Unpacking the Neural Correlates of Flow

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Thesis Abstract

Flow is a highly positive experience occurring during an intense engagement in a challenging and enjoyable activity. Although this psychological construct was introduced decades ago, its underlying neural correlates have yet to be properly characterised. Further, most relevant research has considered tasks (like mental arithmetic) that are less engaging and when conducted in the controlled environment of a lab, do not reflect the conditions under which flow is usually experienced. Here, we suggest an alternative framework to study flow by studying musicians, who are engaged in a complex activity they find intrinsic enjoyment and meaning in, and argue that this represents a valid, if technically challenging, opportunity to collect neurophysiological data under conditions conducive to flow and reflect an experience more recognisable as the optimal experience often described as flow. We conducted several independent electrophysiological experiments on professional musicians' (N=88) self-induced flow state during music performance. Brain responses in the post-flow state, as compared to the post-non-flow state, were associated with lower delta (1-4 Hz) and increased upper alpha (10-12 Hz) and beta (15-30 Hz) power. Effects were predominantly observed over prefrontal brain regions. A neural index of interoception, or how the brain perceives visceral signals, also differed after musicians played music that induced flow versus music that did not. These findings offer novel insight into the neural mechanisms underlying flow experience. Finally, this state of effortless attention and high performance has been described in remarkably similar terms across a wide range of activities. Therefore, as a proof of concept, we conducted a pilot experiment on climbers in action on a climbing wall outside the laboratory environment and discuss some initial findings. Resting state data was also studied to look for neural correlates to dispositional

flow. Finally, monoaural beats were used to alter brain states in order to induce flow. These experiments reflect three different ways of studying the neural correlates of flow that can help us reach a comprehensive picture of the brain in flow.

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Author’s Declaration

I hereby declare that the content of this dissertation is original and has not been submitted in whole or in part for consideration for any other degree or qualification in this, or any other University. The format of the present thesis adheres to the Goldsmiths' University of London guidelines for thesis presentation.

The research conducted within the frame of this thesis was supported by a PhD studentship from the Economic and Social Research Council (ESRC) UK. The project was conducted and executed by myself, Jasmine Tan, at the Goldsmiths, University of London. The experiments were designed in collaboration with my supervisor Professor Joydeep Bhattacharya. Data presented in Chapter 8 was collected out of a project supported by the Universal Records. Stimuli employed in the experiment presented in Chapter 8 was provided by Universal Records. Part of the Introduction is based on writing contributed towards a chapter on the psychophysiology of flow in the second edition of Advances in Flow Research. Findings in Chapter 6 are based on a paper written in collaboration with Professor Joydeep Bhattacharya and Kelly Yap. As such, I declare that the research presented here is issued from my own intellectual work and was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Data was handled in MATLAB, SPSS and R. Raw data and custom scripts used for data processing and analysis will be provided upon request. Code for stimuli presentation and data collection will be provided upon request.

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Unpacking the Neural Correlates of Flow

Chapter 1 Introduction

This review will first describe how flow was conceptualised and how this influenced how it has been studied. Then it will evaluate methods for inducing it and studying it under laboratory conditions. Finally, it will review the current literature about the neuroscience of flow, discussing recent findings and their implications for our understanding of flow.

1. 1. Conceptualisation of flow: What is flow?

Flow refers to an altered state of consciousness involving highly focused engagement in a challenging, enjoyable and intrinsically rewarding activity. Associated with high levels of performance as well as positive subjective experience, it is considered an optimal psychological state (Jackson & Eklund, 2004). Csikzentmihalyi (1990) proposes a nine-dimensional construct of flow with the following characteristics: challenge-skill balance, merging of action and awareness, clear goals, unambiguous feedback, concentration on task at hand, sense of control, loss of self-consciousness, transformation of time and autotelic experience. This conceptualisation of flow has been taken up by much of the field. Research suggests that a balance between challenge and skill, clear goals and unambiguous feedback are antecedents of flow while the other characteristics are consequents of flow (Nakamura & Csikszentmihalyi, 2014). Flow can be experienced in many activities and has been researched in both work and play activities and across cultures (Fullagar & Kelloway, 2009; Moneta, 2004).

The study of flow distinguishes between dispositional flow and state flow. Dispositional flow refers to the personality trait of being predisposed or more likely to experiencing flow state in a specific activity while state flow refers to the actual experience of an altered psychological state during a particular activity at a specific time and place.

Csikzentmihalyi took from a great deal of textual material from qualitative interviews the most vivid descriptions and turned them into a bunch of statements with agree/disagree answers. This became the Flow Questionnaire. It included features like time perception, action-awareness merging and undivided attention (Csikzentmihalyi & Csikzentmihalyi, 1988). Further research was done with the Experience Sampling Method to examine flow in naturalistic environment in a variety of contexts helped to refine a model of flow, identifying its antecedents and consequences.

A large part of flow research involves self-reports of dispositional flow experience and state flow collected from people outside the lab everyday going about their daily activities. Hence, the tendency is for studies to be correlational rather than experimental (Landhäußer & Keller, 2014). A correlational design means that it is difficult to rule out an unexamined factor as a possible cause of the supposed consequence of flow. A deeper understanding of flow state necessitates not only going beyond self-report but also an experimental paradigm capable of testing for causal effects of flow.

1. 2. Flow under laboratory conditions: Experimental paradigms

In this part of the review, I will examine paradigms used to induce and study flow under laboratory conditions and evaluate their advantages and shortcomings.

1. 2. 1. The challenge-skill balance model

Csikzentmihalyi identified 3 conditions conducive to flow: a perception that the challenges of a task are matched to one's capacities, the task having clear proximal goals and immediate feedback on one's progress towards those goals. Based on these conditions, the most popular method for inducing flow in the lab has involved manipulating the difficulty levels of simple computer games. Flow is hypothesized to occur when the challenge of the situation matches the person's skill. When skill exceeds challenge, boredom occurs. When challenge exceeds skill, the person is overwhelmed and frustrated (Moneta, 2014). Hence, laboratory-based studies induce these three conditions by adjusting the demands of the task, usually setting one condition as 'easy', another as 'overload' and an 'optimal' condition thought to induce a flow-like experience. The optimal condition may be set up so that the task demands are adaptive to the ability of the participant (Ulrich, Keller, Hoenig, Waller, & Grön, 2014) or it may be set to a level determined before the experiment as suitable for the individual participant's skill (Rheinberg, Vollmeyer, & Engeser, 2003). Tasks utilised have included mental arithmetic, inductive reasoning tasks, computer games such as Tetris and Pacman and video games like first-person shooters such as Half-Life and HALO. The advantage of this approach is that objective conditions for flow can be established. However, the disadvantage is that flow could be easily confused with mental effort. It also rests on the assumption that challenge-skill balance is sufficient for flow experience.

Studies using this model tend to find results in the pattern of an inverted u-shaped curve. Self-reports of involvement on tasks are highest in the optimal condition relative to the overload and boredom conditions (Keller, Bless, Blomann, & Kleinböhl, 2011). Physiological features like low frequency HRV, a marker of sympathetic arousal, also show an inverted u-shape relationship with flow (Peifer, Schulz, Schächinger, Baumann, & Antoni, 2014).

Being able to manipulate conditions in the lab allow researchers to put flow under the microscope under laboratory conditions where physiological measures like heart rate variability (HRV) can be collected and used to answer pressing questions on flow, for example, if the reported effortlessness of flow was merely subjective or not. Keller and Bless (2011) found lower HRV, an index of mental effort, in a flow condition on a quiz show game (Keller et al., 2011). Further research found increased LF/HF ratio and increased heart rate in flow experienced in daily activities (Gaggioli, Cipresso, Serino, & Riva, 2013) and in experimental flow induced by a game (Harris, Vine, & Wilson, 2017). These cardiovascular measures are thus able to show that the apparent effortlessness of flow is a subjective experience that is dissociated from the actual physical costs. Harris (2017) showed that his objective data and subjective data follow different dynamics. His objective data (HRV and GSR) show a u-shaped curve but his self-report data follow a linear pattern.

Despite their limitations, studies have found differences among the conditions set up by the challenge-skill balance model. Behaviourally, participants report differences based on various questionnaires measuring self-reported flow. Physiological studies are promising in that they are able to distinguish flow and high mental effort (Harris et al., 2017; Peifer et al., 2014). However, while challenge-skill balance has been shown to be reasonably successful in inducing flow in the lab, it is important to note that many authors have acknowledged that this factor alone cannot be expected to reliably induce flow.

1. 2. 2. Beyond the challenge-skill balance model

Alternative methods of determining flow have also been put forward. Several studies have extrapolated flow from observed behaviour, reasoning that the chance of experiencing flow is increased when features associated with flow - such as challenge-seeking or success in an activity -are observed in their behaviour (Custodero, 2002, 2005; Klasen, Weber, Kircher, Mathiak, & Mathiak, 2012). The advantage of this method is that it avoids interrupting a flow experience during an activity. However, it is possible to argue that as flow is a subjective experience, subjective reports are absolutely necessary.

The balance between challenge and skill is not the only antecedent of flow that can be manipulated. An early study by Mannell and Bradley (1986) examined the unambiguous feedback precondition of flow. In this case, the manipulation was of clear instructions versus unclear instructions (Mannell & Bradley, 1986).

Other studies rely on engaging participants in an enjoyable activity such as video games or music and measuring fluctuating experiences of flow over time. de Manzano et al (2010) brought in expert pianists and, to keep conditions the same, had them play the same piece 5 times and measured flow as it fluctuated between repetitions. While this controlled for sensorimotor processing and output, the range of experience induced was not high (de Manzano, Theorell, Harmat, & Ullén, 2010). Klasen et al (2012) had observers rate features of in-game behaviour during free play of a first-person shooter and determined flow as occurring when participants are exhibiting behaviour corresponding to the nine characteristics of flow, namely balance between challenge and skill, concentration and focus, direct feedback of action results, clear goals and control over the activity (Klasen et al., 2012). This usually occurs when participants are experiencing success in the game. This is somewhat unusual as most research has maintained that flow is a subjective experience and lacking subjective report of flow, it is difficult to say if participants are in flow or not. However, the authors have noted that they do not claim participants are experiencing flow but reason that the chances of the gamers experiencing flow is increased when features associated with flow are observed in their gameplay. This is similar to early studies observing flow characteristics in the musical activity of children (Custodero, 1999, 2002, 2005). Children's experience of flow is extrapolated from behaviour like challenge-seeking and self-assignment. However, it is possible to argue that as flow is a subjective experience, subjective reports from the person experiencing the activity are absolutely necessary.

1. 3. Neural correlates and theories of flow

1. 3. 1. Theories of the brain in flow

Early theories of the brain in flow drew on the subjective sense of effortlessness and suggested that it was due to reduced cortical activation, where a minimum of neural activation is nevertheless extremely efficient (Goleman, 1995). Dietrich (2004) suggested that flow was the result of transient hypofrontality. Inhibition of the frontal areas may block out the conscious mind and allow the subconscious to take over, especially in situations that call for the automaticity that comes with well-practiced movements (Dietrich, 2004).

More recent theories have tried to describe flow in terms of neural synchronization. Weber (2009) has theorized that flow involves synchronization of attentional and reward networks (Weber, Tamborini, Westcott-Baker, & Kantor, 2009). De Manzano (2010) on the other hand, posited that it involves synchronizing emotion and attentional mechanisms. An early exploratory study correlated neural activity to observed gameplay of participants in a first-person shooter game (Klasen et al., 2012). In moments rated more conducive to a flow experience, Klasen (2010) found increased activity in the neocerebellum, left and primary somatosensory cortex, and motor areas and suggested that the experience of flow involved activation of a reward-motor loop, synchronizing brain structures sensitive to reward with task-relevant cortical and cerebellar areas.

These theories on the flow experience offer hypotheses testable with neuroscientific methods. There is a growing body of studies utilising neuroimaging methods to study flow both in terms of testing these hypotheses and in developing new ones.

1. 3. 2. A brief note on methods of neuroimaging

Electroencephalography (EEG), Functional Magnetic Resonance Imaging (fMRI) and functional near-infrared spectroscopy (fNIRS) are various neuroimaging methods that have been used to study flow. They have different advantages and disadvantages in relation to measuring the brain in flow.

Electroencephalography (EEG) measures electrical neural activity recorded by electrodes on the scalp. EEG records the integrated and synchronized activity of pyramidal neurons in the cerebral cortex. Data collected can be in the form of postsynaptic potentials associated with neural activation time-locked to a stimulus (for example, various event-related potentials (ERPs)) or changes and strengths of various oscillations in different frequency bands (delta, theta, alpha, mu, beta, and gamma) which are expressed as power spectral density or coherence (Berger, Horst, Müller, Steinberg, & Doppelmayr, 2019). Able to collect data at the level of milliseconds, EEG has excellent temporal resolution. Though data is collected at the cortex, reasonable spatial resolution can be achieved with new high-density systems or statistical methods such as independent component analysis (ICA) decompositions that reconstruct the origin of EEG activity (Makeig, Debener, Onton, &

Delorme, 2004; Onton, Westerfield, Townsend, & Makeig, 2006). Source-space analysis combines precise information of the anatomy of the head and sophisticated source localisation algorithms to allow researchers to make claims about activity in specific regions of the brain (Michel & Brunet, 2019). Furthermore, EEG has robust artifact removal methods that can remove artifacts due to head movements, eye movements or muscle activity to improve signal to noise ratio (Blum, Jacobsen, Bleichner, & Debener, 2019; Gwin, Gramann, Makeig, & Ferris, 2010).

Functional Magnetic Resonance Imaging (fMRI) examines neural activity indirectly by detecting changes in blood flow. fMRI relies on blood oxygen level dependent (BOLD) effect. Hemoglobin with and without oxygen has different magnetic properties. When a stimulus is applied, hemoglobin balance in various brain regions shift to favor deoxyhemoglobin concentration before switching to favor oxyhemoglobin concentration. This results in a signal change that can be detected and translated into images which can be analysed to show the activations of specific brain areas following a task or stimulus. It offers high spatial resolution, able to record signal from all regions of the brain, instead of mainly the cortex.

Like fMRI, functional near-infrared spectroscopy (fNIRS) relies on the principle of neurovascular coupling, indexing neural activation by measuring changes in regional cerebral blood flow, oxygenated hemoglobin, and deoxygenated hemoglobin (Ferrari, Mottola, & Quaresima, 2004). Both provide information about the spatial location of the recorded activity, but due to the intrinsically slow processes of hemodynamic changes, temporal resolution is limited. Compared to fMRI, fNIRS has lower spatial resolution and penetration depth (Koch, Koendgen, Bourayou, Steinbrink, & Obrig, 2008), but is less vulnerable to head and body motion artifacts than fMRI, has greater temporal resolution, and like EEG, can be performed while subjects perform tasks in a natural and comfortable environment (Yoshida et al., 2014). However, the challenge remains to distinguish physiological changes through brain activity from noise and artifacts (Berger et al., 2019).

The following table lists the neuroimaging studies that have examined flow, briefly stating the way they operationalised flow, the tasks they used, and their findings. It also classifies their definitions of flow following Abuhamdeh (2020)'s classification system of the various different types of flow definitions being used in research today. In brief, whether or not flow is continuous or discrete refers to whether experimenters conceive of flow and non-flow as a matter of degree or as two distinct different states. Enjoyment is not always included as part of the definition of flow. Flow conditions refer to whether at least one or all of Csikzentmihalyi's conditions for flow to occur, namely perception that the challenges of a task are matched to one's capacities, clear proximal goals and immediate feedback on one's progress towards those goals, is taken into account when setting up a condition in the experiment in which participants are meant to experience flow.

