Degree project

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Brain activity during flow: A systematic review

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Abstract

The flow state is a subjective experience that most people can relate to. It represents an optimal balance between skills and difficulty and is the state that people often refer to when performing their best, with phrases like: "I was in the zone" or "I was in the bubble". The flow state has mainly been studied through its psychological and behavioral components; it is not until lately the neuroscientific aspects have been investigated. This review attempts to go through the existing literature and find potential neural signatures of the flow state. The studies indicate that flow is related to activity in the dorsolateral prefrontal cortex and putamen, but the findings are too divided to reach a conclusion.

Keywords: flow state, neural signatures, functional magnetic resonance imaging, functional near-infrared spectroscopy, electroencephalogram.

Brain activity during flow: A systematic review

Introduction

Try to remember those moments as a child when you were fully absorbed with the game you played. You could continue all day and the time seemed to fly away. The same can be experienced when you get stuck in an extremely interesting topic around the dinner table and have a feeling that everything you say comes out automatically. Csikszentmihalyi (1990) describes this state as the "optimal experience", which refers to a sense of excitement and full enjoyment when individuals voluntarily and with full immersion accomplish something challenging.

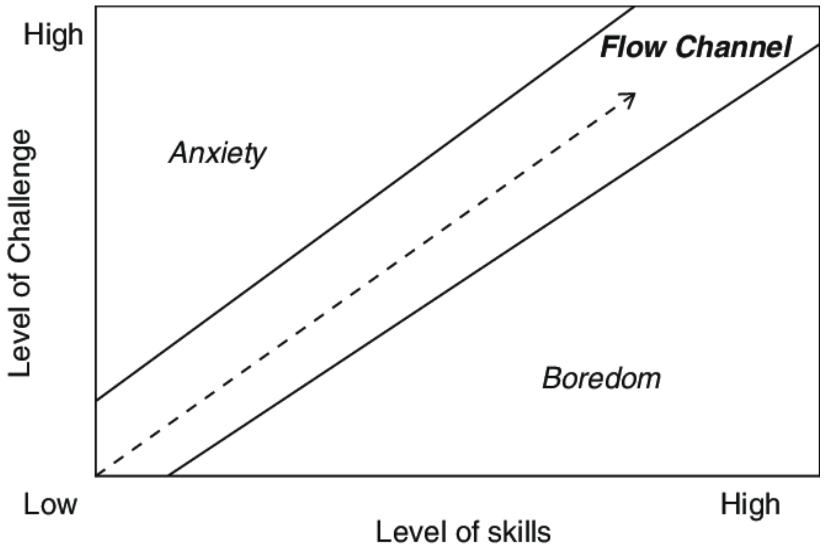
The state described above is called the *flow state*. The term was introduced by Csikszentmihalyi (1975) and his findings became a starting point for the science of flow. The flow state has ever since been connected to positive psychology and is an important aspect of wellbeing (Seligman & Csikszentmihalyi, 2000).

To experience flow, some conditions must be fulfilled (Csikszentmihalyi, 1990). The established characteristics include nine components: (a) clear goals, where the person feels that the goals are attainable; b) the task at hand requires full attention; c) reduced self-awareness where the person does not analyze her actions; d) reduced sense of time; e) immediate feedback on the action, i.e., the person knows immediately if the action is successful; f) the activity has a balance between challenge and skill level; g) a feeling of control; h) the task is rewarding in itself and guided by intrinsic motivation; and i) the focus is limited, affording full absorption with the task (Kawabata & Mallett, 2011; Nakamura & Csikszentmihalyi, 2002). Most essentially, the flow state requires a balance between self-perceived skill and challenge (Csikszentmihalyi, 1990; Engeser & Rheinberg, 2008). This is illustrated by Csikszentmihalyi (1975) in the *Flow Channel Model* (see Figure 1). People tend to become anxious when a task becomes too difficult, while they become bored when it becomes too easy.

Similar experience to flow has been of interest in science historically, especially within humanistic psychology (Gold & Ciorciari, 2020). Maslow (1964) named a similar experience a "peak experience": a feeling of fulfillment, happiness, and a sense of reaching one's full potential. However, a deep examination of flow was not conducted until Csikszentmihalyi (1975) coined the term "flow".

Figure 1.

Csikszentmihalyi's (1975) Flow Channel Model



Note. The flow state requires a balance between skills and challenge, or it can lead to anxiety or boredom. Adapted from *Beyond Boredom and Anxiety* (p. 49), by M. Csikszentmihalyi, 1975, Jossey-Bass Publishers. Copyright 2000 by John Wiley & Sons. Adapted with permission.

Benefits of flow

The flow state is beneficial in several areas of life. One of the most studied areas is sports, primarily focused on the correlation between the reported flow experience and performance (Jackson & Csikszentmihalyi, 1999). The flow state is often referred to as "being in the zone" or the athlete's "optimal performance state". Studies suggest that flow leads to increased performance (Ferrell et al., 2006; Jackson et al., 2001; Wolf et al., 2015). Other research areas of flow are, among others, computer gaming, learning, music, and productivity. In computer gaming, games are designed to heighten the feeling of flow during play: e.g., a balance between skill and difficulty arranged by different levels of difficulty (Chou & Ting, 2003; Harmat et al., 2015). This facilitates opportunities to use games for learning, where recent studies suggest that flow could be used to learn more efficiently (Yazidi et al., 2020; Yeh et al., 2019). In music, musicians report flow experiences during their performance, which is most verifiable during improvisation pieces where musicians report a sense of total immersion with the music (Keeler et al., 2015; de Manzano et al., 2010).

