombardment*. In contrast to the findings of the study by Nacke and  
246 Lindley, (2008), the authors reported no correlations between ZM activity and flow scores as  
247 assessed by the FKS questionnaire (Bian et al., 2016). Using a mental arithmetic task, a study by  
248 Ulrich and colleagues found an inverse U-shaped pattern for EDA with significantly greater  
249 values during the flow condition than during the boredom and anxiety conditions, highlighting



250 higher arousal levels during the experience of flow (Ulrich, Keller, & Grön, 2016). EDA was  
251 also assessed during playing *Blocmania 3D* game with three difficulty levels corresponding to  
252 boredom, flow, and anxiety (Tian et al., 2017). Difficulty manipulation was assessed with the  
253 FSS questionnaire and the highest flow state which was reported during the flow condition of the  
254 game was associated with moderate EDA activity, which reflects moderate sympathetic arousal.  
255 In a single case-study, Moreno et al.(2020) reported that a flow-like state in an expert gamer  
256 during playing the puzzle game *Portal*, coincided with increased EDA. It should be considered  
257 that in their study physiological assessment was conducted not during the moments of flow but  
258 when individuals were goal-oriented during gameplay.

### 259 **Co-activation of sympathetic and parasympathetic nervous system**

260 Findings regarding the relation between the flow state and ANS are mixed, as both sympathetic  
261 and parasympathetic activities have been shown to correlate with flow, both in combination and  
262 alone. De Manzano et al. (2010) argued that the flow state experienced while playing piano is  
263 linked to increased parasympathetic modulation of sympathetic activity. Their study showed that  
264 the flow reports of the players (as assessed by the FSS questionnaire) correlated with a decreased  
265 heart period (HP, increased SNS activity), decreased heart rate variability (HRV, fluctuations in  
266 the time intervals of adjacent heartbeats and an index of parasympathetic activity (Laborde,  
267 Mosley, & Thayer, 2017)), an increased LF/HF ratio (low frequency HRV/high frequency HRV,  
268 reflecting autonomic balance between SNS and PNS), and larger respiratory depth (RD,  
269 increased PNS activity) (de Manzano et al., 2010). Chanel et al. (2011), in contrast, reported less  
270 low frequency heart rate variability (LF-HRV) power during the experience of flow compared to  
271 boredom and anxiety while playing *Tetris*. In a computerized knowledge task, with the three  
272 levels of boredom, flow, and anxiety, Keller et al. (2011) reported lower HRV during the flow  
273 condition as compared to boredom and anxiety, indicating lower parasympathetic activity. A  
274 more detailed assessment of cardiovascular and respiratory responses was performed by Harmat  
275 et al. (2015) during trials of *Tetris* gameplay in three conditions: boredom, flow, and anxiety.  
276 The flow condition was characterized by the highest levels of flow measured by the FSS  
277 questionnaire, positive affect, and effortless attention. More flow was associated with larger  
278 respiratory depth (reflecting increased parasympathetic activity) and lower LF-HRV (reflecting  
279 both sympathetic and parasympathetic influences). Given the lack of a significant relation  
280 between HF-HRV (high-frequency HRV, a direct measure of parasympathetic activation) and  
281 flow, their results could not clearly support the hypothesis that the flow state is linked to  
282 activation of sympathetic, as well as to the parasympathetic nervous system (Harmat et al.,  
283 2015). Tian and colleagues (2017) also reported moderate HR and HRV along with increased  
284 RD during the flow condition of playing the game, suggesting increased parasympathetic  
285 modulation of sympathetic activity during flow experience. In a FPS game called *Unreal*  
286 *Tournament 2004*, lower HF-HRV was reported in players playing the game during the flow  
287 condition compared to boredom and anxiety conditions (Kozhevnikov, Li, Wong, Obana, &  
288 Amihai, 2018). Given the lack of significant change in the LF-HRV values, authors argued that

289 this pattern of reduction in parasympathetic activity is critical for reaching flow. Nonetheless, the  
290 flow experience was not assessed directly in their investigation and it is not clear whether  
291 subjects felt higher flow while playing the game during the flow condition as compared to the  
292 other two conditions.