Flow operationalisation	Study (n)	Task	Continuous/Discrete?	Enjoyment included?	Flow conditions included?	Imaging modality	Main neural findings
Flow index - the difference in enjoyment and challenge-skill balance between an optimally matched condition and boredom and frustration	Ulrich, Keller, Hoenig, Waller, & Grön, 2014 n = 22	Mental arithmetic	Continuous	Yes	Yes (partly)	fMRI	Increased neural activity in left anterior inferior frontal gyrus (IFG) and left putamen and decreased activity in the medial prefrontal cortex (MPFC) and amygdala
	Ulrich, Keller, & Grön, 2016 n = 22						Neural activation of the dorsal raphe nucleus (DRN) increases in flow while activity in the MPFC and amygdala decreases Increased activity in a 'multiple demand' network Reduced activity in the default mode network, including the medial prefrontal cortex (mPFC)
	Ulrich, Keller, & Grön, 2016a n = 22						Dynamic causal modelling suggests that reduced activity in the mPFC is due to DRN exerting stronger down-regulatory influences on the MPFC during flow
	Ulrich et al., 2018 n = 22						In low flow subjects, relative deactivation of the right amygdala got more pronounced under anodal and cathodal tDCS, and changed inconsistently in high flow subject.s

Full questionnaire from Ulrich et al (2014)	Katahira et al., 2018 n = 16	Mental Arithmetic	Continuous	Yes	Yes (partly)	EEG	Increased theta activity in the frontal areas and moderate alpha activities in the frontal and central areas during flow
Three-channel flow model	Huskey, Craighead, Miller, & Weber, 2018 n = 18	Computer game: Asteroid Impact	Discrete	No	Yes(fully)	fMRI	High levels of intrinsic reward associated with a balance between task difficulty and individual ability are associated with increased functional connectivity between cognitive control and reward networks. A mismatch between task difficulty and individual ability is associated with lower levels of intrinsic reward and increased activity within the default mode network
Three-channel flow model	Huskey, Wilcox, & Weber, 2018 n = 18	Computer game: Asteroid Impact	Discrete	No	Yes(fully)	fMRI	The fronto-parietal control network, implicated in cognitive control, had the lowest global efficiency value, indicating low metabolic cost, suggesting an energetically optimized configuration of cognitive control and reward regions during flow

Flow state scale (FSS-2) (S. A. Jackson, Martin, & Eklund, 2008)	Harmat et al., 2015 n = 35	Tetris	Continuous	Yes	Yes (partly)	fNIRS	No associations between reported flow scores and frontal cortical oxygenation
Flow state scale for occupational tasks (Yoshida et al., n.d.)	Yoshida et al., 2014 n = 20	Tetris	Discrete	Yes	Yes (partly)	fNIRS	Cortical oxygenation increased in right and left ventrolateral prefrontal cortex during flow
Flow Short Scale (Rheinberg et al., 2003)	Barros, Araújo-Moreira, Trevelin, & Radel, 2018	Tetris and Pong	Continuous	No	Yes (partly)	fNIRS	An optimal level of difficulty led to greater flow and more cortical oxygenation in the fronto-parietal network
Observation of gameplay for player activity reflecting five of the nine dimensions of flow	Klasen, Weber, Kircher, Mathiak, & Mathiak, 2012 n = 13	Computer game: First-person shooter	Discrete	Yes	Yes (partly)	fMRI	Player activity reflecting flow dimensions was linked to distinct brain activation patterns reflecting a synchronisation between reward structures with task-relevant cortical and cerebellar areas.
Flow subscale of Game Experience Questionnaire (GEQ) (Ijsselsteijn, Kort, & Poels, 2013)	Ju & Wallraven, 2019 n = 31	Computer game: Racing car game	Continuous	Yes	Yes (partly)	fMRI	Flow correlated with activity in the dorsal and ventral visual streams, higher level visual association areas and the insula
Study 1: Three-channel flow model Study 2: Supported by the Flow Short Scale scores	Núñez Castellar et al., 2019 n = 21	Computer game: Star Reaction Secondary task: reacting to an auditory novelty	Continuous	Yes	Yes (fully)	EEG	Delayed response-locked frontocentral negative deflection, likely signaling the reallocation of attentional resources

		oddball					and increase in alpha power in flow condition
Flow was operationalised as a match between subjective flow and a reduced auditory evoked potential to an auditory oddball	Yun, Doh, Carrus, Wu, & Shimojo, 2017 n = 29	Computer game: First-person shooter	Discrete	Not known	Yes (partly)	EEG	Neural response to an auditory probe matched subjective reports of flow and objective performance level Anterior cingulate cortex and temporal pole showed increased beta band activity and connectivity with primary motor cortex in flow
Questionnaire on challenge-skill balance, sense of control, automaticity, enjoyment and time perception Team flow operationalised with questions relating to awareness of partner, teamwork and coordination	Shehata et al., 2020 n = 15	Computer game: music rhythm game	Continuous	Yes	Yes (partly)	EEG hyperscanning	Higher beta/gamma power at left temporal regions during team flow Team flow was associated with higher intra- and inter-brain synchrony
Flow Short Scale (Rheinberg et al., 2003)	Wolf et al., 2015 n = 35	Imagining a move in table tennis	Continuous	No	No	EEG	A shift towards more right temporal cortical activity was associated with greater self-reported flow experience in experts and may reflect automaticity of a highly trained skill.
Flow subscale of Game Experience Questionnaire (GEQ) (Poels, de Kort, &	Nacke, Stellmach, & Lindley, 2011	Computer game: First person shooter	Discrete	No	Yes (fully)	EEG	No differences in neural activity between flow and boredom

Ijsselsteijn, 2007)	n = 25						
Three-channel flow model Three questions on concentration, control and perceived length of time	Berta, Bellotti, De Gloria, Pranantha, & Schatten, 2013 n = 23	Computer game: plane battle video game	Discrete	No	Yes (partly)	EEG	Alpha and lower- and mid-beta power most reliably distinguished between flow, boredom and frustration
Questions on enjoyment, effort expended and concern about task performance	Ma, Pei, & Meng, 2017; Meng, Pei, Zheng, & Ma, 2016 n = 18	Two-player stopwatch game	Not applicable	Yes	Yes(partly)	EEG	A larger stimulus-preceding negativity (SPN) in an optimal challenge condition, linking it to increased motivation and anticipatory attention

1. 3. 3. fMRI studies on flow

An early work on flow in the brain recorded fMRI data while participants engaged in free play of a video game (Klasen et al., 2012). To identify flow state, a coding system was developed based on Csikzentmihalyi's nine dimensions of flow. The participant was considered to be in flow when the game play was coded as fulfilling five of the flow dimensions. While this method was chosen because the authors considered flow state a construct that cannot be measured directly and they thought it would be more objective to focus on observable events in the game play, it necessarily makes the assumption that as long as the flow state requirements are fulfilled, all their participants would be in flow state. It would have been helpful to include a self-report measure of flow to corroborate with the coding. Klasen et al (2012) found evidence of a synchronisation between reward structures with task-relevant cortical and cerebellar areas.

Some of the most comprehensive work done on the neuroscience of experimentally induced flow is by the series of fMRI experiments conducted by Ulrich et al. Ulrich operationalised subjective flow as the experienced balance between individual skill levels and task difficulty combined with an increased experience of pleasure and an increased propensity to repeat the mathematical tasks under flow conditions. In all conditions, the participants were asked to sum two or more numbers in their mind and to enter the result as accurately and quickly using an on-screen keyboard in combination with a trackball. Taking a cue from the inverted u-shape relationship between difficulty and flow found in psychophysiological studies of flow, they applied an inverted u-shaped model to the data to detect neural activation that was significantly different in flow compared to boredom and frustration. The flow condition was associated with an increase of neural activity in the putamen, possibly reflecting increased outcome probability, and in the left inferior frontal gyrus which might reflect a deeper sense of cognitive control. Reductions in neural activity were observed in the medial prefrontal cortex, suggesting decreased self-referential processing. Decrease of rCBF was also evident in the amygdala which might mirror a decrease in arousal contributing to or reflecting the positive emotional experiences during flow. Furthermore, neural activity in the IFG and amygdala correlated with subjective flow ratings during the activity (mental arithmetic) (Ulrich et al., 2014)

Using BOLD imaging, a more time-sensitive measure, Ulrich et al (2016) tried to replicate their previous findings and included a measure of electrodermal activity as an additional physiological index of flow. They found that compared against conditions of boredom and overload, neural activation was relatively increased during flow, particularly in the anterior insula, inferior frontal gyri, basal ganglia and midbrain. These areas are thought to be part of the 'multiple demand network', a general purpose network for tasks, including mental arithmetic. Flow was also associated with decreases in activation in the medial prefrontal (mPFC) and posterior cingulate cortex, and in the medial temporal lobe including the amygdala. These are part of the default mode network (DMN). Dynamic causal modelling suggested that the reduced activity in the mPFC is due to the dorsal raphe nucleus (DRN) exerting stronger down-regulatory influences on the mPFC during flow (Ulrich et al., 2016a). It is suggested that decreased MPFC activity under flow may reflect an absence of self-reflective thoughts (Csikszentmihalyi, 1990; Peifer, 2012), mainly driven by the DRN.

Ulrich et al (2018) then further tested the hypothesis that the medial prefrontal cortex (mPFC) plays a causal role in mediating flow experience by using transcranial direct current stimulation (tDCS) to interfere with the MPFC’s deactivation during flow. They found that tDCS-modulatory effects on flow-specific regional cerebral blood flow (rCBF) and subjective flow experience significantly depended on participants' baseline level of flow experience during sham tDCS. Participants with lower-flow experience during sham tDCS (LF) benefitted from tDCS, particularly from the anodal polarity, whereas both active treatments did not substantially affect subjects with relatively higher baseline flow experience (HF). Relative deactivation of the right amygdala got more pronounced under anodal and cathodal tDCS in LF subjects,, and changed inconsistently in HF subjects. Inter-individual regression analyses of rCBF data suggested that involvement of the subgenual anterior cingulate cortex appears crucial for affecting the response pattern in the right amygdala and can be modulated by tDCS (Ulrich et al., 2018).

Huskey et al (2018) examined experimentally induced flow using a point-and-click style video game in the scanner. Participants collected targets around the screen while avoiding rings that bounced around the screen. Difficulty was manipulated by altering the number of targets to be collected, the number of obstacles to be avoided and the rate at which everything moved around the screen. However, the two studies based on this method do not precisely reference flow, but rather, examined intrinsic reward as a function of challenge-skill balance. Participants were only asked about the intrinsic motivation they experienced. While the balanced-difficulty condition elicited activity in structures commonly implicated in cognitive control and reward processing, the low-difficulty condition showed activations in the DMN. High levels of intrinsic reward were associated with a balance between task difficulty and individual ability, and associated with increased functional connectivity between key structures within cognitive control and reward networks. By comparison, a mismatch between task difficulty and individual ability was associated with lower levels of intrinsic reward and corresponded to increased activity within the default mode network (DMN).

A key contribution of Huskey et al (2018) is their introduction of network neuroscience as a fruitful way to conceive of neural activations pertaining to flow. To test the Synchronisation theory, graph theoretical analyses were used to show that the balanced-difficulty condition was associated with the highest average network degree in the fronto-parietal control network, which is implicated in cognitive control and had the lowest global efficiency value, indicating low metabolic cost. This shows support for the Synchronization Theory's core predictions, that flow results in a synchronisation between cognitive control and reward networks, corresponding to an energetically optimised brain state that manifests as an enjoyable experience (Weber et al., 2009) .

Though their findings are specific to intrinsic motivation, they do provide some insights about flow. Even with a different task, a game rather than mental arithmetic, they also found that activity in the DMN increased when task demands did not match skill.

Flow is also discussed in gaming research. A number of studies measure flow with the flow subscale of the Game Experience Questionnaire (GEQ). The GEQ, while drawing on Csikzentmihalyi's work , mainly conceives of flow as a state of total involvement. The two questions pertaining to flow in the GEQ , "I forgot everything around me." and " I felt completely absorbed", relate only to the attention dimension of flow. Ju and Wallraven (2019) related neural activity during a race car game to aspects of the gaming experience, as measured by the GEQ, which are immersion, flow, competence, tension, challenge, positive and negative affect (Ijsselsteijn et al., 2013). Flow correlated with challenge and positive affect. While they were not explicitly trying to induce flow by manipulating the difficulty of the game, they did vary parameters in the game in different ways that resulted in making it more difficult or easier. Flow increased in the *goal decrease* condition, which made the game harder by reducing the number of tokens they had to collect. Using multivariate analysis, they found that in reference to neural activity in a baseline gaming condition, ratings of immersion, flow and challenge positively correlated with neural features related to visually- and spatially-related execution as well as attentional processes. Despite the different definition of flow, their findings share some similarities with Ulrich et al's (2016) and Weber and Huskey's (2018) work. Consistent with Ulrich et al (2016) and Huskey et al (2018), activity in the default mode network was negatively correlated with scores on the flow and challenge dimensions of the GEQ. Immersion and flow were positively correlated with parts of the dorsal and ventral visual streams and higher-level visual association areas. This is consistent with results from Klasen et al (2012), who found that an increased level of concentration and focus led to activity in visual processing areas. Interestingly, they also find that immersion and flow positively correlated with activity in the insula, which is known to encode the passage of time (Wittmann et al., 2010) and which may also be implicated in bodily self-awareness (Heydrich & Blanke, 2013; Tsakiris, Longo, & Haggard, 2010). They posit that it represents highly immersed people “losing themselves” in the game, hence losing track of time. Though their measure of flow only accounted for the attention dimension of flow, they find results that overlap with those found by Ulrich's and Weber's previous work on flow (Huskey, Craighead, et al., 2018; Huskey, Wilcox, et al., 2018; Ulrich et al., 2016b, 2014).

1. 3. 4. fNIRS studies on flow

The three studies using fNIRS to examine flow are a rare example of comparable studies in flow neuroscience. In Harmat et al (2015), Yoshida et al (2014), and Barros et al (2016), participants played TETRIS in a number of trials which differed in difficulty. The design of the game drew on the experimental flow induction validated by Keller and Bless (2008). In boredom, the shapes fell at a very slow rate and the player was not allowed to accelerate the falling speed. In the adaptive condition, the speed at which the shapes fell adapted to the player's performance. Players start the game with the shapes falling at a medium rate but when they successfully create 5 lines or more, the speed is increased. When the player completes fewer lines, the speed decreased. In the overload condition however, shapes fell at a fast pace and the speed increased if the player managed to complete five lines. Thus, the conditions of the game was thought to induce boredom, flow and frustration. Yoshida (2014) did the same but did not include a difficult condition. Barros et al (2018) had the easy, optimal and overload condition but also added a condition where participants chose the level they wanted to play at, so autonomy could be tested as a factor influencing experimental flow induction (Barros et al., 2018). As flow is an autotelic experience, autonomy and choice are important determinants of flow (Moller, Meier, & Wall, 2010). Barros et al (2018) also included a second game, Pong, using both the ball speed and velocity of the virtual opponent to manipulate game difficulty. Unlike the others, Barros et al (2018) aimed for a challenging situation where task difficulty slightly exceeded individuals' skills. Optimal and autonomy conditions both had higher flow scores. In fact, in all three experiments, flow scores were highest in the optimal condition. However, in the case of Yoshida et al (2014), this was by design as participants were excluded if they had lower scores in the flow condition than the boredom condition. These participants were determined as not having entered flow state. Yoshida et al (2014) noted that as flow state is affected by proficiency, motivation and interest for a task, not all individuals will enter a flow state for a given task (Yoshida et al., 2014).