Some studies (Ara et al., 2009; Bakker & van Woerkom, 2017; Eisenberger et al., 2005) suggest that workplaces can benefit from applying organizational structures that allow workers to achieve flow experiences, including provision of direct feedback, a balance between the skills and difficulty and a sense of controlling the outcome (Ara et al., 2009;

Bakker & van Woerkom, 2017; Eisenberger et al., 2005). Ara et al. (2009) mean that there is an association between flow and productivity, which can increase efficiency in the workplace.

In a study by Engeser and Baumann (2016), 100 workers with different professions were evaluating their experience at random times for one week. With a total of 4,504 measurements, the results showed that flow was most frequently reported at their respective workplace. This was especially reported when the workers were planning and organizing. They mean that the lowest rate of flow experiences occurs in passive leisure (e.g., passively resting, watching TV, etc.). This is confirmed by other studies (Bassi & Delle Fave, 2012; Csikszentmihalyi & LeFevre, 1989). That would expectedly lead to a willingness to work instead of being home and participating in leisure activities. However, studies have shown that workers report that they want to do leisure activities if they have a choice. This has been referred to as the "paradox of work" (Csikszentmihalyi & LeFevre, 1989). However, the results of the mentioned studies cannot tell whether the individuals experienced flow, only that the results from the questionnaire indicate when it did or not. It is possible that there are other factors related to the flow experience at work.

Downsides of flow

Although flow is rewarding and, in many ways, positive, it can have negative effects. According to Csikszentmihalyi (1990), flow can become addictive and things outside the flow state can become less interesting compared to the flow activity. Flow is not always correlated with activities that generally have positive outcomes. Some individuals who cannot find flow experiences in daily life may find flow activities in addictive or destructive behavior, such as internet game addiction or vandalism (Chou & Ting, 2003; Csikszentmihalyi, 1999). Hull et al. (2013) measured the relationship between game addiction and the flow state of 110 video game players and found that the most significant predictor of addiction was the distortion of time perception in the flow state. They suggest that setting time limits when playing would help gamers to avoid addictive tendencies. It should be mentioned, however, that the negative sides of the flow state have not been studied as much as the positive sides. The addictive aspects of flow are therefore mostly theoretical and need more empirical data.

Who experiences flow?

Cultural differences

There seem to be cultural differences regarding the frequency of flow experiences, although research is limited. In a study of Japanese college students, more than 90% reported that they experienced flow less than once a week, 1.2% once a day, and 27.3% reported that they never had flow experiences (Asakawa, 2009). Earlier research in Germany and the USA suggests that 10% of Germans and 12% of Americans never experience flow, whereas 23% of Germans and 16% of Americans reported an experience of flow daily

(Csikszentmihalyi, 1997; Nakamura & Csikszentmihalyi, 2002). These results should be interpreted with caution, as the measurement tools were different and performed on different subject groups.

According to some researchers, these differences might be explained by cultural differences regarding the view of the individual. Kitayama et al. (1997) claim that North Americans and Western Europeans have a tendency toward independence and self-actualization among individuals: i.e., putting one's own rights and needs first. They suggest that people in Japan generally have a more interdependent approach: i.e., individuals work best as a part of a larger community and thrive in connectedness to others. This is, however, a simplified view of culture.

Personality differences

Personality differences affect the flow experience. In studies of proneness to flow, researchers have found a negative correlation between flow and neuroticism (Heller et al., 2015; Mosing et al., 2012). Neuroticism, as one of the factors in the Big Five model of personality traits (John & Srivastava, 1999), reflects anxiety, self-consciousness, and increased awareness of dangers. This leads to the conclusion that neuroticism harms the ability to be fully absorbed during a task. People who are high in openness to experience and self-determination more easily concentrate on a task with an autotelic nature (i.e., rewarding in itself) which affords more flow experiences (Baumann & Scheffer, 2010). Other individual differences, like age and gender, do not show significant relation to reported flow (Bonaiuto et al., 2016).

Passion for the activity seems to modulate flow experiences. Vallerand et al. (2007) define passion as a strong tendency to participate in an activity that individuals enjoy, find important and want to invest their time and energy in. Vallerand et al. divide passion into two categories: harmonious and obsessive. Harmonious passion facilitates more flow experiences compared to obsessive passion. Although people with obsessive passion are better prepared with clear goals, they tend to focus on the results rather than being in the moment. They also have higher risk of burnout, while people with harmonious passion report higher subjective well-being (Lavigne et al., 2012).

How to measure flow

The most used method to measure flow is questionnaires and interviews: for example, the Flow Short Scale (Rheinberg et al., 2003) or Flow State Scale (Jackson & Marsh, 1996). The questionnaires are constructed differently but commonly consist of a Likert-scale to rate the experience. A downside of these methods is that it is impossible to answer the questions in a flow state since flow requires full attention and reduced self-consciousness

(Csikszentmihalyi, 1990). Another common measure of flow experiences in a more ecological setting is the Experience Sampling Method (Larson & Csikszentmihalyi, 2014). In this method, participants are asked to provide self-reports of their emotions, thoughts and present activity at random times during the day.