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

### 302 **Effortless or effortful attention**

303 According to Ullén et al. (2010), the co-activation of SNS and PNS results from the interaction  
304 between positive affect and high attention, which leads to a state of effortless attention.  
305 Nevertheless, the flow experience is characterized by heightened concentration and high degree  
306 of attention. Specific patterns of activity like increased heart rate, decreased HRV, shallow  
307 respiration, and increased facial EMG activity are signs of mental effort (Aasman, Mulder, &  
308 Mulder, 1987; Backs & Seljos, 1994; Veltman & Gaillard, 1998; Waterink & van Boxtel, 1994),  
309 which are distinctive from the observed results in studies concerned with flow. In contrast to the  
310 idea of effortless attention, Keller et al. (2011) linked reduced HRV to increased mental effort  
311 during the experience of flow in a computerized knowledge task. During simulation-based  
312 training on the use of *enterprise resource planning software* with the three levels of boredom,  
313 flow, and anxiety, Léger et al. (2014) reported less mental effort during the flow situation.  
314 According to their results, participants who exhibited smaller variations in the EDA level (i.e.  
315 being more emotionally stable), lower HR, and higher HRV (indicative of less mental effort)  
316 were reported to be more likely to experience a cognitively absorbed state. Similarly, Peifer et al.  
317 (2014) reported a positive linear relationship between HRV values (HF-HRV) and flow  
318 experience in a computer task (Cabin Air Management System simulation). The participants'  
319 stress level was manipulated via the Trier Social Stress Test (TSST) before they performed the  
320 task. After the task, their flow experience was evaluated with the FKS questionnaire. Flow was  
321 associated to increased HF-HRV and a decrease in mental effort. These results contradicted the  
322 findings by Keller and colleagues (Keller et al., 2011), who found a negative relationship  
323 between flow and parasympathetic activity. Apart from the small number of participants in  
324 Keller's study, these differences showed that during a difficult level of a computerized  
325 knowledge task or game, participants are not likely to perceive as much stress and threat as they  
326 might experience during the TSST, which is designed to create considerable social anxiety.

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

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

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

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

358 The functional association between HRV factors (LF-HRV and HF-HRV) and flow (measured  
359 by the FKS questionnaire) was also assessed during a driving-simulation game (Tozman,  
360 Magdas, MacDougall, & Vollmeyer, 2015). The task used was a driving simulator chosen from  
361 the sporting-race, video-game package *Rfactor* with three fixed levels of difficulty representing  
362 boredom, flow, and anxiety. An increase in task difficulty caused a decrease in the HF-HRV and  
363 LF-HRV components. In contrast to the findings by Peifer et al. (2014), which showed an

364 inverted U-shaped relation between flow and HRV measures, there was a negative linear  
365 connection between LF-HRV and flow when the conditions for flow were met (flow condition)  
366 and an inverted U-shaped relation between LF-HRV and HF-HRV, on the one hand, and flow,  
367 on the other hand, when demands exceeded the skill level (anxiety condition) (Tozman et al.,  
368 2015). In a VR game, Bian et al. (2016) reported similar results to the previous studies showing  
369 that increased HR, HRV, and respiratory rate (RR), as well as shorter inter-beat intervals (IBI),  
370 predict an increase in flow score assessed by the FKS questionnaire. An inverted U-shaped  
371 function between LF-HRV and HF-HRV, on the one hand, and flow on the other hand, was also  
372 reported, highlighting moderate LF- and HF-HRV levels for high flow scores and both low and  
373 high values of LF- and HF-HRV for low-flow scores. The authors stated that the physiological  
374 aspects of flow in VR games might be particularly affected by the VR environment (Bian et al.,  
375 2016).

### 376 **Neural correlates of flow states**

377 There is still considerable conceptual ambiguity concerning the possible brain mechanisms  
378 involved in the flow experience. Here we are going to discuss the main hypotheses established in  
379 the literature. Given the effortlessness and automatic characteristics of flow, Dietrich (2004)  
380 argued that such an optimal performance state is controlled through an implicit rather than an  
381 explicit information-processing system in the brain. The explicit system, which is associated with  
382 higher-order cognitive functions, is rule-based, can be verbalized, is connected to conscious  
383 awareness, and is supported by frontal-lobe activation. In contrast, the implicit system is skill-  
384 based, cannot be verbalized, is inaccessible to conscious awareness, and is supported primarily  
385 by the basal ganglia. Dietrich proposed that inhibition of the explicit system and transient  
386 hypofrontality is a necessary prerequisite for the experience of flow (Dietrich, 2004). The  
387 synchronization theory of flow proposed by Weber et al. (2009) specifies neuropsychological  
388 processes of the flow experience considering that it is characterized by intense concentration and  
389 **an** autotelic activity. This theory is based on Posner's tripartite theory of attention involving  
390 executive, alerting, and orienting networks (Posner, Inhoff, Friedrich, & Cohen, 1987).  
391 Accordingly, the optimal and gratifying experience of flow results from synchronized activity of  
392 the attentional and reward networks under the balanced skill-challenge condition (Weber et al.,  
393 2009).