All three experiments were interested in the prefrontal cortex, though for different reasons. Harmat et al (2015) set out to test Dietrich's theory of hypofrontality, using oxygenation changes in the prefrontal cortex as a potential marker for effortless attention. It has been suggested that flow is associated with reduced activity in prefrontal brain regions where activity typically increases with mental effort (Dietrich, 2004; Ullén, De Manzano, Theorell, & Harmat, 2010). Yoshida et al (2014) was more interested in the effect of experimentally induced flow on various areas of the prefrontal cortex in general, determining that flow is closely related to attention, emotion and reward, all functions that have been linked to the prefrontal cortex.

Barros et al (2018) was specifically interested in examining changes in blood oxygenation in the prefrontal cortex related to mobilisation of attentional resources, with a particular interest in the right DLPFC and the right inferior parietal lobe. The experiment also included a probe that asked participants at random times to indicate whether they were on task on not. Optimal and autonomy conditions had greater attentional focus compared with the easy condition but did not differ from the hard condition. Results indicated that an optimal level of difficulty, compared with an easy or hard level of difficulty led to greater flow feelings and a higher concentration of oxygenated hemoglobin in the regions of the frontoparietal network. The self-selected condition, referred to as "autonomy", did not lead to more flow feelings than the optimal condition but it did show higher activation of the frontoparietal regions.

Yoshida et al (2014) found that during the flow condition, oxy-Hb concentration was significantly increased in the right and left ventrolateral prefrontal cortex (PFC). Oxy-Hb concentration tended to decrease in the boredom condition. There was a significant increase in oxy-Hb concentration in the right and left dorsolateral prefrontal cortex, right and left frontal pole areas (FPA), and left ventrolateral PFC when participants were completing the flow state scale after performing the task in the flow condition but not in boredom condition. Neural activity was measured at this time point to avoid motor-related and task-specific brain activity, assuming that recalling their cognitive and physiological state during the task may also reactivate cortical regions related to the memory so brain activity during the completion of the form should therefore reflect the psychological state during the task. Yoshida et al (2014) concluded that flow is associated with activity of the PFC and may therefore be associated with functions such as cognition, emotion, maintenance of internal goals, and reward processing. However, they noted that the deactivation of the DLPFC and FPA observed during task performance in the flow condition may be specific to video games and therefore the results of this study may not be generalisable to other tasks.

Harmat et al (2015) did not find any association between flow scores and activity in the frontal regions and concluded that the data does not support the hypothesis that flow during computer game playing is associated with decreased activity in frontal brain region, even at very liberal statistical thresholds. They concluded that frontal deactivation is unlikely to be an essential generic mechanism for flow and flow could be more related to activity in deeper brain regions involved in emotional control and autonomous regulation than to frontal systems (de Manzano et al., 2013). They did however, allow that the neural substrates of flow may vary depending on task. A computer game like Tetris may require certain explicit control and, accordingly, more frontal brain activity. It may be that flow experiences during more predictable and automated tasks are accompanied by lower activity in executive cognitive systems (Harmat et al., 2015).

Barros et al (2018) found that in most channels, neural activity followed an inverted-U pattern with the level of difficulty, particularly in the channels located in the lateral part of the frontoparietal network. In these channels, both the autonomy and optimal conditions had higher activations than in the hard conditions. They interpreted these results as an active engagement of attentional resources during flow. Both the optimal and autonomy conditions not only led to strong activations in lateral PFC, but also a deactivation in the medial PFC compared with the previous rest periods. This was not seen in the hard condition. Like Ulrich et al (2016), Barros et al (2018) linked the mPFC behaviour to less mind wandering and self-referential processing in flow. Though they found generally more frontal activity in flow, they suggest that the reduced mPFC activity may provide support to the hypothesis for a state of localized hypofrontality (Dietrich, 2003) during flow.

While Harmat et al suggests that frontal deactivation is unlikely to be an essential generic mechanism for flow, Barros et al, and to some extent Yoshida et al (2014), suggest that we should be looking for more localised hypofrontality during flow.

1. 3. 5. EEG studies on flow

While fMRI has examined the behaviour of networks and deep brain structures like the insula and the amygdala that theoretically and experimentally seem crucial in the flow experience, and fNIRS has mostly examined the effect of flow in the frontal areas, EEG experiments have been more exploratory. EEG's ability to collect data on a much smaller time scale than fMRI adds another dimension to what we know about the brain in flow. EEG also allows for a lot more freedom of movement than fMRI, increasing the contexts in which we can collect neural data of people in flow.

An early study using EEG to study flow was Nacke and Lindley (2011). They designed a computer game to induce flow, immersion and boredom and found no differences in neural activity between flow and boredom in a videogame (Nacke et al., 2011). However, Berta et al (2013) designed a plane battle computer game to induce the conditions of boredom, flow and anxiety and found that, using a 4-electrode EEG set (two frontal and two temporal), the total alpha and lower- and mid-beta power most reliably distinguished between flow, boredom and frustration (Berta, Bellotti, De Gloria, Pranantha, & Schatten, 2013).

Building on the work of Ulrich et al, Katahira et al (2018) used Ulrich's paradigm, both the mental arithmetic task and the questions used, in an EEG study. Ratings on the subjective evaluation items representing the flow state were the highest in the Flow condition. They found that theta activity in the frontal areas was higher in the Flow and the Overload conditions than in the Boredom condition, and alpha activity in the frontal areas and the right central area gradually increased as task difficulty increased. EEG activity correlated with self-reported flow experience, especially items related to the concentration on the task and task difficulty. They concluded that the flow state was characterized by increased theta activities in the frontal areas and moderate alpha activities in the frontal and central areas. The former may be related to a high level of cognitive control and immersion in task, and the latter suggests that the load on the working memory was not excessive.

While Ulrich et al.'s (2014) fMRI findings were interpreted to reflect positive experience in the flow state, that is, the deeper sense of cognitive control and decreased negative emotions, Katahira et al suggested that the EEG indices show a different side of flow, the state of cognitive activity (the level of cognitive effort and cognitive load) during task execution rather than the emotional experience of flow. It was also noted that as this study only studied experimentally induced flow in a mental arithmetic task, its findings would not fully explain the contents of flow that will be experienced in the fields of more complex activities, like music. But the features of internal processing reflected by the EEG activity, namely cognitive control, indexed by frontomedial theta, and working memory load may apply across domains.

Several studies have experimented with using a secondary task to study flow, mainly as a way to index attentional involvement. It is thought that an attenuated neural response to an auditory oddball could be leveraged as an unobtrusive way to track flow. Nunez Castellar et al (2019) set up the classic experimentally induced flow paradigm using different difficulty levels in a simple computer game similar to that used by Huskey et al (2018). But while Huskey et al (2018) used a visual secondary task (participants were asked to press a button in reaction to a visual prompt), Nunez Castellar et al (2019) asked participants to press a button in response to an oddball sound. They found that during flow, reaction times to the oddball and error rates were higher, indicating that performance on a secondary task were impaired when participants are deeply immersed in the game. Though Huskey et al (2018) had used a visual secondary task instead of auditory task, results were similar. These results suggest that recorded error rates and reaction times using an auditory oddball as a secondary task could be used to indirectly assess the extent to which subjects are engaged in a game (Núñez Castellar et al., 2019).

EEG can be included in this use of an auditory oddball paradigm as a probe to gauge attention. The neural response to an auditory oddball, known as a P3 amplitude, is larger for stimuli that is allocated more attention (Polich, 2007). Stimulus-locked ERP results showed that the P3 amplitude was enhanced in the boredom condition, the one with the lowest level of challenge. Additionally, response-locked ERP and EEG spectral correlates revealed a frontocentral negative deflection that was delayed in the flow condition, compared to the conditions of boredom and frustration. Nunez Castellar et al (2019) suggest that this medial frontal activity is a neural correlate of executive attentional processes involved in top-down cognitive control. Significant increases in alpha band power were also found for the flow condition. This finding was suggested to be linked to either reward-related processing (Oya et al., 2005) or top-down modulatory and cognitive control processes (Sadaghiani & Kleinschmidt, 2016), like the suppression of distracters or irrelevant information during attentional tasks (Klimesch, Sauseng, & Hanslmayr, 2007; Mathewson et al., 2012).

Yun (2017) also used a passive auditory probe while participants were engaged in a first-person shooting game to continually tracked the depth of their immersion. Afterwards, participants replayed a video of their own game session and were asked to indicate if they experienced flow or not for each 5 min time period of the video. ERSPs, or the power of oscillations of the ERPs, was found to reflect a suppressed response to the probe that correlated with self-reported experience of flow and with their objective performance levels. Comparing the participants' record of flow experience over time against the overall EEG response to the probe, gameplay moments were classified to be flow only if participants reported flow and showed a suppressed auditory response to the probe. Using this method to define flow, neural correlates of flow were identified in the anterior cingulate cortex and the temporal pole. These areas displayed increased beta band activity, mutual connectivity, and feedback connectivity with primary motor cortex. This was interpreted as reflecting the increased attention and loss of self-consciousness in flow. Motor activity negatively correlated with flow experience and this was interpreted as reflecting efficient motor behaviour (Yun et al., 2017).

While some of the studies described above either examined neural activity during free game play or in the three conditions of boredom, flow and frustration, Meng et al (2016) set up a slightly different paradigm to study the link between challenge-skill balance and intrinsic motivation. Participants played a stopwatch game with a partner that was either a close fight or a blowout (winning by a large margin). The close fight was considered to be optimally challenging while the blowout reflected a lack of challenge. Meng and colleagues

(2016) found a larger stimulus-preceding negativity (SPN) in the close game, linking it to increased motivation and anticipatory attention (Ma et al., 2017; Meng et al., 2016).

In another unusual set up, Wolf and colleagues (2015) measured functional alpha asymmetry while table tennis players imagined returning a serve. They found that a shift towards more right temporal cortical activity was associated with greater self-reported flow experience in experts and interpreted it as reflecting the automaticity of a highly trained skill (Wolf et al., 2015).

A promising area of flow research is the use of hyperscanning, or simultaneous EEG on two or more people, to study team flow. Shehata et al (2020) had people partner up to play a music rhythm computer game. People had to work together to share the screen to play the music by tapping the visual cues. To disrupt flow, they removed the intrinsic reward and enjoyment aspect of the task by scrambling the music. To disrupt team flow, they blocked participants from seeing each other. An auditory probe was also used to index the level of immersion in the game. They found that team flow was related to higher beta and gamma power at the left temporal cortex and that the left temporal cortex was significantly involved at integrating information on the intra-brain and inter-brain levels. Team flow also resulted in enhanced global inter-brain integrated information and neural synchrony (Shehata et al., 2020).

1. 3. 6. Neuroimaging studies on flow proneness

Given the difficulty of inducing flow under laboratory circumstances, an interesting twist on the measurement of flow activity under lab conditions is via measuring behavioural and physiological aspects of flow proneness. One of the earliest physiological studies on flow found that people who scored high on a scale for intrinsic motivation in daily life had a surprisingly reduced evoked potential in response to a flashing light they were told to pay attention to. The authors interpreted it as these individuals had better attentional control and could sustain attention with less effort (Hamilton, Haier, & Buschbaum, 1984). From this study, Csikzentmihalyi suggested that people who experience more flow were able to reduce mental activity that was irrelevant to the task to concentrate fully on what they decide to be relevant at the moment (Csikzentmihalyi, 1990). Using positron emission tomography, flow proneness was shown to be positively associated with the availability of dopamine D2 receptors in the striatum (de Manzano et al., 2013), which parallels Ulrich and colleagues (2014) findings of an association of flow during a mathematical task with the nigrostriatal dopamine system. Kavous and colleagues (2019) also found a small positive correlation (0.13) between proneness to experience flow in everyday life and the volume of gray matter in the dopaminergic system, specifically in the right caudate (Kavous, Park, Silpasuwanchai, Wang, & Ren, 2019). The advantage of these studies have in studying dispositional flow is that they did not have to rely on inducing flow.

1. 3. 7. General overview of neural studies on flow

Reviewing the neural studies on flow so far has turned up several recurring themes.

Studies have examined Dietrich's hypofrontality hypothesis with contradictory results. Using fNIRS to examine flow in the context of Tetris, Harmat and colleagues (2015) did not find any associations between reported flow scores and frontal cortical oxygenation, concluding that there was no support for relating flow to a state of hypofrontality. However, using the same task, Yoshida et al., (2014) found that activation of the right and left ventrolateral prefrontal cortex was greater in flow compared to boredom in the final 30s of the task and suggested that these areas are processing reward and emotion during flow. Studies have also found that an optimal level of difficulty, compared with an easy or hard level of difficulty, led to greater self-reported flow and reduced activity in the medial PFC (Barros et al., 2018; Ulrich et al., 2016b). These recent findings suggest that frontal activation during flow is more complex than currently proposed by Dietrich's theory of flow as transient hypofrontality.

Many of these studies also find differences in the default mode network. It seems that flow results from a downregulation of task-irrelevant processes, which leads to decreased activity in the default mode network due to focused attention. This has been borne out by recent neuroscientific findings. By balancing the challenge of a mental arithmetic task with participants' ability, Ulrich and colleagues (2014) found that flow was characterized by reduced activity in the mPFC and PCC, both part of the default mode network, with the extent of reduced activity correlating with self-reported flow experience (Ulrich et al., 2014). When task difficulty was matched with individual ability in a computer game, it was associated with higher levels of intrinsic reward and decreased activity within the default mode network (Huskey, Craighead, et al., 2018).

Studies also show that task-relevant neural activity increases during flow. During a mental arithmetic task, Ulrich and colleagues (2016a) found increased activity in a 'multiple demand' network, which has been suggested to function in a wide array of demanding cognitive tasks including mental arithmetic (Ulrich et al., 2016b). Klasen et al. (2012) found increased activity in the neocerebellum, left and primary somatosensory cortex, and motor areas during flow in a computer game (Klasen et al., 2012). Engaging in any activity also involves planning, goal maintenance, performance monitoring, response inhibition and reward processing, all aspects of cognitive control. A balanced difficulty condition elicited robust neural activity in neural structures related to cognitive control, specifically the dorsolateral prefrontal cortex (DLPFC), and attention (Huskey, Craighead, et al., 2018). An EEG study also found increased frontal theta activity, a marker of cognitive control, in flow, alongside moderate levels of frontal and central alpha activity, suggesting that the working memory load is not excessive (Katahira et al., 2018).

Reflecting the intrinsically rewarding nature of flow, activity in areas related to reward such as the caudate nucleus, nucleus accumbens and putamen, also increase during flow (Huskey, Craighead, et al., 2018; Klasen et al., 2012; Yoshida et al., 2014). The nucleus accumbens also becomes more functionally connected with the DLPFC when task difficulty is balanced with individual ability, suggesting a link between reward and cognitive control. Weber and colleagues' (2009) Synchronisation Theory stated that during flow, neural areas that are task-relevant and involved in cognitive control become synchronised with reward structures in the brain, resulting in an energetically-optimised state (Weber et al., 2009). Graph theory analysis has found evidence for this hypothesis. In an experimental flow condition, the fronto-parietal control network, implicated in cognitive control, had the lowest global efficiency value, indicating low metabolic cost, suggesting an energetically optimized configuration of cognitive control and reward regions during flow (Huskey, Wilcox, et al., 2018).

Work is also being done on developing neural markers for flow, mainly by indexing the level of immersion in a task via the auditory response to a task-irrelevant stimuli (Núñez Castellar et al., 2019; Shehata et al., 2020; Yun et al., 2017). The more attention is being paid to the task at hand, the less the auditory response. This is particularly promising as it can be a way to index flow experience without interrupting the person experiencing flow to ask about it.