To detect neural correlates of flow, psychophysiological measures like electrocardiography, skin conductance, electromyography and brain scanning are used (Gold & Ciorciari, 2020). The most frequently used brain-scanning methods are electroencephalography (EEG), functional magnetic resonance imaging (fMRI) and functional near-infrared spectroscopy (fNIRS). All methods are used differently and have their own strengths and limitations. EEG measures the brain's electrical activity in cortical areas and can easily be administered at low cost. However, EEG has poor spatial resolution and is unable to detect activity deeper than on the cortical surface (Beres, 2017). fMRI and fNIRS measure the neural metabolism in the change of oxygenated hemoglobin. fMRI uses magnetic fields to measure changes in blood flow and is capable of both localized and whole-brain measurements. However, the scanner is expensive to use and relatively difficult to administer (Glover, 2011). On the other hand, fNIRS uses near-infrared light from electrodes located on the scalp to detect neural metabolism. Some of the benefits of fNIRS are that it uses a portable device which is relatively cheap and easy to administer. Some limitations of the method are that it has lower spatial resolution compared to EEG and lower temporal resolution compared to fMRI (Ferrari & Quaresima, 2012; Lloyd-Fox et al., 2010).

More recently, there have been attempts to create flow states through transcranial direct current stimulation (tDCS). This technique uses electrical currents to stimulate specific brain areas to alter neuronal activity (Thair et al., 2017). In a study by Gold and Ciorciari (2019), the authors stimulated the left dorsolateral prefrontal cortex and right parietal cortex during a video game (Tetris). The results showed that the participants who received the stimulation rated higher flow experiences compared to participants who received sham stimulation (i.e., did not receive a real stimulation) where the rated flow experience was nearly unaffected.

The neuroscience of flow

Most studies of flow state have been from a psychological perspective, rather than a neuroscientific view (Gold & Ciorciari, 2020; van der Linden et al., 2020). However, there are some generally accepted theories of the neural correlates of flow.

Transient Hypofrontality Hypothesis

The Transient Hypofrontality Hypothesis suggests that the brain's frontal lobe (responsible for reasoning and executive function, etc.) and medial temporal lobe (responsible for memory; includes the hippocampus) have less activity while the basal ganglia (which controls voluntary motor movements) is more activated during flow (Dietrich, 2004). This means that the brain has less activation in higher processes, such as abstract and self-referential thinking. At the same time, the theory supports activity for automated control, which is faster and requires less effort. This theory is supported by studies (Hirao, 2014; Ulrich et al., 2014, 2016) that found decreased prefrontal activity during flow, especially in the medial prefrontal cortex.

Synchronization Theory of Flow

Studies using fNIRS (Yoshida et al., 2014) and fMRI (Ferrell et al., 2006; Ulrich et al., 2014, 2016) have shown *increased* activity in the prefrontal networks during moments of flow, in contrast to the Transient Hypofrontality Hypothesis. These results could be taken to suggest that the Transient Hypofrontality Hypothesis is too simplified to explain the flow state (Harris et al., 2017). Weber et al. (2009) instead focus on synchronized networks of neurons that create a holistic experience, leading to a flow state. Their theory is based on Posner et al.'s (1987) tripartite theory of attention, which involves the alerting (becoming aware of a stimulus: frontal and parietal cortices), orienting (allocating attentional resources to a stimulus: superior and inferior parietal lobes, superior colliculus and frontal eye field) and executive functions of attention (goal-directed processing, modulates the alerting and orienting network: medial prefrontal cortex, anterior cingulate cortex and lateral prefrontal cortex). Weber et al. believe that a coordinated neural firing rate of the mentioned attentional networks, together with the reward network (orbitofrontal cortex, striatum and dopamine neurons: Schultz, 2006) creates the experience of flow. The theory is called the Synchronization Theory of Flow and has support from results showing activity in the frontal and parietal cortices (de Sampaio Barros et al., 2018), anterior cingulate cortex (Klasen et al., 2012), lateral prefrontal cortex (Klasen et al., 2012) and striatum (Ferrell et al., 2006).

Large-scale network approach

Van der Linden et al. (2020) suggest that the neural underpinnings of flow could be explained by activity in large-scale networks: i.e., the default mode network (involved in self-referential thinking, mind-wandering, etc.), central executive network (involved in full concentration and engagement) and salience network (involved in coordination of neural resources and maintains a balance between networks: Davey et al., 2016; Menon & Uddin, 2010; Raichle et al., 2001; Seeley et al., 2007). The authors suggest that consistent interaction between these networks leads to the state of flow. The resulting neural activity may be described in this way:

a) reduced activity in the medial prefrontal cortex, posterior cingulate cortex and angular gyrus: the main parts of the default mode network (Davey et al., 2016; Gusnard et al., 2001; Raichle et al., 2001).
b) increased activity in the dorsolateral prefrontal cortex and posterior parietal cortex, which are parts of the central executive network (Menon & Uddin, 2010).
c) consistent activity levels in the anterior cingulate cortex and anterior insula cortex as the main parts of the salience network (Menon & Uddin, 2010; Seeley et al., 2007).