394 Csikszentmihalyi (1975) described the flow experience as "self-forgetfulness" or "loss of self-  
395 consciousness," highlighting the fact that, when the demands of the activity require the allocation  
396 of all attentional resources, attention is directed away from the self. Loss of self-awareness, as  
397 one of the important components of flow, sheds light on another interesting line of research that  
398 investigated default mode networks (DMN) activity during the flow experience (Sadlo, 2016).  
399 The activity of the DMN has been linked to self-referential thinking, and therefore declines in  
400 task-focused and goal-directed actions (Goldberg, Harel, & Malach, 2006; Raichle et al., 2001).  
401 During moments of flow, the activity of DMN decreases, highlighting less self-referential

402 processing (Peifer, 2012; Sadlo, 2016). Table 2 presents a set of articles exploring brain  
403 activation during the flow experience.

404 \*\* INSERT TABLE 2 HERE \*\*

### 405 **Transient Hypofrontality**

406 The transient hypofrontality hypothesis proposed by Dietrich (2004) was addressed by a few  
407 studies. Applying brain imaging techniques in a blocks of mental arithmetic task with the three  
408 levels of task difficulty of boredom, flow, and anxiety, Ulrich et al. (2014, 2016) reported a  
409 relative decrease in the activity of the medial prefrontal cortex (MPFC). However, other studies  
410 failed to further support this idea. In a functional near-infrared spectroscopy (fNIRS) study,  
411 Yoshida et al. (2014) explored the activity of the prefrontal cortex (PFC) during flow while  
412 playing a video game and failed to support the transient hypofrontality hypothesis. The task was  
413 performed under the two conditions of boredom and flow while playing *Tetris*. Flow score  
414 assessed with the flow state scale for occupational tasks (Yoshida et al., 2013), was higher in the  
415 flow than the boredom condition. Significantly higher activation of the left and right  
416 ventrolateral prefrontal cortex (VLPFC) was reported during the last 30 seconds of flow than  
417 throughout the entire flow condition, while the same trend was not seen during the boredom  
418 condition (Yoshida et al., 2014). Harmat et al. (2015) also failed to show an association between  
419 flow while playing a video game and decreased activity in frontal brain regions. None of their  
420 fNIRS analyses revealed associations between lower frontal cortical activation and flow,  
421 suggesting that the neural substrates of flow may vary depending on the task (Harmat et al.,  
422 2015). De Sampaio Barros et al. (2018) recorded the cerebral hemodynamics of 20 volunteers  
423 while they played *Tetris* and *Pong*. The flow and autonomy playing conditions not only led to  
424 higher activation in the lateral PFC, but also led to higher deactivation in the MPFC compared to  
425 the other conditions.

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







514 cathodal tDCS) and the measured flow index across all subjects. After splitting the subjects into  
515 two groups based on the flow index in the sham condition (lower-flow and higher-flow), a  
516 significant increase in the flow index in the lower-flow group under anodal tDCS stimulation  
517 was reported. Correspondingly, anodal tDCS elicited a significantly stronger deactivation of the  
518 right AMY in this group compared to the higher-flow group (Ulrich et al., 2018).

### 519 **Neural oscillations and flow**

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

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

538 \*\* INSERT TABLE 3 HERE \*\*

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





627 extent to which subjects experience flow by assessing their levels of attention engagement.  
628 Based on the flow theory (Csikszentmihalyi & Csikszentmihalyi, 1992), focused attention during  
629 the experience of flow leads to complete absorption in an activity to the extent that one does not  
630 allocate attentional resources to irrelevant external stimuli. During boredom or anxiety,  
631 attentional disengagement from the task makes it more likely that an individual will pay attention  
632 to irrelevant stimuli. These considerations led to an interesting line of research using dual-task  
633 paradigms to indirectly measure electrophysiological correlates of the flow experience (see Table  
634 4). Secondary-task reaction times were suggested as reliable and valid measures of available  
635 attentional resources (Weber, Alicea, Huskey, & Mathiak, 2018).