A more recent development in neuroscience of flow is using transcranial direct current stimulation (tDCS) to influence flow experience by stimulating the brain. Ulrich et al (2018) used it to test the causal role of the mPFC in flow. Surprisingly, participants who experienced less flow were more likely to benefit from neural stimulation (Ulrich et al., 2018). Another study tested the role of DLPFC and the prefrontal cortex in general in flow and found that stimulation over the left DLPFC resulted in increased flow experience in a game for both trained and untrained gamers (Gold & Ciorciari, 2019). However, performance only increased in the untrained group.

1. 3. 8. Problems and issues

Studies on the neuroscience of flow have revealed much insight about the flow experience, linking it to neural features associated with attention, reward, cognitive control and emotion. However, this quote by Ulrich et al (2016) also takes note of the limitations of such work.

> " The fit between subjective skills/abilities and adjusted task demands may trigger differences in neural activations compared to both control conditions that may support the experience of flow but do not necessarily represent the pure neuronal correlates of flow... ... ... However, whether the intensity of present experiences of flow corresponds to intensities experienced in everyday situations cannot be answered with present data. Particularly, altered experiences of time spent during task processing and the feeling of absorption or immersion are likely to differ between experimental and everyday situations. Insofar, our results here should be understood as a more abstract approximation to the experience of flow, a price to pay when a

> complex construct is to be brought under rigorous experimental control in a laboratory setting".

It is fair to say that the vast majority of the neuroscientific studies on flow are structured around an implicit definition of flow that centres on the finding that challenge-skill balance is an important antecedent of flow that leads to reduced self-referential processing (Ulrich et al., 2016b), intrinsic motivation (Huskey, Craighead, et al., 2018; Meng et al., 2016) and greater cognitive control and attention (Katahira et al., 2018; Núñez Castellar et al., 2019). However, researchers are aware that while challenge-skill balance is a central antecedent of flow, it is not sufficient for flow and cannot, on its own, reliably induce flow (Moller et al., 2010). This is why in the above quote, Ulrich states that a fit between challenge and skill may result in neural activity that support the experience of flow but that neural activity cannot be said to represent flow in the brain.

Ulrich also gives voice to a doubt shared by many researchers that the kind of flow they are inducing under experimental conditions accurately reflects the deep flow experiences that people experience in their favourite activities. Many of these studies note that their findings may not apply to the more complex tasks that people usually experience flow in (Katahira et al., 2018; Yoshida et al., 2014). Ulrich et al (2014) selected mental arithmetic as a task specifically to avoid movement artifacts. But the restricted circumstances of many neuroimaging experiments may actively impede people from experiencing deep flow experiences because it is not reflective of real life (Shamay-Tsoory & Mendelsohn, 2019).

Ultimately, Ulrich makes a good point in emphasizing that the flow that they measured in the lab is at best an abstract approximation of flow experience and a necessary price to pay when we choose to bring such a phenomenon into lab. But what if we didn't have to stay within such strict restrictions? What if we could take research in flow neuroscience back out of the lab and examine whether the findings from experimental flow studies do apply to the more complex activities we typically experience flow in? Abuhamdeh (2020) notes that flow is an optimal state that is rarely experienced and the difficulty of capturing flow is compounded when the experiment is conducted in the lab where participants typically engage in an unfamiliar task in an inherently evaluative context. Both of these factors are likely to work against the already slim chances of experiencing flow given that flow is more likely with people who are highly skilled at the activity and performance anxiety is not conducive to flow. Arguing for a definition of flow as a rare, discrete optimal phenomenon, Abuhamdeh (2020) suggests that many of these studies are not investigating flow per se, but could be better conceived of as investigations into task involvement. So while they reveal much about neural activity that could be conducive to the flow experience, we may still be missing part of the picture if we only look at experimentally induced flow.

1. 4. Research questions

In light of the literature outlined above, the following research questions have emerged:

1. **What are some neural correlates of state flow in actual flow-inducing activities measurable with EEG?**

Compared to fMRI, EEG allows for more naturalistic environments which are more conducive to flow experience. EEG also allows for a lot more freedom of movement than fMRI, increasing the variety of activities in which one could measure flow experience. The use of EEG enables us to capture the neural effects of flow over time as well as localisation as it works on a much smaller time scale than fMRI. Hence, to contribute to the literature, I propose to use EEG to examine neural correlates in flow in music performance and music listening and as a proof of concept, conduct a pilot experiment on climbers in action on a climbing wall outside the laboratory environment.

2. Given the unpredictability of flow induction, are there neural correlates of dispositional flow observable from resting state data?

If flow induction, even with the challenge-skill paradigm, cannot reliably induce flow, and researchers who induce flow under experimental conditions note that it is at best, an approximation of flow, is looking for correlates of dispositional flow in resting state data perhaps a better way to find neural correlates of flow? I propose to correlate dispositional flow with neural indices taken from resting state data.

3. Knowing some of the neural features associated with flow, can we manipulate neural activity to facilitate flow?

Although EEG studies have found neural oscillations in various frequency bands that are associated with flow, a causal role can only be demonstrated by directly modulating such oscillatory signals. Previous studies have used neural stimulation to test if modulating the activity of the medial prefrontal cortex and the dorsolateral prefrontal cortex modulate flow experience (Gold & Ciorciari, 2019; Ulrich et al., 2018). Is it possible to modulate neural oscillations to facilitate flow?

Chapter 2 Neural correlates of subjective flow in musicians

2. 1. Introduction

Despite the wealth of information from studies on experimentally induced flow, researchers have often noted that we do not know if their findings would apply to flow in a more complex activity like music (Ulrich, Keller, & Grön, 2016c; Yoshida et al., 2014). Thus, it seems paramount to examine neural correlates of flow firstly, in an activity that is recognised as frequently inductive of flow and secondly, self-induced by the participants rather than induced by the experimental variables.

2. 2. Flow experience in musicians

Flow experiences involving music are common and flow has been studied in various musical contexts. (Chirico, Serino, Cipresso, Gaggioli, & Riva, 2015) Flow is associated with creativity in composition (Byrne, MacDonald, & Carlton, 2003). Macdonald (2006) found that students' assessment of creativity and flow experience while working on group compositions were significantly positively correlated with the quality of the group compositions as rated by specialists (MacDonald, Byrne, & Carlton, 2006). In the area of music teaching, Bakker (2005) showed that music teachers' experience of flow is affected by their working environment and that contagion of flow experience exists, with the students of music teachers with high degrees of flow experience also being more likely to experience flow (Bakker, 2005). Flow in musical performance is frequently studied. An early study found a positive relationship between high achievement in music performance and the number of experienced flow states in adolescent musicians (O'Neill, 1999). Flow and performance anxiety were inversely related in music performance students and professionals, with performance anxiety being lowest when flow experience was highest (Cohen & Bodner, 2019a; Fullagar, Knight, & Sovern, 2013). Consistent with that finding is Wrigley and Emmerson (2013)'s study on live music performance which measured state flow after performances and showed that performance anxiety was a big factor hindering the ability to get into flow (Wrigley & Emmerson, 2013). Aspects of dispositional flow, specifically challenge-skill balance, clear goals, concentration on task and autotelic experience, predicted subjective well-being in music performance (Fritz & Avsec, 2007). Flow's impact on musical learning has been continually touched upon in the research. Custodero (2005) observed and coded flow-like behaviour in children, from infants to school-aged, in different musical learning environments and posits that the challenge-skill balance dimension of flow played a role in helping children learn more music (Custodero, 2005). This is consistent with the flow channel model of flow which suggests that flow encourages people to improve in their chosen activity to continue experiencing flow (Csikzentmihalyi, 1990). Thus, Macdonald and Byrne (2006) also suggest considering flow state as a teaching tool (MacDonald et al., 2006). To sum up, the benefits of flow state to musicians are manifold.

Musicians are an ideal population to study as music is recognised as offering many chances to enter flow state (Bakker, 2005). de Manzano et al (2010) has shown that playing music is effective as a naturalistic flow experience (de Manzano et al., 2010). They found measurable psychophysiological correlates, specifically EMG, cardiovascular and respiratory measures, that were associated with flow in a group of 21 professional pianists. The results were interpreted as an increased parasympathetic modulation of sympathetic activity. However, De Manzano (2010) only had the pianists play one piece and to reproduce it five times. The purpose was to keep sensorimotor processing and physical output similar across five sessions. However, without a control condition where participants are playing music but not in flow, it is not clear if the effects found are due to flow state or merely due to just playing music. Thomson and Jaque (2011) conducted a case study on the action of the autonomic nervous system in performing artists (conductors, singers and dancers) and replicated de Manzano's findings of decreased autonomic balance in the high flow group but again, lacked a control where participants were performing but not experiencing flow. However, their studies on the physiological effects of flow are induced by naturalistic stimuli (ie. actual performance and music) and indicate that music is a good and reasonably reliable way for participants to self-induce flow state to be measured (Thomson & Jaque, 2011).

The paradigm was drawn from that of strong experiences in music, such as chills, in which participants self-induce the experience using music they know has the effect (Salimpoor, Benovoy, Larcher, Dagher, & Zatorre, 2011). There has not yet been any neuroimaging study looking specifically at flow experience in musicians. Hence, this study is exploratory in nature, examining if there are systematic differences between the state immediately following flow state and the state immediately following non-flow state using EEG.

Abuhamdeh (2020) suggested that rather than the researchers deciding which experiences qualify as flow experiences, an alternative strategy would be to have the participants decide for themselves. Indeed, this is how Csikszentmihalyi initially began measuring flow experiences. When flow experience is studied using the Flow Questionnaire (FQ), respondents are first provided with a description of a flow experience, and then are asked to indicate whether they have ever experienced flow. If so, various follow-up questions about these experiences are then asked (Csikzentmihalyi & Csikzentmihalyi, 1988). In this way, the experimental design of this study differs from the typical experimental flow paradigm in a crucial way. It anticipates that musicians understand their own flow state and what reliably induces it. Instead of manipulating conditions, it requires participants to self-induce flow. In this respect, it is more similar to the design of studies on musical chills than classical experiments on flow, relying on subjective measures of flow. Similar to the de Manzano et al (2010) experiment, participants will bring their own music that they know will get them into flow. However, they will also be asked to bring a piece to perform that they know does not get them into flow. Because movement from playing an instrument can cause artifacts, the experiment will also measure data immediately after participants stop playing. This post-performance data, recorded while participants are still and have their eyes closed, is anticipated to be relatively free of artifacts and being temporally close to the experience, should be a suitable proxy.

Marin and Bhattacharya (2013) found that familiarity and preference influenced the frequency of experiencing flow in a particular musical genre (Marin & Bhattacharya, 2013). Hence, the decision was made to ask about liking and familiarity of the flow and non-flow pieces.

Hypothesis: There is a discernible difference between EEG data of post-flow state and post-non-flow state which is measurable with EEG.

2. 3. Methods

2. 3. 1. Design

The study was a within-participant, repeated measures design where participants took part in both conditions. The independent factor was type of music the participant played. In one condition, participants played a piece that induced flow and in the other, a piece that did not. The dependent factor was power spectrum of the 60 sec of EEG data recorded at the end of the piece.

2. 3. 2. Participants

48 amateur and professional musicians (mean age = 24.25 years, *SD* = 4.076 years, 20 males, 28 females, 4 left-handed) of varying levels of skill and musical involvement participated in the study. There were 9 wind players, 5 singers, 6 guitarists, 12 string players and 16 pianists. 16 of the participants were currently studying an undergraduate or postgraduate music performance programme at either a conservatory or a university. 15 of those who did not had graduated from a music performance course and remained active in the music scene to varying degrees. 17 had never studied music at tertiary level but played often as a hobby. Participation was entirely voluntary. 3 participants provided pilot data and due to modifications made to the experiment after the pilot, did not have post-flow data to be analysed. One participant was removed because of a misunderstanding of the task. Thus, only 44 participants were considered in the analysis of the post-flow EEG data. All participants provided written informed consent. The study was approved by the local ethics committee of the Department of Psychology at Goldsmiths, University of London, and conducted in accordance with the Declaration of Helsinki.

2. 3. 3. Materials

The Dispositional Flow Scale-2 (DFS-2) (S. A. Jackson & Eklund, 2004) comprised of 36 items referencing the nine-dimensional nature of flow and had been shown to be reliable in assessing flow in musicians (Sinnamon, Moran, & O’Connell, 2012). Dispositional flow was calculated as a measure of how often participants experience conditions that contribute to flow. Answers were collected on 5-point scales (1 = never to 5 = always). Participants were instructed to answer it as a general measure of their experience whenever they are playing their instrument, regardless of whether it is practice or performance.

The Flow State Scale-2 (FSS-2) (S. A. Jackson & Eklund, 2004) comprised of 36 items, similar to the DFS-2 but answers were collected on a 5 point scale where 1 = completely disagree and 5 = completely agree. It was administered right after participants finished playing each piece. Participants were instructed to answer it only in the context of the experience they just had. The FSS-2 had been used by Wrigley and Emmerson (2013) and shown to be suitable for use in studying musicians' state flow (Wrigley & Emmerson, 2013).

2. 3. 4. Experimental procedure

Participants were asked to bring two familiar and fluent pieces for the two conditions of the experiment. One piece was flow-inducing (referred to as the flow condition) and one was not (referred to as the non-flow condition). Each piece was repeated three times in a block design so that there were three consecutive flow trials and three consecutive non-flow trials. EEG data was recorded while they play. Participants stood or sat to play as they felt comfortable. To control for fatigue effects, the conditions was counterbalanced. Participants were told that the experiment was mainly concerned with what they were experiencing while they were playing and that the quality of their performance was irrelevant. Due to the difficulty of getting artifact-free EEG data from playing musicians, EEG data was also recorded right after participants finish playing to get the state right after the experience, which we called the post-playing state. Therefore, upon finishing each piece, participants sat down if they were not already sitting, closed their eyes and 1 minute of EEG data was recorded. After that, they answered the Flow State Scale (FSS-2) to report how much in flow they felt while playing the piece.

2. 3. 5. EEG recording and analysis

EEG signals were recorded using 64 active electrodes placed according to the extended 10-20 system of electrode placement and amplified by a BioSemi ActiveTwo amplifier (www.biosemi.com). To monitor eye blinks and horizontal eye movements, vertical and horizontal EOGs were recorded using four additional electrodes. The EEG signals were recorded with a sampling frequency of 512 Hz, band-passed filtered between 0.16 and 100 Hz. The MATLAB toolbox EEGLAB (Delorme & Makeig, 2004) was used for data-processing and FieldTrip (Oostenveld, Fries, Maris, & Schoffelen, 2011) was used for data analysis and statistical comparisons. Statistical analyses were conducted in IBM SPSS Statistics version 22 (SPSS Inc., Chicago, IL, USA) and in Matlab R2013b (The MathWorks, Inc., Natick, Massachusetts, USA) (MATLAB, 2013).

2. 3. 6. Preprocessing

The EEG data was re-referenced to the average of the two earlobes. The data was high-passed filtered at 0.5Hz and epoched from -2s before and 60s after participants stop playing and close their eyes. The post-flow data was relatively artefact-free. No eye-blink corrections were needed because the data was recorded while participants had their eyes closed.

2. 3. 7. Time-Frequency Analysis

Due to the nature of the experiment, there was a lack of an ideal baseline. Therefore the decision was made to calculate relative power without removing baseline. After preprocessing, the 60s of post-playing data divided into two time windows. Power analysis was done using Welch's power spectral density estimate for 7 frequency bands, delta (1-4 Hz), theta (4-8 Hz), lower alpha (8-10 Hz), upper alpha (10-12 Hz), beta (12-30 Hz), lower gamma (30-45 Hz) and upper gamma (55–70 Hz). The data was divided into segments of 2 sec with an overlap of 500 msec. The resulting power values were averaged among 3 flow states and 3 non-flow states.