This theory has found support in studies showing decreased activity in the medial prefrontal cortex (Ulrich et al., 2014, 2016), with increased activity in the dorsolateral prefrontal cortex and anterior cingulate cortex (Klasen et al., 2012).

Aim of research project

Even though the flow state has been studied for many years, it remains unclear what happens in the brain during flow. The current findings are divided: some studies suggest that there is increased activity in the brain's frontal areas during flow (Katahira et al., 2018; de Sampaio Barros et al., 2018) while others suggest decreased activity (Harmat et al., 2015; Hirao, 2014). To clarify the ambiguity in the literature, this review tries to answer whether the flow state has a sufficiently distinctive neural signature to allow it to be distinguished from non-flow states, simply by looking at a brain scan of a person in a flow state. If this is not possible at present, it will be discussed what the current evidence says about its likelihood in the future. It is hypothesized that the existing findings are too diverse to communicate any firm conclusions about the neural signatures of flow at present.

Methods

Search strategy

Articles were collected through Scopus, Medline EBSCO and PubMed on 22 April 2022. For all databases, the following search string was used: ("flow state" OR "flow experienc*" OR "optimal experience") AND (brain OR neuro* OR neural) AND NOT ("traffic flow" OR "blood flow"). The search string resulted in 245 articles in Scopus, 105 in Medline EBSCO and 126 articles in PubMed. One article (Ferrell et al., 2006) was added from another review's (Gold & Ciorciari, 2021) reference list. The first filtering excluded 167 duplicates and 281 irrelevant articles which led to 28 articles that were further investigated by full text. Seventeen of the analyzed studies were excluded for different reasons. Five of these articles did not use a brain-scan in their analysis (e.g., stimulated the brain to induce flow), eight articles discussed flow but examined other things, two studies used a sample with participants under 18 years old and two studies used tasks that was performed in pairs or in a group setting. This left 11 articles for the review. See Figure 2 for an overview of the search process.

Eligibility criteria

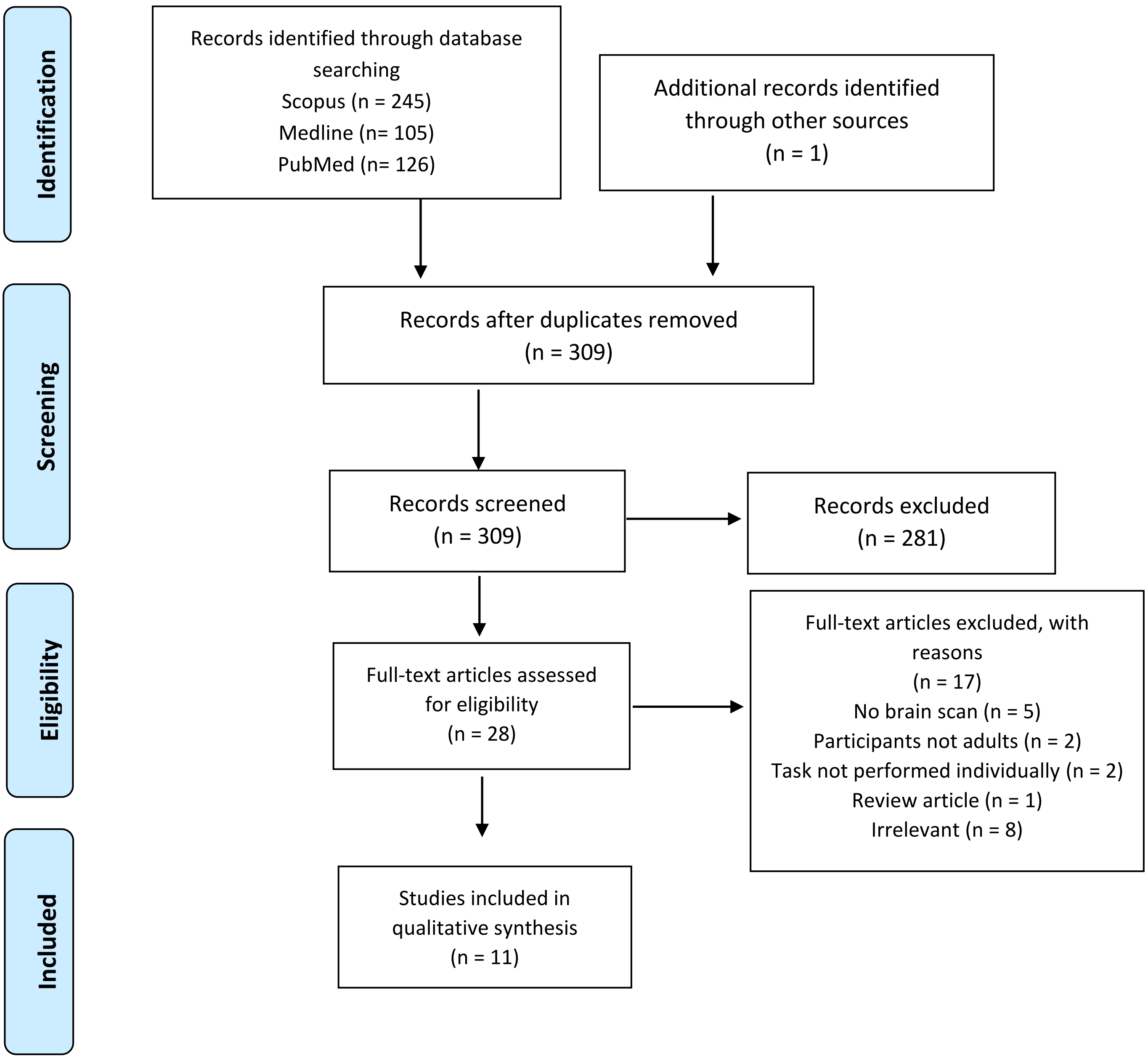
All articles were written in English from peer-reviewed sources. An article was accepted if it 1) examined participants' flow experience, 2) measured brain activity during flow through brain-scanning methods, 3) used a representative sample of a general population rather than a clinical population, 4) used tasks that were performed individually and 5) only used adult participants (i.e., over 18 years old).