636 \*\* INSERT TABLE 4 HERE \*\*

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

648 A study by Yun et al. (2017) extended the secondary-task idea by adding a passive random  
649 beeping sound while subjects played an FPS game (*Call of Duty : Modern Warfare 2*). Complete  
650 absorption in the game world was expected to lead to the neglect of the game-irrelevant sensory  
651 stimulation from the real world, which is reflected by the suppression of auditory evoked  
652 potentials (AEPs) of EEG signals elicited by random beeps. Due to the insufficient number of  
653 trials and background noise, the typically detected AEPs were not observable, and the authors  
654 instead analyzed event-related spectral perturbation (ERSP) suppression at low frequencies in the  
655 flow trials. A significant correlation was reported between the suppressed evoked potential  
656 derived from ERSP and the self-reported experience of flow. By utilizing source-localization  
657 algorithms, the activation of the ACC and temporal pole was reported during flow trials only in  
658 the beta-frequency range. Subjective flow ratings also positively correlated with activation in  
659 these regions, suggesting a link between the flow experience and high concentration, focused  
660 attention, and less self-referential processing (Yun et al., 2017). Auditory oddball sounds were  
661 also applied as a secondary task in a VR gaming context to explore attentional allocation during  
662 the experience of flow (Bombeke, Dongen, Durnez, & Anzolin, 2018). Participants played a  
663 shooter game *Counter-Strike: Global Offensive* under three conditions (boredom, flow, and  
664 anxiety) both in a 2D and a VR set-up while they were simultaneously asked to respond to the

665 oddball sounds. Their results did not replicate the results of the previous study by Castellar et al.  
666 (2016) reporting higher reaction times and more errors in the flow condition. A smaller posterior  
667 mid-line P300 amplitude was reported (marginally significant) in VR compared to playing on 2D  
668 during the flow condition. The flow ratings measured with the Flow Questionnaire (FQ, Sherry  
669 et al.,(2006)) did not show significant differences among the different gaming conditions, and it  
670 is unclear whether participants really experienced boredom, flow, and anxiety in this set-up.  
671 Through the application of a secondary-task reaction time (STRT) procedure while playing the  
672 game *Asteroid Impact* at three levels of difficulty (boredom, flow, and anxiety), Huskey et al.  
673 (2018) reported the greatest intrinsic reward (measured by the autotelic experience subscale of  
674 the FSS questionnaire) and longer reaction times during the flow condition. Their results  
675 revealed that the flow condition elicited significantly greater activity in the areas related to  
676 cognitive control (DLPFC), orienting attention (superior parietal lobe; SPL), attentional alerting  
677 (dorsal anterior insula, dAI), and reward networks (putamen). These results correlate well with  
678 the synchronization theory of flow. The low-difficulty condition evoked activity in DMN  
679 structures which was absent in the high-difficulty condition (Huskey et al., 2018).

## 680 **Discussion**

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

## 689 **State of positive valence and heightened arousal**

690 Activity in the smiling (ZM, positive association) and frowning muscles of the face (CS,  
691 negative association), and larger respiratory depth during flow states represent positive affect (de  
692 Manzano et al., 2010; Harmat et al., 2015; Kivikangas, 2006; Mauri, Cipresso, Balgera,  
693 Villamira, & Riva, 2011; Nacke & Lindley, 2008). The pattern of arousal modulation, however,  
694 is somewhat complex and varies in how studies used it to distinguish flow states from straining  
695 experiences such as stress. Peifer and colleagues (2014) proposed an inverted U-shaped function  
696 between flow experience and physiological arousal. If we consider the relationship between flow  
697 and performance (Csikszentmihalyi et al., 2005; Engeser & Rheinberg, 2008; Jin, 2012; Keller &  
698 Bless, 2008; Landhäußer & Keller, 2012), this pattern aligns well with the classic Yerkes-  
699 Dodson Law, which proposes an inverted U-shaped association between arousal and  
700 performance (Yerkes & Dodson, 1908). Nevertheless, findings concerning the sympathetic and  
701 parasympathetic reflections of arousal are heterogeneous, given that both linear (Chanel et al.,