2. 3. 8. EEG Statistical analysis

To find significant differences between the two conditions, a paired t-test was carried out on the EEG data points. In dealing with the issue of multiple comparisons, Bonferroni's correction proved to be too conservative. Therefore, to conduct exploratory analyses on the data without compromising on the issue of multiple comparisons, we applied spatial constraints. For an effect to be both statistically significant and biologically relevant, it needs to be found over a cluster of data points in the analysed dimensions of time, space (electrodes), and frequency. An isolated significant difference found at a nonspecific data point would not be considered biologically relevant and would not be considered a significant cluster even if highly significant. A threshold of $p < .05$ across the entire 60s and at least three neighbouring significant electrodes to the sample-specific statistics was applied and connected clusters that exceed the threshold and have the same sign were constructed. This method was used to define the regions of interest (ROIs) in the topography of the head and the frequency bands, which were later analysed with a standard ANOVA. The ANOVA was carried out to allow comparisons between groups and interactions, which were not accounted for in the t-test on the EEG data points.

2. 3. 9. EEG Connectivity Analysis

To maximise differences, the highest rated flow and lowest rated non-flow were selected. Phase slope index (PSI) was calculated for the 60s time window (Nolte et al., 2008) to measure directed connectivity between electrode regions. A grand average was taken and

PSI values were plotted to find frequencies of interest. When electrodes were plotted against AF8, there was found to be a peak in connectivity values at 5 Hz. PSI was then extracted for a between groups t-test to compare functional connectivity in participants high in dispositional flow and participants low in dispositional flow.

2. 4. Results

2. 4. 1. Behavioural data

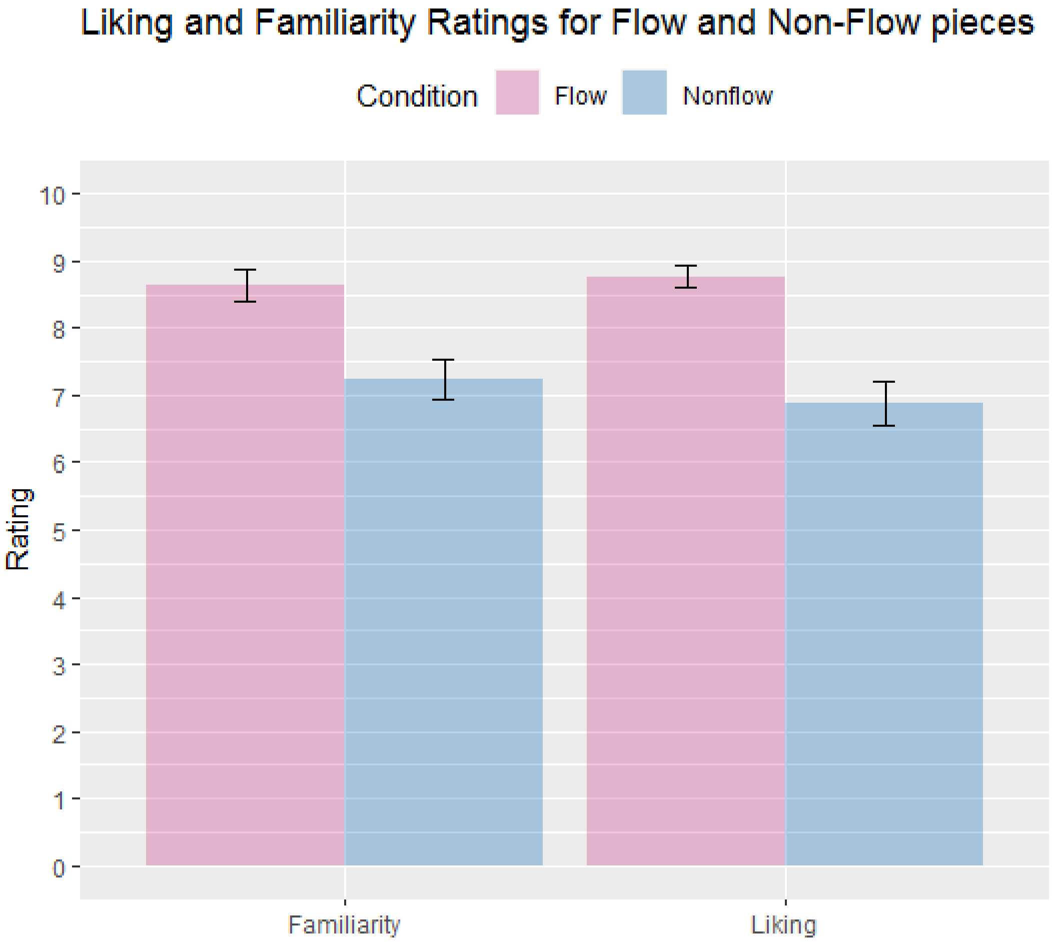


Figure 2.1: Liking and familiarity ratings for flow and non-flow pieces.

Participants rated their flow piece significantly higher in both liking and familiarity (Liking: *t*(42) = 5.89, *p* < .001; Familiarity: *t*(42) = 3.89, *p* < .001).

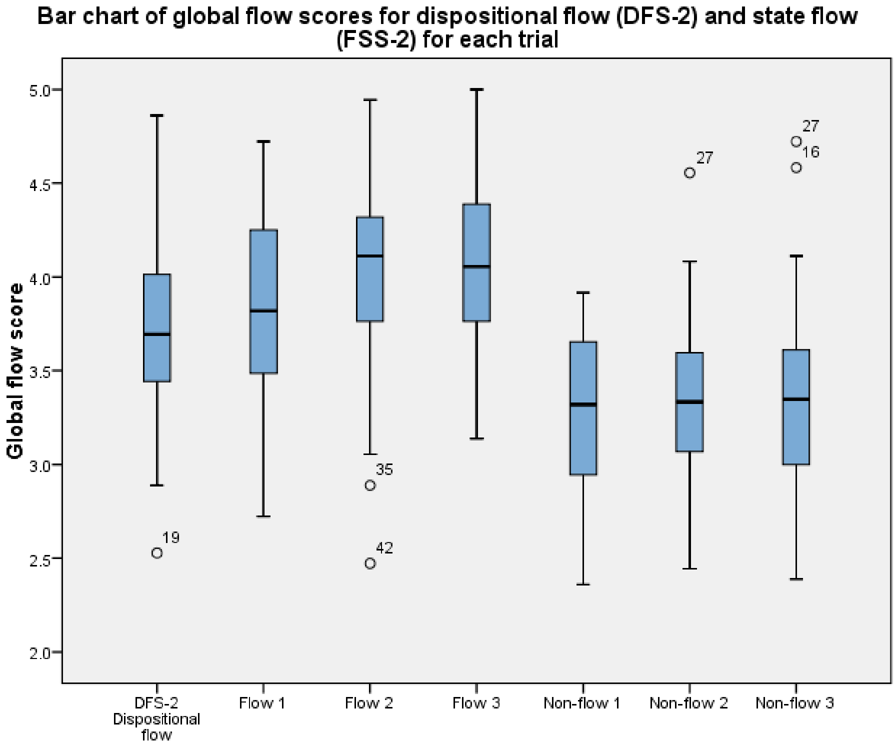


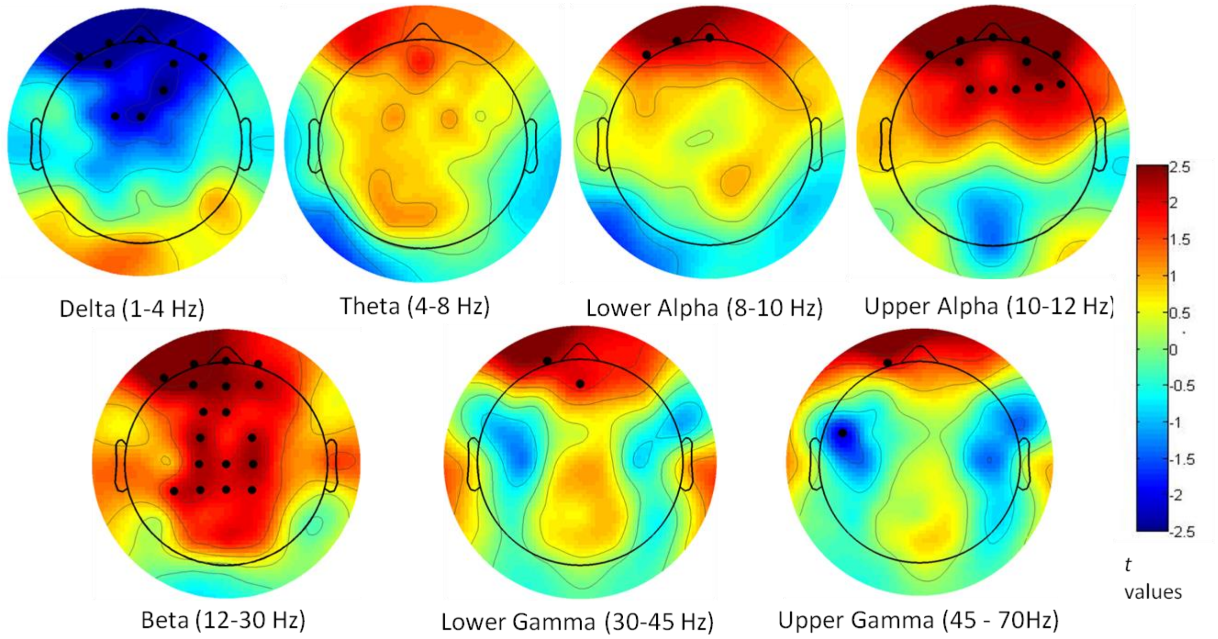
Figure 2.2: Bar chart summarising dispositional flow and state flow for each trial. Flow 1 (M = 3.85, S.D = .45), Flow 2 (M = 4.03, S.D. = .51) and Flow 3 (M = 4.10, S.D. = .45), Non-flow 1 (M = 3.29, S.D. = .41), Non-flow 2 (M = 3.33, S.D. = .44) and Non-flow 3 (M = 3.34, S.D. = .51) and compares it to their self-reported dispositional flow.

Participants' reported state flow scores for the flow sessions and the non-flow sessions were averaged. A paired samples t-test showed that the difference between the average of the FSS-2 scores for flow (*M* = 3.99, *S.D.* = .40) and the average for non-flow (*M* = 3.32, *S.D.* = .42) is significant (*t*(47) = 9.642, *p* <.001). This suggests that participants brought pieces that accurately represented flow and non-flow. Both the average Non-flow FSS score and the average Flow FSS scores correlated with the DFS-2 scores (*r* =.282, *p* = 0.05) for Flow and (*r*=.554, *p* <0.01) for Non-flow, suggesting that participants are being quite consistent with their reported flow tendencies and their actual flow experience in the lab. However, dispositional flow seems to be more highly correlated to non-flow scores, suggesting that it was more difficult for participants to enter flow state than non-flow under lab conditions.

2. 4. 2. Neural data

Based on the significance threshold described in Methods, the difference between the state after flow and the state after non-flow was deemed to be significant in the delta band, upper alpha band in the frontal area and in the beta band, all in the frontal regions (see Fig 2.3).

2. 4. 2. 1. Neural oscillations



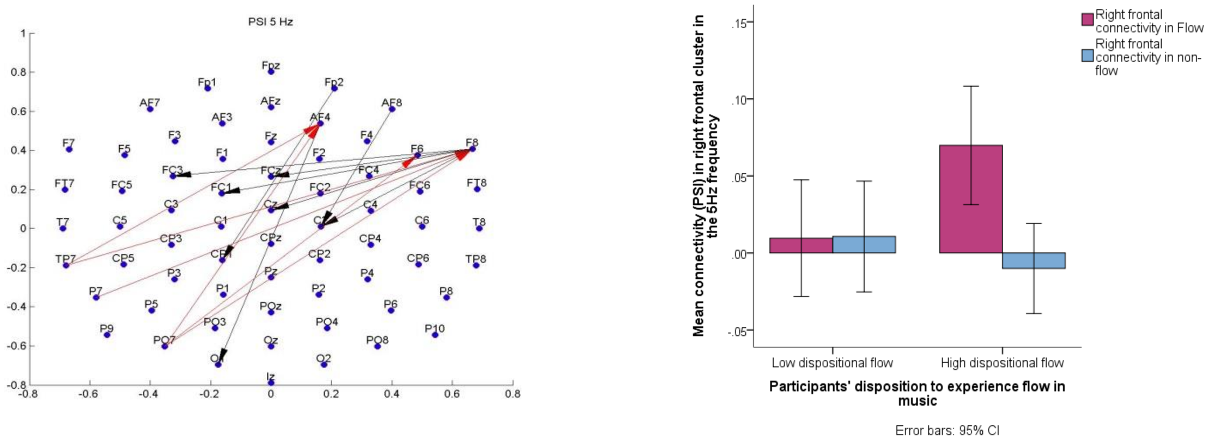
Topoplots of *t*-values by comparing EEG power of seven frequency bands between flow and non-flow states. Red indicates that power is higher in the flow condition while blue indicates that the power is higher in non-flow condition. Statistically significant electrodes ($p < .05$) are indicated by black dots.

Figure 2.3: Topoplots comparing the relative spectral power of flow and non-flow conditions

Delta power was significantly higher in the non-flow condition than flow condition in electrodes FP1, AF7, AF3 and FPz (F (1,42) = 7.718, p = .008). Power in the upper alpha band is significant between conditions across many of the frontal electrodes (F(1, 42) = 7.178, p = .001). Beta band power was significant between time windows, F (1, 42) = 5.034, p <.05. Only power in the beta band increased over time.

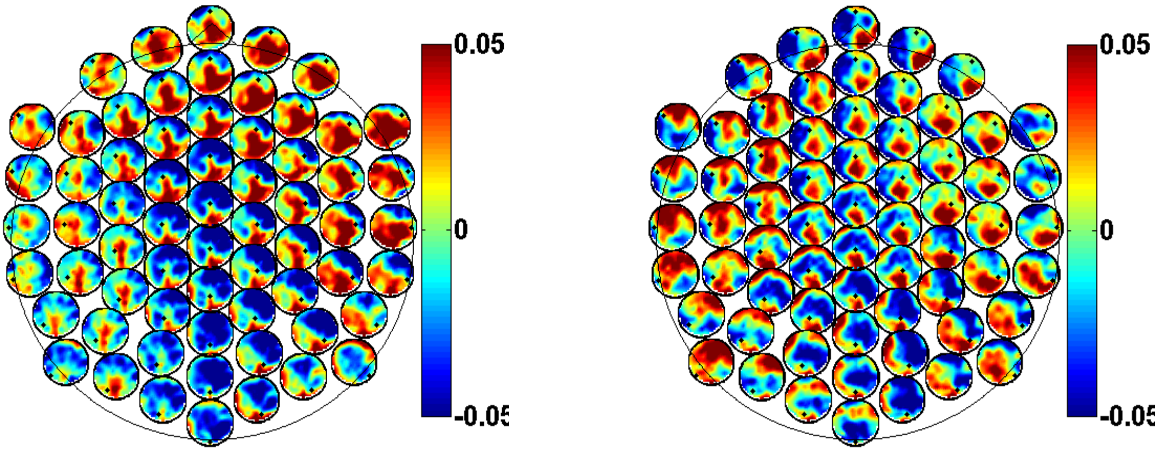
2. 4. 2. 2. Functional Connectivity

The post-playing state also showed differences across conditions in connectivity (see Fig 2.4).