Data extraction

Extracted data include a) characteristics of the sample (i.e., age, gender, number of participants), b) intervention (e.g., video games or problem solving), c) brain-scanning method (e.g., EEG, fMRI, fNIRS) d) flow measure (e.g., questionnaire), e) researcher's hypothesis and f) main findings.

Figure 2.

PRISMA 2009 Flow Diagram: Literature Search Process



From: Moher D, Liberati A, Tetzlaff J, Altman D. G, & The PRISMA Group (2009). Preferred Reporting Items for Systematic Reviews and Meta-Analyses: The PRISMA Statement. *PLoS Med*, *6*(7): e1000097. https://doi:10.1371/journal.pmed1000097

Results

After the search process, 11 articles were included in the review with a total of 292 participants (male *N*= 184, female *N*= 73, undefined *N*=35). The brain-scanning methods were fMRI (*N*= 4), fNIRS (*N*= 5) and EEG (*N*= 2). All studies were designed to test all participants in every condition.

The results indicate that the brain's frontal areas seem to play a crucial role in the flow experience with increased activity in the dorsolateral prefrontal cortex, which is related to executive functions like cognitive control and motor planning (Klasen et al., 2012; de Sampaio Barros et al., 2018; Yoshida et al., 2014; Yu et al., 2022); and putamen, which is involved in motor control and cognitive function (Ferrell et al., 2006; Klasen et al., 2012; Ulrich et al., 2014, 2016). As part of the dorsal striatum, putamen relates most directly to the reward system since it is part of the dopaminergic system (Hori et al., 2009; Jääskeläinen et al., 2001). The current review finds decreased activity in the medial prefrontal cortex, which relates to self-self-referential thinking and mind-wandering (Klasen et al., 2012; de Sampaio Barros et al., 2018; Ulrich et al., 2014, 2016). There is no other common activity across the reviewed studies. All articles are summarized in Table 1.

Table 1.

Overview of the included articles

Author	Sample	Intervention	Comparison	Flow measure	Brain scanning method	Researcher's hypothesis	Main findings
Ferrell et al. (2006)	*n* =8 archers female *n*= 1 age *m*= 37.63, 1sd= 9.30 years exclusively right-handed	hypnosis	hypnotic flow, hypnotic rest and normal rest	hypnotic induction	fMRI	increased activity in functions supporting learned motor activity and areas supporting planning of motor activity would decrease in activity	increased activity in left cerebellar region, left posterior temporal region, putamen, claustrum and left insula
Harmat et al. (2015)	Swedish students *n*= 77 female *n*= 40 age *m*= 27.8 1sd =5.4 years exclusively right-handed	Tetris (video/computer game)	three levels of difficulty (easy, optimal, difficult)	Flow-State-Scale-2 (Kawabata et al., 2008)	fNIRS	decreased activity in the prefrontal regions	no association between prefrontal brain activity and flow
Hirao (2014)	Japanese students *n*= 60 female *n*= 22 age *m*= 19.52 1sd= 0.96 years	verbal fluency task	flow state of experienced vs. non-experienced video-game players	Flow Questionnaire (Kobayashi et al., 2005)	fNIRS	not specified	prefrontal cortex is suppressed during task performance activity in prefrontal cortex did not correlate with task performance

Katahira et al. (2018)	university students *n*= 16 female *n*= 6 age *m*= 21.9, 1sd = 1.1 years exclusively right-handed	mental arithmetic task	three levels of difficulty (boredom, flow and overload)	Flow Index (Ulrich et al., 2014)	EEG	not specified	theta activity in frontal areas and moderate alpha activity in the frontal and central areas
Klasen et al. (2012)	German volunteers *n*= 13 female *n*= 0 age *m*= 23 exclusively right-handed	free play of a virtual video game	baseline vs. flow experience	psychological indications of flow	fMRI	central motivational processes shares network that supports flow states	activation in sensorimotor networks and cerebellum in situations where flow is likely to occur
de Sampaio Barros et al. (2018)	French volunteers *n*= 20 female *n*= 7 age *m*= 26.56 1sd= 4.83 years right-handed *n*=17 left-handed *n*= 3	Tetris and Pong (video/computer games)	levels of difficulty (easy, optimal, hard or self-selected)	Flow Short Scale (Rheinberg et al., 2003)	fNIRS	not specified	activity in all frontal areas, except for the most medial area. correlated to the most inferior/lateral channels of the parietal area during flow
Ulrich et al. (2014)	German students *n*= 27 female *n*= 0 age *m*= 23 1sd= 2.3 years exclusively right-handed	mental arithmetic task	three levels of difficulty (boredom, flow, overload)	Flow Index (Ulrich et al., 2014)	fMRI	involvement of striatum during flow and down-regulation in regions of the medial prefrontal cortex	increased activity in inferior frontal gyrus, putamen, and posterior cortical regions decreased activity in medial prefrontal cortex, left amygdala, hippocampus and parahippocampal gyrus