740 in contrast, studies with observed higher HRV suggested lower mental effort (Bian et al., 2016;  
741 Peifer et al., 2014). The inconsistencies of findings regarding mental effort and flow experience  
742 could be partly traced back to the imprecise measures used for assessing mental effort. Although  
743 HRV has been found to be a sensitive measure of mental effort (Aasman et al., 1987; Backs &  
744 Seljos, 1994; Waterink & van Boxtel, 1994), Veltman and Gaillard (1998) argued the opposite,  
745 as it can be affected by respiratory activity. For instance, during moments with more respiration,  
746 differences in mental effort measured by HRV might be overestimated. It is therefore necessary  
747 to test more precise measures of the cardiovascular control system's suppression as a result of  
748 mental effort. Blood glucose and pupil dilation were suggested as sensitive measures for  
749 exploring mental effort (Sapuro, Shih, Jangraw, & Sajda, 2016; Tozman & Peifer, 2016) which  
750 has not been investigated in the concept of flow.

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

## 767 **Synchronized activation of attentional and reward networks**

768 Flow is considered to be a state with focused attention which is intrinsically rewarding, as the  
769 flow-inducing task is performed for its own sake. Some studies support the synchronization  
770 theory of flow (Weber et al., 2009) by showing the joint activation of frontoparietal attention  
771 networks (e.g. IFG and inferior parietal lobe) and reward networks (e.g. putamen, thalamus)  
772 during the flow experience (Castellar et al., 2016; De Sampaio Barros et al., 2018; Huskey et al.,  
773 2018; Ju & Wallraven, 2019; Klasen et al., 2012; Ulrich et al., 2016, 2014; Yoshida et al., 2014).  
774 A positive correlation between dopaminergic receptor availability in the striatum and putamen  
775 and flow proneness supports this theory and shows that the experience of flow is intrinsically  
776 rewarding (de Manzano et al., 2013).







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

### 863 **Remaining issues and future research considerations**

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

876 The associations between performance and arousal (Yerkes & Dodson, 1908) and flow and  
877 arousal (Peifer et al., 2014) suggest a close relationship between flow experience and  
878 performance. Nonetheless, the direction of this association has not yet been clearly investigated.  
879 It has been demonstrated that flow as a state of high concentration and a sense of control could  
880 actually motivate subjects to improve their performance (Engeser & Rheinberg, 2008; Jin, 2012;  
881 Landhäußer & Keller, 2012). While the association between flow and optimal performance has  
882 been described in academic activities, music, and sports (Landhäußer & Keller, 2012), there  
883 were few studies reporting a relationship in the gaming context (De Kock, 2014; Engeser &  
884 Rheinberg, 2008; Jin, 2012; Keller & Bless, 2008; Yun et al., 2017). Some studies failed to find  
885 an association between flow and optimal performance (Harris et al., 2016; Katahira et al., 2018;  
886 Ulrich et al., 2016, 2014) reporting medium levels of performance for the flow condition. It is  
887 noteworthy that the positive association was mostly reported in studies in which components of  
888 subjective flow were directly measured instead of assessing behavioral levels of challenge and  
889 skills (De Kock, 2014; Yun et al., 2017). More precisely, the causal relationship between flow  
890 and performance cannot be tested in typical cross-sectional experimental paradigms using

891 difficulty manipulations. A longitudinal design is required to assess causality (Keller & Bless,  
892 2008; Landhäuser & Keller, 2012). Considering this, performance might also be considered as  
893 an objective measure that, in combination with other measures (e.g. physiological and neural  
894 indices, subjective self-reports, and secondary reaction times), could precisely capture the actual  
895 emergence of flow. We argue that future studies should consider using objective measures beside  
896 subjective scales and self-reports to capture the actual emergence of flow.

## 897 **Conclusions**

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

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914

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**Table 1** (on next page)

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

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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 Bloccmania 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 supercillii; 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

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

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

<b>Ref.</b>	<b>N</b> subjects	<b>Age</b> mean/ range	<b>Sample</b>	<b>Experiment</b> <b>type</b>	<b>Design</b>	<b>Measure</b>	<b>Neural correlates of flow</b>
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

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

<b>Ref.</b>	<b>N</b> subjects	<b>Age</b> mean/ range	<b>Sample</b>	<b>Experiment</b> <b>type</b>	<b>Design</b>	<b>Measure</b>	<b>Neural correlates of flow</b>
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

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**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