Significant electrode pairs at 5Hz (PSI). Black arrows indicate significant electrode pairs in flow and red arrows indicate significant electrode pairs in non—flow.

Bar plot showing a significant interaction effect with dispositional flow, *F(1,42)* = 5.778, *p* =.021. Only participants with high dispositional flow show a decrease in connectivity between conditions.



Phase slope index at 5 Hz for the flow (left panel) and non-flow (right panel) states. Each small topoplot represents an electrode with the colours representing the connections with that electrode. Red indicates that the selected electrode drives other electrodes and blue indicates it is driven by others.

Figure 2.4 Functional connectivity (PSI) in theta band significantly differs between flow and non-flow, but only for participants high in dispositional flow

PSI values show an increase in information being sent from a right frontal cluster (FP2, AF4, AF8, F4, F6) to central and parietal areas in the flow condition. In contrast, there was an increase in information being sent to the right frontal cluster from parietal regions in non-flow. An ANOVA showed that this significant difference between flow and non-flow was mainly found in participants with high dispositional flow scores (DFS-2).

2. 5. Discussion

2. 5. 1. Behavioural data

FSS-2 scores were significantly different between flow and non-flow conditions, suggesting that participants accurately brought pieces that induced the desired state for them. Non-flow inducing pieces were rated significantly lower in both liking and familiarity, which aligns with Marin and Bhattacharya (2013)'s finding that liking and familiarity plays a role in the music that induces flow during performance for musicians.

2. 5. 2. Neural data

Post-playing EEG data was found to be significantly different between the two conditions, leading us to reject the null hypothesis and conclude that there are differences in the neural correlates of flow and non-flow measurable with EEG. The fact that a significant neural difference between the conditions was found in the post-playing state demonstrates that the state immediately after flow is tied to the flow experience even after the activity is over. Hence, it may be safe to assume that we can observe and conclude some neural characteristics of flow from the post-flow data.

The most significant difference found was that upper alpha activity in the frontal areas is much higher in the flow condition than the non-flow condition. Alpha oscillations can be thought of as a general inhibition mechanism across cortical networks (Klimesch et al., 2007). Increased alpha oscillations have been shown to be related to decreased BOLD fMRI signal and increase in default-mode networks (Scheeringa et al., 2011). The inhibition in the frontal areas may provide some evidence for Dietrich's theory of flow as transient hypofrontality (Dietrich, 2004). That we could record this in the time after the musicians have stopped playing suggests that this inhibition lasts beyond the end of performance. Delta activity is also associated with lower activation (Buzsáki, 2006) so significantly lower delta power in the frontal regions after flow may provide further support for hypofrontality in the flow condition. The fact that all the power values calculated were relative values supports this conclusion.

However, the theory of flow as transient hypofrontality could be said to be too simplistic as studies in fNIRS and fMRI have shown that areas of the frontal cortex could increase or decrease in flow. Yoshida et al., (2014) found that activation of the right and left ventrolateral prefrontal cortex was greater in flow compared to boredom in the final 30s of the task and suggested that these areas are processing reward and emotion during flow (Yoshida et al., 2014). On the other hand, flow was associated with reduced activity in the medial prefrontal cortex (Barros et al., 2018; Ulrich et al., 2016a). A more intriguing explanation suggests that frontal alpha may be linked to cognitive control (Mathewson et al., 2012). Recent reports have linked frontal alpha to control processes and attentional engagement, perhaps related to the suppression of irrelevant information (Jensen & Mazaheri, 2010; Klimesch et al., 2007). During an experimentally induced flow condition, Nunez Castellar et al (2019) found increased frontal alpha and suggested that it could linked to either reward-related processing, or suppression of distractors or irrelevant information (Núñez Castellar et al., 2019). It is possible that as flow is a state of high attentional engagement, musicians could still be experiencing such attentional engagement in the moments immediately after they finish playing. Alternatively, they may find it easier to maintain focus in the time period where resting state data is being collected after they self-induce flow, rather than non-flow.

However, the exploratory nature of this experiment means that we cannot rule out other explanations for increased alpha activity. Listening to music, regardless of whether it is calming or stimulating, increases upper alpha amplitude and power in the frontal and parietal regions (Iwaki, Hayashi, & Hori, 1997; Kawasaki, Karashima, & Saito, 2009). Because we controlled for the effects of music by having them play in a non-flow state, the observed alpha results cannot solely be attributed to music-induced emotion or arousal but the effects of flow cannot be distinguished from the effects due to arousal from music. Given the emotion inherent in music, it is possible that this could be a neural correlate of flow state that is specific to musicians.

Beta activity is usually associated with motor activity. One interesting study has suggested that frontal beta oscillations may reflect post-processing of successful motor activity (Feingold, Gibson, DePasquale, & Graybiel, 2015). Feingold et al (2015) has found, through intracranial recording in monkeys, that beta oscillations are larger following correct movements than wrong movements. Flow is associated with peak performance and depends on a balance between challenge and skill (Engeser & Rheinberg, 2008). Hence, it is reasonable to assume that more correct movements were made in the flow condition than the non-flow condition.

Connectivity results show that there is a right frontal cluster which significantly differed in activity between flow and non-flow. That the pattern of activity was only found in people rated high in dispositional flow suggests that this area may play an important role in flow experience. Theta band connectivity has been recently linked to attentional processes. Theta connectivity within the frontoparietal control network has been reported to facilitate cognitive control and goal-directed attention (Cooper et al., 2015; Fellrath, Mottaz, Schnider, Guggisberg, & Ptak, 2016). As flow is a state of goal directed attention, those who are more likely to experience flow while playing music may be better at controlling their attention in face of distraction and thus show more theta connectivity after playing music. Past studies have linked this to the right dorsal lateral prefrontal cortex. While the functional theta connectivity here is projecting from the right frontal areas, a source space analysis will be needed to locate the source of this theta connectivity.

Our findings also share some similarities with the other EEG studies on experimentally induced flow. Using Ulrich's (2014) mathematical sums paradigm, Katahira et al (2018) found increased alpha activity at the frontal area, right central area, and parieto-occipital area (Katahira et al., 2018). the left occipital beta activity. They linked the observed alpha activity with the difference in the working memory load induced by the different task difficulty levels. Nunez Castellar et al (2019) also found increased alpha in an experimentally induced flow condition and proposed that it could either be linked to reward-related processing or cognitive control processes, possibly reflecting the suppression of distractors or irrelevant information during a task that requires devotion of full attention (Núñez Castellar et al., 2019). While both Katahira et al (2018) and Nunez Castellar et al (2019) showed findings from experimentally induced flow, Yun et al (2017) looked at neural activity during gameplay of a first-person shooter (Yun et al., 2017). Like our experiment with musicians, it could be said to be closer to a more naturalistic flow experience. Yun et al (2017) found that flow was associated with increased beta band activity in the anterior cingulate cortex and suggests that it reflects attention and focus. To sum up, early exploratory findings on the neural correlates of self-induced flow in musicians share some similarities with findings on experimental flow and flow during computer gaming.

This study is promising in showing that it is possible to study flow using naturalistic stimuli and that there are distinct differences between the neural correlates of the state immediately following flow and the state immediately following non-flow that are measurable with EEG. The differences in the upper alpha and beta bands parallel an earlier study in which support vector machine classification on EEG data collected during a plane battle video game found that alpha (8-12 Hz) and lower- (12-15 Hz) and mid-beta (15-20 Hz) power most reliably distinguished between flow, boredom and frustration (Berta et al., 2013).

2. 5. 3. Limitations of study and further improvements

Studies to date have not been optimised to assess flow state due to the inherent difficulties in trying to call up flow state on demand and the various problems of measuring it objectively, flow being an inherently subjective state. Neuroimaging adds an additional set of physical limitations.

This study has managed to measure flow using naturalistic stimuli and has controlled for the effects of simply playing music. However, some of the ways it can be improved are as follows. It is difficult to ascertain if the participants' understanding of flow was the same as our construct. It would be useful to conduct qualitative research on interviews with participants to see if their understanding of flow matches our stated definition of flow and matches between participants. This experiment also relied a lot on participants' self-report on their experience of flow state, in particular, that their flow-inducing piece was actually flow inducing. There may be better ways to control for this. For example, for a non-flow-inducing piece, participants instinctively brought something a bit too hard or a bit too easy, suggesting that Csikzentmihalyi's qualifications for inducement of flow state are accurate. It would be good to have a bit more control over the non-flow condition, and specify to them to bring both kinds of non-flow. It may be more accurate to contrast flow state with the states of boredom (low challenge, negative affect) and overload (high challenge, negative affect)as well, as was done in Ulrich et al (2014).

It is possible that due to the voluntary nature of the experiment, most of the participants self-reported high flow levels. It may be more helpful to get a wider range of flow experiences.

The psychophysiological correlates of flow are well researched and it may be useful to include psychophysiological measures as a less subjective measure of whether participants experienced flow when they self-report it.

In this experiment, it was assumed that the direction of association between flow and EEG measures would be the same independent of the average emotional and physiological state, which could be affected by the mood of the piece. This could be a problem as EEG is sensitive to mood and mental exertion. It is also possible that musicians associate certain moods and tempi with flow more than others. This could potentially be a confound as music involves emotion which would affect EEG activity, particularly in the frontal regions (Schmidt and Trainor, 2001). With a larger sample size, it would be possible to break participants into groups based on the tempo and mood of the piece inducing flow and non-flow. It would also be interesting to see how the emotion involved affects flow state.

2. 5. 4. Conclusion

In summary, there are distinct differences between the neural correlates of the state immediately following flow and the state immediately following non-flow that are measurable with EEG. The differences are most notably in the upper alpha (10-12 Hz) band which has implications for our understanding of the mechanism of flow. The differences and time courses of beta and delta frequency bands offer opportunity for speculation but more research is needed to clarify the roles beta and delta may play in flow. Also found were more factors that predicted flow state in musicians' performances, namely liking and familiarity. Due to the exploratory nature of this study, more research is necessary to confirm the role these factors play in affecting the flow musicians experience during musical performance.

Chapter 3 Differentiating enjoyment and challenge-skill balance from flow

3. 1. Introduction

In the first study, participants brought a flow-inducing and non-flow-inducing piece to the lab. However, little is known about why these pieces were considered flow-inducing or not. The first study also left the definition of flow up to the participants, making it difficult to link the experiment to established flow theories and compare findings with other studies on flow neuroscience. Hence, this experiment sets out to address some of these issues and shed some light on musicians' conception of flow.

In the last study, participants rated their flow piece both higher in liking and familiarity than their non-flow piece. This is in line with Marin and Bhattacharya's (2013) finding that liking and familiarity plays a role in whether a piece induces flow in musicians. However, it is not know how these separately contribute to the neural correlates of flow found in the previous experience. Theoretically, liking the piece seems to reflect the autotelic nature of flow, or the enjoyment of the activity for its own sake rather than monetary rewards or recognition for performing the activity. While enjoyment is part of flow, Baumann et al (2016) suggests that it is necessary to differentiate between flow and general enjoyment. Flow should be defined as a positive experience supported by conditions of slight overload while general enjoyment can be experienced without overload (Baumann, Lürig, & Engeser, 2016).

Assuming that a less familiar piece would be more challenging to perform, the concept of familiarity was subsumed under the concept of challenge, which is more well-studied in flow. Based on the challenge-skill balance model of flow, musicians would experience flow as long as the challenges of the piece matched their level of skill. Trying to distinguish the subjective experience of challenge-skill balance from flow goes directly against the assumptions of the experimental flow paradigm. But from the musicians' perspective, Marin and Bhattacharya (2013) found that musical emotions may play an important role in the induction of flow in performing artists. The majority of pianists agreed that flow states are more easily reached when a piece induces emotions that they particularly like. Interestingly, both positive and negative emotions were included under emotions they liked music to induce in them. Pianists also largely agreed that flow states are more easily reached when playing pieces that they particularly like. Most participants also agreed that the musical style played a role in flow states. For this specific sample of classically trained piano performance students, the Romantic style was the most familiar, preferred and also the most flow-inducing. Certain styles and composers were particular flow-inductive. There was high agreement among pianists that Chopin’s music is particularly flow-inducing. But for forty-two out of 68 participants, the most favorite musical style was also the most flow-inductive style, regardless of the type of musical style. So presumably, for a non-flow inducing but equally challenging piece, musicians could choose to play something of equal challenge but was not of the style that they found particularly flow-inducing, or did not induce an emotion they particularly like, or just not a piece they liked very much.

As was done in the first experiment, participants will bring their own music that they know will induce flow for them. But to establish flow as a construct, this experiment will first provide participants with a definition of flow, ask if they recognise the experience and then ask the participants to bring a piece that induces that experience for them. They will also be asked to bring a piece that they find equally challenging as their selected flow piece. Thus it is at the right level to induce flow based on challenge-skill balance but yet, it lacks something that induces flow in the participant. In this way, we can rule out the possibility that any difference between flow and non-flow is due to the effect of cognitive load from the challenge of the task. They will also be asked to bring a piece they like as much as the flow-inducing piece but which does not induce flow for them. In this way, we can rule out the effects of mere enjoyment

Post-playing data will again be collected to avoid movement artifacts from playing an instrument. As post-playing data was found to differentiate flow and non-flow in the previous experiment, it is considered a suitable proxy for the actual experience during playing.

Hypothesis: That there is a discernible difference in the neural states between flow, enjoyment and equal challenge measurable with EEG.

3. 2. Methods

3. 2. 1. Design

The study was a within-participant, repeated measures design in which participants took part in all three conditions. The independent factor was the type of music the participant played. In the first condition, participants played a piece that induced flow. In the second, they played something that they liked as much as the flow-inducing piece but which did not induce flow. In the third, they played a piece that they found as challenging as the flow-inducing piece but did not induce flow. The dependent factor was the spectral power in delta, theta, lower alpha, upper alpha and beta bands averaged over the 75 seconds of EEG data recorded after the piece ended.

	Flow	Non-flow: Equal Challenge	Non-flow: Equal Liking
Subjective perception of challenge-skill balance	✓	✓	χ
Enjoyed and valued experience	✓	χ	✓

3. 2. 2. Participants

An opportunity sample of 44 amateur and professional musicians (23 female) of varying levels of skill took part in the study. There were 14 wind players, 10 pianists, 10 singers, 5 guitarists and 5 string players. 3 participants were currently enrolled on either an undergraduate or postgraduate music performance programme at either a conservatory or a university. 18 of those who were not currently enrolled in a music performance programme had graduated from a music performance course and remained active in the local music scene to varying degrees. 9 had never studied music at tertiary level but played often as a hobby or part of a job. Participants were paid 25 pounds for taking part in the experiment. The data of one participant was excluded because the participant misunderstood the task. Another participant had to be excluded because of faulty data collection. All participants provided written informed consent. The study was approved by the local ethics committee of the Department of Psychology at Goldsmiths, University of London, and conducted in accordance with the Declaration of Helsinki.

3. 2. 3. Materials

Two questionnaires relating to flow were administered: The Dispositional Flow Scale-2 (DFS-2) and the Flow State Scale -2 (FSS-2).

The Dispositional Flow Scale-2 (DFS-2) (S. A. Jackson & Eklund, 2004) consisted of 36 items which were based on the nine-dimensional construct of flow. Dispositional flow was calculated as a measure of how frequently participants experience conditions that are conducive to experiencing flow in the chosen activity. It had been shown to be a reliable tool applicable to measuring flow in musicians (Sinnamon et al., 2012). Answers were collected on a 5-point Likert scale, where 1 = never and 5 = always. Participants were instructed to answer it in the context of playing their main instrument, regardless of whether it is practice or performance.