Ulrich et al. (2016)	German students *n*= 23 female *N*=0 age *m*= 24.0 1sd= 2,7 years exclusively right-handed	mental arithmetic task	three levels of difficulty (boredom, flow, overload)	Flow Index (Ulrich et al., 2014)	fMRI	flow is highest during the flow condition	increased activity in lateral, frontal and posterior parietal areas, the thalamus, the midbrain and basal ganglia decreased activity in medial prefrontal cortex, posterior cingulate cortex, lateral temporoparietal and medial temporal regions including amygdala
Wolf et al. (2015)	German table tennis players *n*=29 female *n*=9 age *m*= 23.8 1sd= 4.86 years exclusively right-handed	mental imagery	flow experience of amateurs vs. expert players	Flow Short Scale (Rheinberg et al., 2003)	EEG	elite players have higher brain activity in right hemisphere temporal than and less left hemisphere temporal activity compared to amateurs elite players rely more on attentional motor processes than verbal-analytical cortical processes	experts show increased activity in right temporal hemisphere and decreased activity in left temporal hemisphere
Yoshida et al. (2014)	Japanese students *n*= 20 female *n*= 10 age *m*= 22,3 1sd= 1.2 years (n=15, male n=6, female 9) age *m*= 22.0 +- 1.03 years	Tetris (video/ computer game)	boredom vs. flow experience	Flow State Scale for occupational task (Yoshida et al., 2013)	fNIRS	not specified	increased activity in the ventrolateral prefrontal cortex, frontal pole area and dorsolateral prefrontal cortex during flow
Yu et al. (2022)	Chinese students *n*= 20 female *n*= 10 age not specified	music game, Rhythm Master	video-game players vs. non-video-game players	Flow State Scale (Engeser & Rheinberg, 2008)	fNIRS	game difficulty and player experience affect the flow experience dorsolateral prefrontal cortex and ventral lateral prefrontal cortex correlate with the flow experience.	activity in the dorsolateral prefrontal cortex and frontal pole area correlates with flow experience had no impact on the level of flow, only balance between skill and difficulty did.

fNIRS analyses

Video games

Three studies used the video game Tetris to induce flow (Harmat et al., 2015; de Sampaio Barros et al., 2018; Yoshida et al., 2014). Tetris is a game where the participants arrange falling pieces composed of conjoined squares to form lines. Once a line is full, it disappears. All studies compared the flow experience at three levels of game difficulty (easy, optimal and difficult) adjusted by the speed of the falling pieces. All studies used questionnaires to measure the participants' subjective experience, including the Flow Short Scale (Rheinberg et al., 2003; de Sampaio Barros et al., 2018), Flow-State-Scale-2 (Kawabata et al., 2008; Harmat et al., 2015) and Flow State Scale for occupational task (Yoshida et al., 2013, 2014). Harmat et al. (2015) used 16 channels in the prefrontal cortex, de Sampaio Barros et al. (2018) eight channels in the right dorsolateral prefrontal cortex and inferior parietal lobe and Yoshida et al. (2014) 58 channels in the prefrontal cortex. De Sampaio Barros et al. (2018) and Yoshida et al. (2014) found that flow corresponds to increased activity in the prefrontal cortex, especially areas that relate to cognitive control (dorsolateral prefrontal cortex), reward and emotion processing (ventrolateral prefrontal cortex) and multitasking (frontal pole area). Harmat et al. (2015) did not find any neural activity in the prefrontal cortex that was related to flow.

Verbal fluency task

Hirao (2014) used a verbal fluency task to induce flow. The task was designed to confront participants with one or several letters (for example: a/to/ki) from which participants should come up with words that start with the letters. They compared experienced and non-experienced video-game players. Participants' subjective rating of flow was made through the Flow Questionnaire in which the participants evaluated their experience of emotional aspects, satisfaction, activity, concentration, loss of self-consciousness and sociability after completion of the task (Kobayashi et al., 2005). Hirao used two fNIRS channels, located in the right and left prefrontal cortex. Their study showed suppressed oxygenation in the prefrontal cortex during flow, suggesting that flow was guided by automated instead of cognitive control.