The Flow State Scale-2 (FSS-2) (S. A. Jackson & Eklund, 2004) measured state flow, the extent to which a specific experience resembled flow. It asked the same 36 questions as the DFS-2 but answers were collected on a 5 point Likert scale where 1 = completely disagree and 5 = completely agree. Participants answered the questionnaire immediately after playing each piece and were instructed to answer it only in reference to the experience they just had. The FSS-2 had been shown to be suitable for use in studying musicians' state flow (Wrigley & Emmerson, 2013).

3. 2. 4. Experimental procedure

Participants were given an instruction sheet prior to attending the EEG session. The instruction sheet asked the following questions.

1. Do you ever do something where your concentration is so intense, your attention is so undivided and wrapped up in what you are doing that you sometimes become unaware of things you normally notice (for instance: other people talking, loud noises, the passage of time, being hungry or tired, having an appointment, or having some physical discomfort)? *Yes* *No*

2. Do you ever do something where your skills have become so "second nature" that sometimes everything seems to come to you "naturally" or "effortlessly" and where you feel confident that you will be ready to meet any new challenges? *Yes* *No*

> 3. Do you ever do something where you feel that the activity is worth doing in itself? In other words, even if there were no other benefits associated with it (for instance, financial reward, improved skills, recognition from others, etc.), would you still do it? *Yes* *No*

These questions have been used to establish flow as a construct (Csikszentmihalyi, 1975). Participants are then instructed to select a familiar and fluent piece that induces the feeling described by the questions. This is to be played in the Flow condition. They then rated this piece on how challenging they found it and how much they liked it. Then they were told to pick another piece which they would give the same liking score but which does not induce the feeling described by the questions. This was to be played in the Non-flow Equal Liking condition. They then chose a piece they would rate as equally challenging as the flow-inducing piece yet does not induce flow, this one to be played in the Non-flow Equal Challenge condition. Each piece was played twice in a block design so that there were two consecutive trials for each condition. The three conditions were counterbalanced to control for fatigue and order effects. Participants stood or sat to play depending on what they individually felt most comfortable with. Participants were informed that the experiment was concerned with their experience while playing their instrument so the quality of their performance was irrelevant. EEG data was recorded during playing. Because playing musicians tended to produce many artifacts, to ensure useable data was obtained from all participants, EEG data was also recorded immediately after participants finish playing to get the cleanest possible data closest to the experience. Therefore, participants were instructed to sit down after finishing the piece (if they were not already sitting) and press a button indicating they were done with the piece. Then they closed their eyes and 75s of EEG data was recorded. After the post-performance state was recorded, participants answered the FSS-2 to indicate how much in flow they felt while playing the piece. Resting state data, 1 minute each with eyes open and eyes closed, was also recorded both before and after performance. After the session, participants were asked to rate their pieces on liking and challenge based on how they felt while playing them on that day in the lab.

3. 2. 5. Statistical analyses

The statistical analyses were conducted in IBM SPSS Statistics version 22 (SPSS Inc., Chicago, IL, USA) and in Matlab R2013b (The MathWorks, Inc., Natick, Massachusetts, USA).

3. 2. 6. EEG recording and analysis

The EEG recording was done using 64 active electrodes placed in the extended 10-20 system of electrode placement and amplified by a BioSemi Active Two amplifier (www.biosemi.com).Four additional electrodes recorded vertical and horizontal EOGs, which were used to monitor horizontal and vertical eye movement. A sampling frequency of 512 Hz was used to record the data. Additional external electrodes were placed on the left and right earlobes as a reference.

3. 2. 7. Preprocessing

EEG data was re-referenced to the average of the two earlobes. The data was high-passed filtered at 0.5Hz and the data was low-passed at 30Hz to remove high-frequency noise. It was then epoched from 2s before to 75s after participants stopped playing and closed their eyes. The post-performance data was relatively artefact-free. Eye-blink corrections were not necessary as participants had their eyes closed during post-performance recording.

3. 2. 8. Time-Frequency Analysis

Due to the nature of the experiment, there was a lack of an ideal baseline. Therefore, the decision was made to calculate relative and absolute power without removing baseline. After preprocessing, the 75s of post-playing data divided into two time windows. Power analysis was done using Welch's power spectral density estimate for 5 frequency bands, delta (1-4 Hz), theta (4-8 Hz), lower alpha (8-10 Hz), upper alpha (10-12 Hz) and beta (12-30 Hz). This decision was made because the results of the previous experiment suggest these as frequency bands of interest. The data was divided into segments of 2 sec with an overlap of 500 msec. The resulting power values were averaged among 2 flow states, 2 non-flow equal liking states and the two non-flow equal challenge states. Spectral power in separate frequency bands can be reported as both an absolute value, and as a proportion of the total power of the signal, or a relative value. Both relative and absolute power values are reported.

3. 2. 9. EEG Statistical analysis

To find significant differences between the two conditions, a paired t-test was carried out on the EEG data points. The flow condition was separately compared with the non-flow equal liking condition and the non-flow equal challenge condition. In dealing with the issue of multiple comparisons, Bonferroni's correction proved to be too conservative.Therefore, to conduct exploratory analyses on the data without compromising on the issue of multiple comparisons, we applied spatial constraints. For an effect to be both statistically significant and biologically relevant, it needs to be found over a cluster of data points in the analysed dimensions of time, space (electrodes), and frequency. An isolated significant difference found at a nonspecific data point would not be considered biologically relevant and would not be considered a significant cluster even if highly significant. A threshold of $p < .05$ across the entire 75s and at least three neighbouring significant electrodes to the sample-specific statistics was applied and connected clusters that exceed the threshold and have the same sign were constructed. This method was used to define the regions of interest (ROIs) in the topography of the head and the frequency bands, which were later analysed with a standard ANOVA. The ANOVA was carried out to allow comparisons between groups and interactions, which were not accounted for in the t-test on the EEG data points.

3. 3. Results

3. 3. 1. Behavioural results

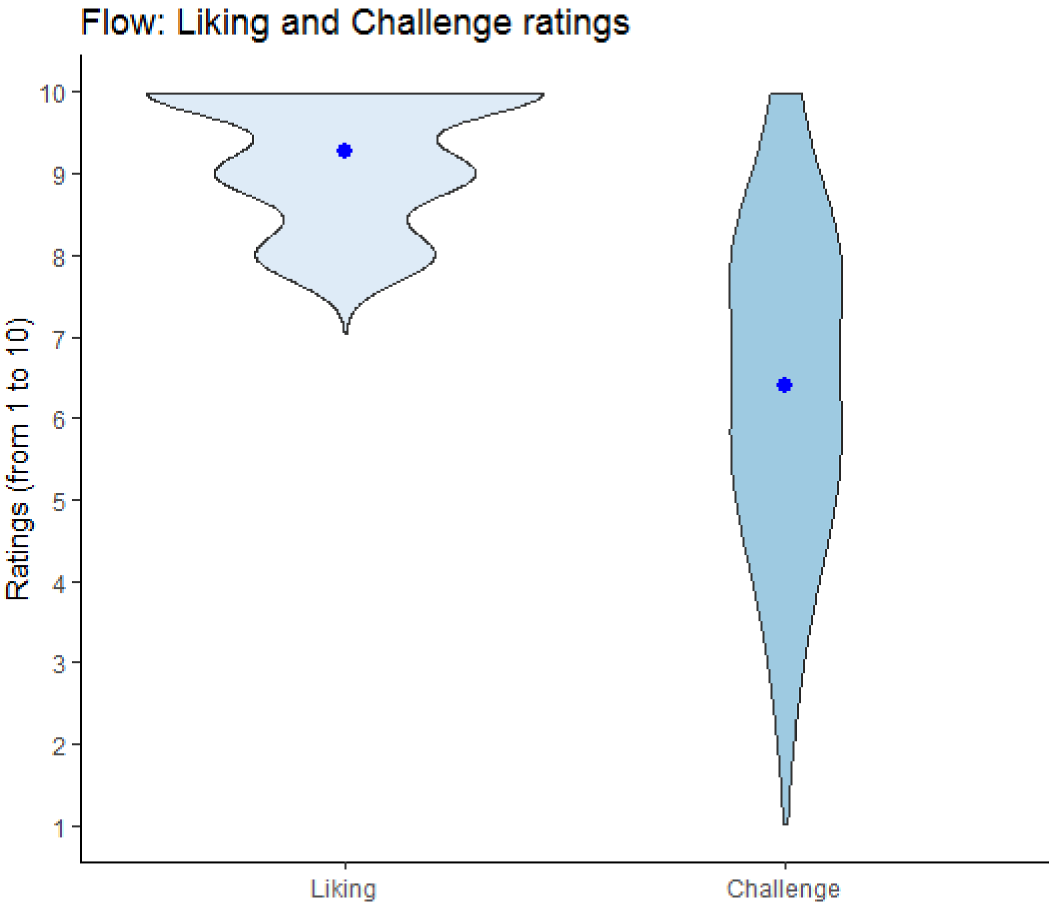
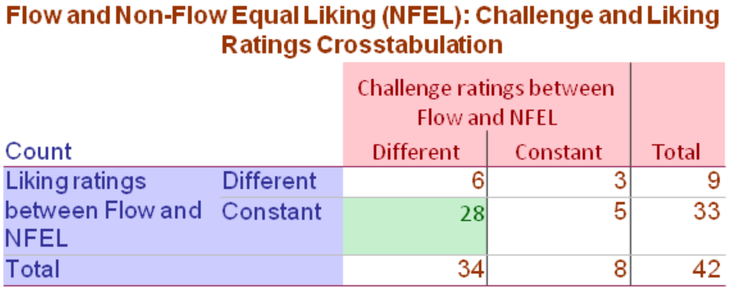


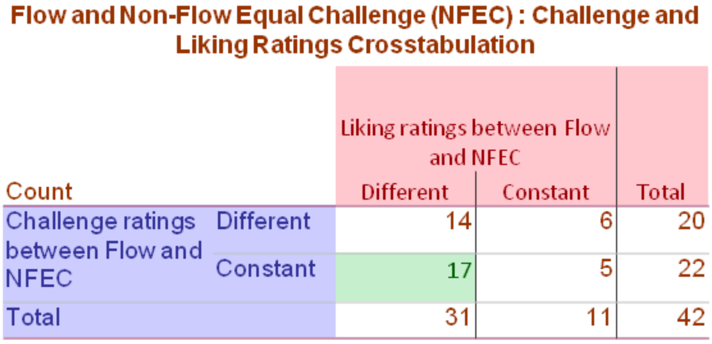
Figure 3.1: Liking and challenge ratings for flow-inducing piece

Participants were given a description of flow and brought a piece that typically induced the described feeling for them. They rated these pieces on liking and challenge. Liking ratings were high but challenge ratings were more varied. This is likely due to personal preference for difficulty, particularly in a performance context. More conscientious people were more likely to bring flow pieces that were rated more challenging (r = .369, p = .016). Likely, they practiced more and were more confident in performing a piece that induced flow even if it was challenging.



Flow and Non-Flow Equal Liking (NFEL): Challenge and Liking Ratings Crosstabulation

Count		Challenge ratings between Flow and NFEL		
		Different	Constant	Total
Liking ratings between Flow and NFEL	Different	6	3	9
	Constant	28	5	33
Total		34	8	42



Flow and Non-Flow Equal Challenge (NFEC) : Challenge and Liking Ratings Crosstabulation

Count		Liking ratings between Flow and NFEC		
		Different	Constant	Total
Challenge ratings between Flow and NFEC	Different	14	6	20
	Constant	17	5	22
Total		31	11	42

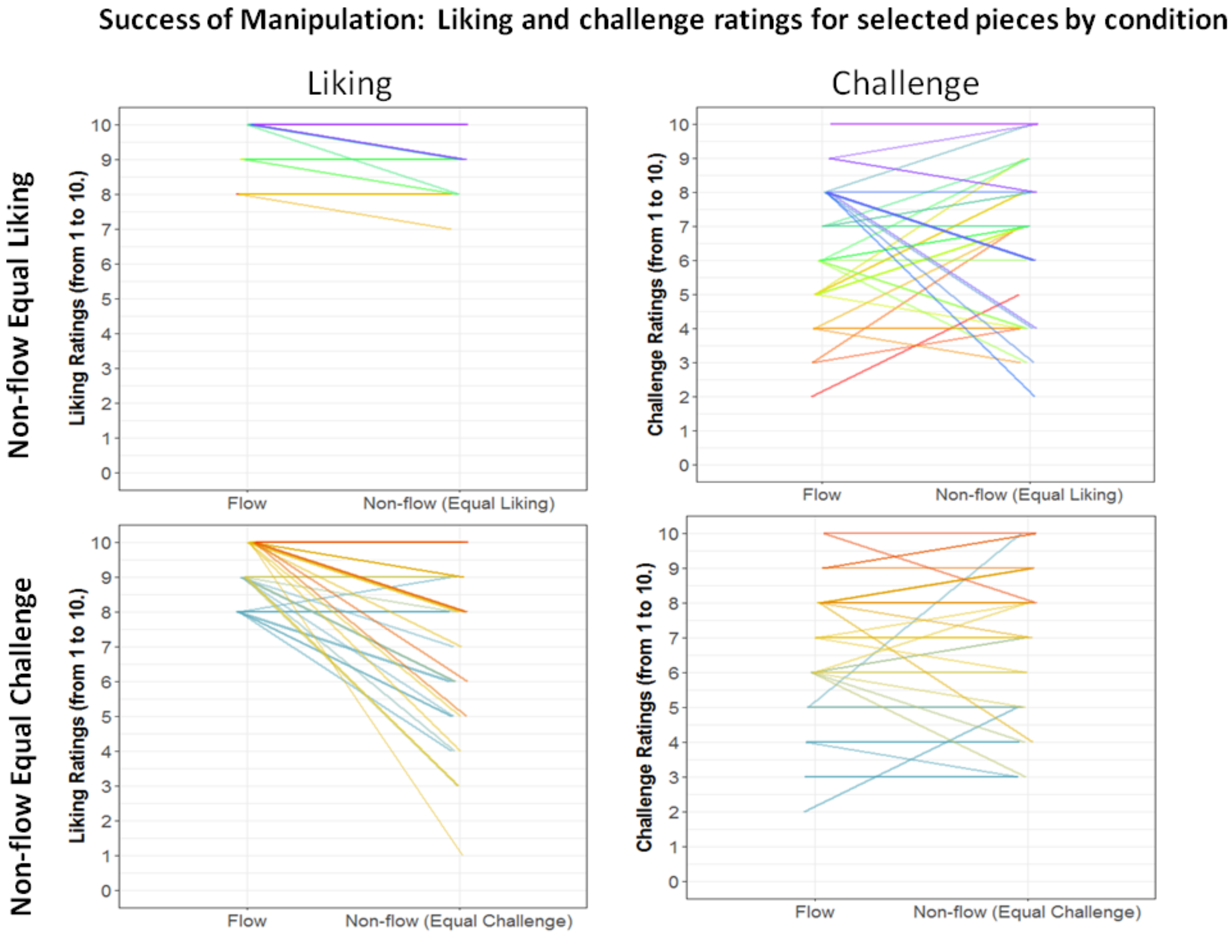
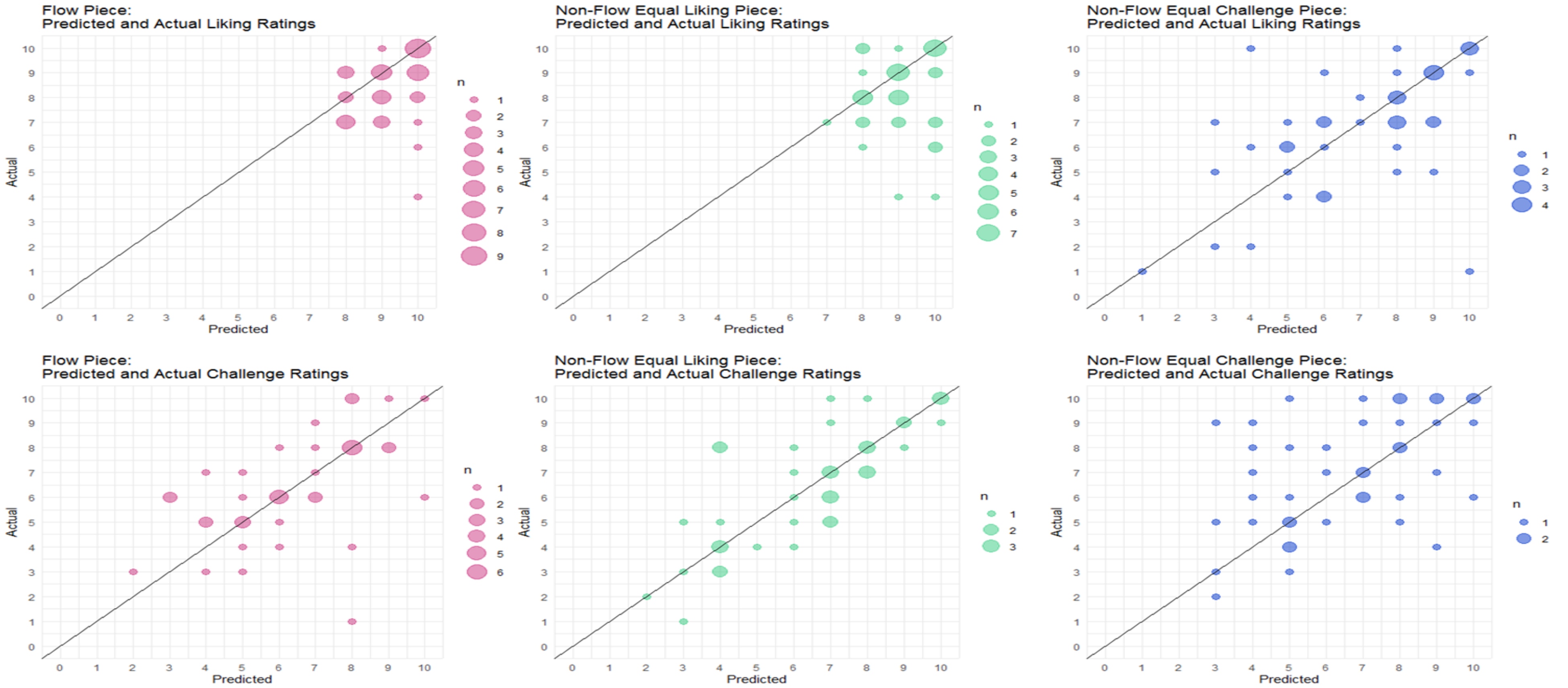