Music game

Yu et al. (2022) induced flow by using the music game Rhythm Master, performed on a digital tablet. While the participants hear a melody playing, notes are falling in several lanes on the screen. When the note gets to the bottom of the screen, the participants mission is to tap on the screen with perfect timing. To adjust difficulty, the game play changes with more lanes and faster melody. Participants were divided into two groups: video-game players (N= 20) and non-video-game players (i.e., inexperienced players) (N=20). To find neural correlates, they used 32 fNIRS channels covering the entire prefrontal lobe. Scores on the Flow State Scale (Engeser & Rheinberg, 2008) showed a linear correlation with activity in the dorsolateral prefrontal cortex and frontal pole area, which suggests that flow is related to attention, cognitive control, and reward mechanisms.

fMRI analyses

Hypnosis

In a study by Ferrell et al. (2006), they used hypnosis to induce flow. Previous research has suggested that hypnosis could be used to vividly imagine an activity and generate similar brain activity as in a real execution of a task (Calvo-Merino et al., 2004; Williamson et al., 2002). By using hypnosis in the fMRI scanner, participants could recall a flow experience without having to move. The participants were elite archers from the USA (N= 8). Each participant had a two-hour session with a certified hypnotist, asking them to recall a flow experience. Together with the hypnotist, the participants developed hypnotic inductions for the flow state. The flow state was then compared with a hypnotically recalled normal performance and a normal rest in the fMRI scanner. Analysis of the flow state showed a significant increase in neural activation in the left cerebellar region, left posterior-temporal region, putamen, claustrum and left insula. There were no significant patterns of deactivation in the flow state compared to normal performance.

Video game

Klasen et al. (2012) used German volunteers playing a first-person shooter war game, seen through the eyes of the main character. To measure the flow state, the authors investigated psychological indicators of the characteristics of flow (Csikszentmihalyi, 1990). Specifically, they looked at indicators of balance between ability and challenge, concentration/focus, direct feedback, clear goals, and control over action.

Balance between ability and challenge was observed when participants performed the game successfully. Increased activity was seen in the caudate nucleus accumbens, putamen, cerebellum, thalamus, superior parietal cortex, motor and premotor areas.

To measure the participants' levels of concentration/focus, the authors compared three game situations: 1) waiting time for a new round to begin, 2) moments in the game where dangers appeared, and 3) moments when the game required increased active engagement. The most demanding phases were characterized by increased activation in the precuneus, premotor areas, cerebellum and visual system and decreased activity in the bilateral intraparietal sulcus, orbitofrontal cortex and rostral part of the anterior cingulate cortex.

Direct feedback was observed when participants could observe at once that their action was successful (the target was dead). The authors did not find any significant effects on flow.

Having clear goals meant participants knowing where they were going. This was characterized by increased activation in the bilateral intraparietal sulcus and fusiform face area and decreased activity in the dorsal anterior cingulate cortex and precuneus.

The sense of being in control was characterized by participant's influence over the game content (e.g., change of weapon) and how easily they could transform their choices into successful actions. The authors found that levels of control related to increased activity in networks of the visual, cerebellar, thalamic, and motor-cortical regions and decreased activity in the bilateral temporal poles and bilateral angular gyrus.

Mental arithmetic task

A mental arithmetic task was performed similarly in two studies by Ulrich et al. (2014, 2016). The task is a math test that evaluates participants' ability to work without notes or calculator. Three conditions were compared: boredom, flow and overload. The boredom condition involved low task demands, the flow condition was adjusted to match the individual's skill level and the overload condition had a high task difficulty. Participants performed the task three times in each condition. They evaluated their subjective flow experience on the Flow Index, a nine-item Likert-scale questionnaire. In the first study, Ulrich et al. found that flow was related to increased activity in the inferior frontal gyrus (connected to increased sense of cognitive control) and putamen (involved in guidance of behavior and reward). Decreased activity was found in the medial prefrontal cortex (leading to decreased self-referential thinking) and amygdala (leading to less negative arousal). The second study showed the same activity patterns, but also found decreased activity in the posterior cingulate cortex, which had previously been correlated with effortless concentration (Garrison et al., 2013).

EEG analyses

Mental imagery task

Wolf et al. (2015) used German table-tennis players (*N*= 29), asked to watch video clips of another table tennis player serving a ball towards them. Participants were asked to visualize themselves responding to the serve with either a back- or sidespin, depending on the serve. The study was designed to test whether the flow state is modulated by experience between elite and amateur players. The results showed that flow in expert players correlated with decreased activity in the left temporal hemisphere and increased activity in the right temporal hemisphere. In amateur players, the authors found increased activity in the left temporal hemisphere. According to the authors, the left temporal regions are involved in analytical verbal processing while the right-temporal regions relate to skilled performance. They conclude that experts rely on their skill (using their right temporal regions) and analyze their performance less (using their left temporal regions). In contrast, amateurs need to analyze their performance verbally, resulting in increased activity in the left temporal regions.

Mental arithmetic task

Katahira et al. (2018) replicated the study by Ulrich et al. (2014). They induced flow using the same mental arithmetic task with the same three difficulty levels (boredom, flow and overload) and measured subjective flow experience using the Flow Index. The only difference was their use of EEG instead of fMRI. Katahira et al. take their findings to indicate that flow is related to a high level of cognitive control and absorption (reflecting increased theta activity in the frontal areas), while also suggesting that high levels of working memory is not needed during flow (reflecting moderate alpha activity in the frontal and central areas).

Discussion

The aim of this thesis was to review the empirical literature to decide whether the flow state has a sufficiently distinctive neural signature to allow it to be distinguished from non-flow states, simply by looking at a brain-scan of a person in a flow state. In general, results appear to vary, although a few studies report similar findings. The dorsolateral prefrontal cortex (Klasen et al., 2012; de Sampaio Barros et al., 2018; Yoshida et al., 2014; Yu et al., 2022) and putamen (Ferrell et al., 2006; Klasen et al., 2012; Ulrich et al., 2014, 2016) are the most frequently reported brain areas showing increased activity during flow. Some studies (Klasen et al., 2012; de Sampaio Barros et al., 2018; Ulrich et al., 2014, 2016) report deactivation in the medial prefrontal cortex. The function of these areas reflect three of Csikszentmihalyi's (1990) characteristics of flow: heightened sense of control, the sense of the task as intrinsically rewarding and reduced self-awareness. These areas could indicate an involvement of the default mode network (van der Linden et al., 2020) and central executive network (van der Linden et al., 2020; Weber et al., 2009).

When interpreting the results of this review, some issues with flow research should be acknowledged. Flow theory is mostly based on one man's work (Csikszentmihalyi) and it is possible that the research is biased by his assumptions of what flow is. The results of flow research might not reflect actual flow experience. There could possibly be factors that are missing or should be added. This could explain why flow has been reported in activities that are completely different, e.g., activities related to the workplace or in a sports environment.

What the results show is only a roughly defined set of neural activity. On the one hand, these results could be a consequence of the various methodological procedures of the currently reviewed literature. The included studies use three different brain scanning methods, measures with different regions of interest, different number of electrodes located differently in the fNIRS (ranging from 58 channels to two: Hirao et al., 2014; Yoshida et al., 2014), many ways to induce (seven out of 11 studies induced flow differently) and measure flow (eight different measures). In accordance with previous reviews (e.g., Alameda et al., 2022; Gold & Ciorciari, 2020), it could be argued that these differences do not allow to make any conclusions at present.

On the other hand, the variety of results could be taken to indicate many things. One possibility is that flow is a diverse set of phenomena which present themselves in a similar manner. Imagine two occasions where flow has been suggested to occur: a table tennis game and a mental arithmetic task. They could both generate an experience that fulfills the criteria of flow but could in fact be explained by another, different phenomenon that is not detected or understood yet.

Another implication is that flow could be explained by a complex set of neural activity. The flow state might have a specific neural signature responsible for every behavior which would not allow to distinguish any specific neural signature for the flow state.

It is also possible that flow does not have any specific neural signature. The neural activity found in the respective studies could merely be a result of contextual factors and have nothing to do with the flow state as such. This would mean that the flow state could not be explained by its neural signatures and should be studied by other factors.

Limitations

A major limitation within the current review is that the scope of the review is too broad and ill-defined. The used search string and chosen eligibility criteria include most of the articles in the chosen databases that have tried to measure the flow state by a brain scan. This was the initial aim of the review, but it was realized that this was avoiding the chance of drawing any conclusion because of the variety of methods used in the studies.

The review should instead have aimed to be more restricted. A careful analysis of different experimental procedures before defining the search string and eligibility criteria could have led to more comparable studies with similar methods: e.g., studies in sports combined with a specific questionnaire. If this would result in too few articles, more databases could have been used.

Another limitation is that the included studies do not reflect the background population very accurately. In this review, only 73 of the 292 participants were women and every participant except for 57 was a student. The results from this review mostly reflects neural activity of young men.

Ethical considerations

In all included studies, participants took part voluntarily, were anonymous and signed an informed consent before starting. Every study was approved by the local ethics committee. The brain-scanning methods used are non-invasive and the study of neural signatures of flow has the potential to create high rewards in relation to any potential harm.

Societal considerations

Outlining the neural signatures of flow could increase the understanding of what flow is, what it is not and how it could be used. Understanding the basis of the experience increases the possibility to create flow experiences: e.g., by tDCS (Gold & Ciorciari, 2019) or by creating scientific guidelines on how to reach the flow state: e.g., specific mental practice. According to its proposed link with optimal performance and well-being, a lot of areas would benefit: sports performances (Jackson et al., 2001), increased well-being (Seligman & Csikszentmihalyi, 2000) and more efficient workplaces (Ara et al., 2019), etc.

Another societal consideration is the potential economic benefits of flow. Flow could be used for commercial purposes and indirectly sell products, for example by designing computer games to increase the flow experience (Chou & Ting, 2003; Harmat et al., 2015). If the assumption that flow is addictive is correct, there is a risk that use of the flow state could have negative effects and harm individuals in the long run.

Future research

Flow research needs more data to outline what the flow state really is. One way to approach this is by extended studies on neural signatures of flow, where more research could increase the possibility to compare results and find methods that could effectively measure and induce flow. tDCS could be used to stimulate certain brain regions and then hopefully find out if there are any brain regions that are essential for the flow state to occur.

It would be useful to investigate other factors that might cause the flow experience. One possibility is by neurochemical studies and an increased understanding of neurotransmission during flow. There are some studies suggesting that dopamine and norepinephrine play an essential role in the experience of flow (de Manzano et al., 2013; van der Linden et al., 2021) but it has not been thoroughly studied yet.

Conclusions

The thesis aimed to investigate whether the flow state has a sufficiently distinctive neural signature to allow it to be distinguished from non-flow states, simply by looking at a brain scan of a person in a flow state. The variety of results from the current review does not allow to make any firm conclusions at present. The various results could, however, be indicating that flow is insufficiently described and could be a result of many phenomena that present in a similar manner. It could also indicate that there are no distinctive neural signatures of flow responsible for the flow experience to occur.

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