Figure 3.2: Comparison of liking and challenge ratings between flow and two different non-flow conditions

To set up the conditions, participants were asked to rate their flow piece on liking and challenge, and then to bring a piece that they liked just as much as their flow piece but did not induce flow for them (the Non-flow Equal Liking condition). They were also asked to bring a piece that was of equal challenge to their flow piece but did not induce flow (the Non-flow Equal Challenge condition). For the Non-flow Equal Liking condition, participants brought pieces that were as liked as their flow piece, but to not experience flow, they often chose pieces that were either of greater or less challenge than their flow piece. For the Non-flow Equal Challenge condition, participants were less able to maintain challenge as a constant. Though some were able to select a piece that was of equal subjective challenge to their flow piece, many did not. This may be due to the limitations of repertoire that is ready for performance and subjective perception of challenge. To not experience flow, they chose a piece that they liked less than their flow piece. But many also had to choose something harder or easier to not experience flow. More participants were able to follow the instructions for the NFEL piece than for the NFEC piece. This suggests that participants were better able to distinguish enjoyment from flow than a match between challenge and skill from flow.



Count		Challenge (compared to usual)			
		Harder	Same	Easier	Total
Liking (compared to usual)	More	2	2	2	6
	Same	4	10	2	16
	Less	10	4	8	22
Total		16	16	12	44

Count		Challenge (compared to usual)			
		Harder	Same	Easier	Total
Liking (compared to usual)	More	3	3	0	6
	Same	5	6	9	20
	Less	3	8	7	18
Total		11	17	16	44

Count		Challenge (compared to usual)			
		Harder	Same	Easier	Total
Liking (compared to usual)	More	8	3	4	15
	Same	8	3	3	14
	Less	5	4	6	15
Total		21	10	13	44

Figure 3.3 Scatterplots for how predicted challenge and liking ratings for pieces compared to challenge and liking ratings within the lab. Dots on the line reflect actual ratings that matched predicted ones. Dots above the line reflect either that the piece was experienced as more liked on the day in the lab or more difficult. Dots under the line reflect pieces that were less liked on the day or were considered more easy on the day.

Participants rated their pieces on how much they liked the pieces and how challenging they were before coming to the lab (predicted ratings). These predicted ratings were presumably based on how they usually felt about playing these pieces. However, the lab may be an unusual environment to play in so to see if it affected their experience of the piece, they were asked to rate their pieces again on challenge and liking after the experiment, based on how they felt playing on the day in the lab. The scatterplots show that the enjoyment and challenge associated with the pieces were not stable. On the day of performance, in the lab, participants could find the piece more or less challenging than expected and could also unexpectedly enjoy playing the piece more or less than expected. Correlations conducted between actual and predicted ratings varied according to pieces.

Condition	**Rating**	***r* (Predicted x Actual)**	***p***
Flow	Liking	.293	.059
	Challenge	.556	<.001
Non-flow: equal liking	Liking	.127	.421
	Challenge	.801	<.001
Non-flow: equal challenge	Liking	.531	<.001
	Challenge	.474	<.001

Table 3.1: Correlations between predicted and actual challenge and liking ratings

Predicted liking for the flow piece did not significantly correlate with the actual liking. From the scatterplot, participants often did not like their flow piece as much in the lab. Correlations for challenge ratings were all significant, suggesting that perceptions of challenge may be more stable even when the pieces are brought into the unfamiliar environment of the lab.

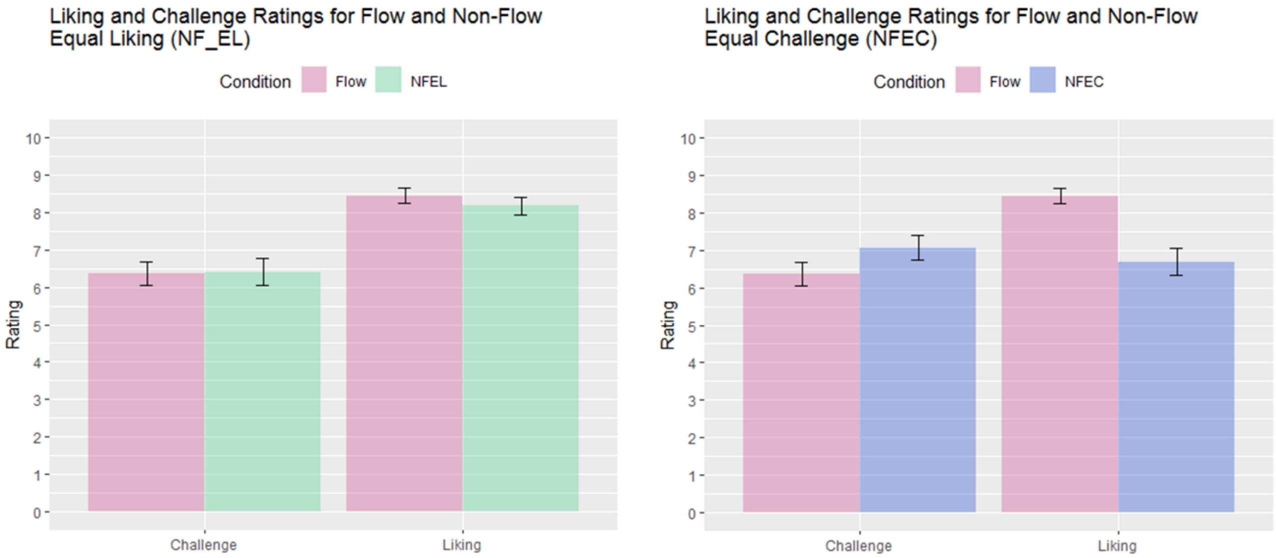


Figure 3.4: Liking and challenge ratings for pieces performed during the experiment

Fig 3.4 shows the actual liking and challenge ratings for the pieces performed during the experiment. Liking and challenge ratings for the NFEL piece were not significantly different from the flow piece (t(43) = 1.02, p = 0.312; t(43) = -0.107, p = 0.915) but while challenge ratings for the NFEC piece were not significantly different from flow (t(43) = -1.89, p = 0.066), liking ratings for the NFEC piece were significantly different from the flow piece (t(43) = 4.21, p < 0.000), suggesting that participants successfully chose pieces that they liked equally but did not experience flow in, as well as pieces that are close in challenge to their flow piece but they did not like them as much, a possible reason that they did not experience flow in them despite the equal challenge.

Figure 3.5: Barplots and radarcharts of FSS scores for flow and the two non-flow conditions

Fig 3.5 shows that the FSS scores in the non-flow equal liking condition was more similar to the flow condition. There were larger differences in FSS scores between flow and non-flow equal challenge.

Behavioural results from FSS scores in the flow, non-flow equal liking and non-flow equal challenge conditions (n = 44)

Dimension	*F(2,86)*	*p*	Pairwise comparisons mean differences	
			Flow vs NFEL	Flow vs NFEC
Balance between Challenge and Skill	6.50	.002	.185*	.369**
Action-Awareness Merging	13.4	< .001	.196*	< .001
Clear Goals	5.86	.004	.162*	.369**
Unambiguous Feedback	1.03	0.36	.094	.108
Total Concentration	2.15	.001	.372**	.392**
Sense of Control	10.1	< .001	.159	.506**
Loss of Self-Consciousness	2.37	.099	.116	.210*
Time Perception	12.6	< .001	.335**	.509**
Autotelic Experience	15.8	< .001	.335**	.767**
Total FSS score	16.9	< .001	.217**	.424**

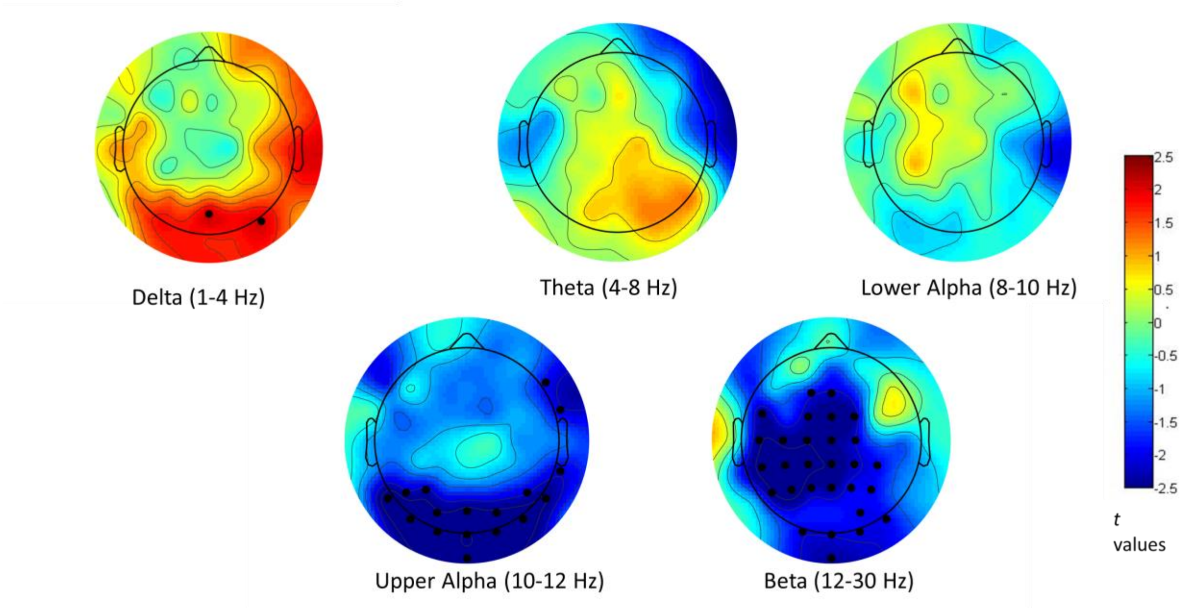
**. The mean difference is significant at the 0.05 level (2-tailed).

**. The mean difference is significant at the 0.01 level (2-tailed).

Table 3.2: Summary of differences in behavioural results between conditions

3. 3. 2. EEG findings

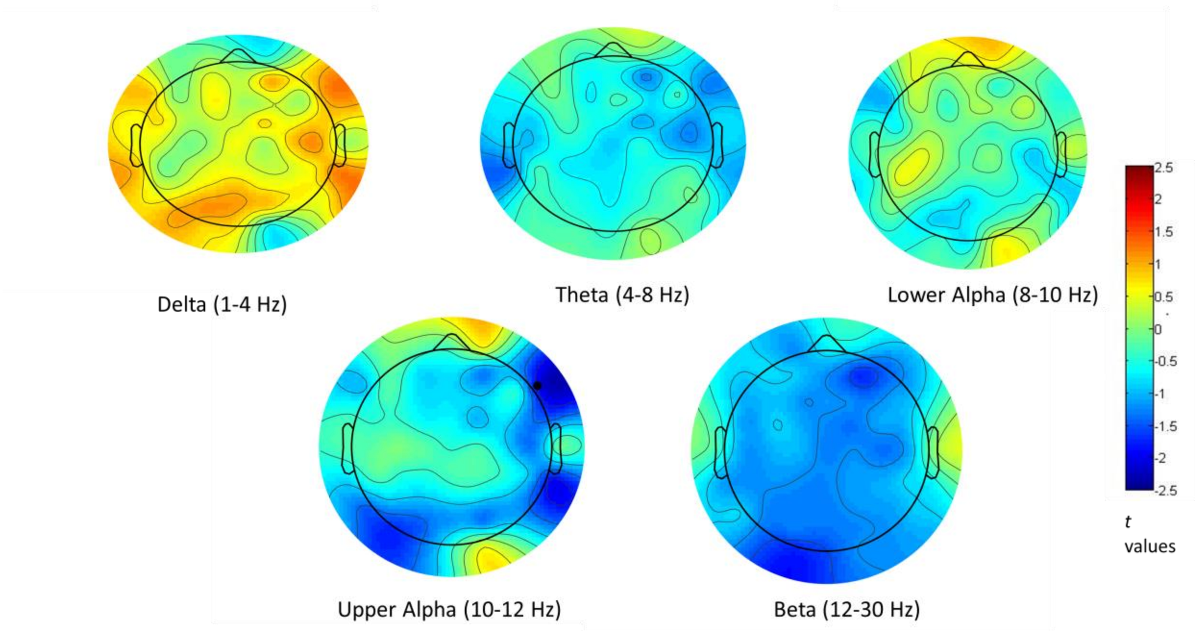
Neural data in the flow condition was compared separately to each of the two different non-flow conditions. Relative power is of especial interest as the earlier study described in Chapter 2 found that relative power in the upper alpha and beta band differentiated flow from non-flow. Hence, we first looked at relative power to see if our earlier finding can be replicated. Fig 3.6 shows the relative spectral power differences between post-playing state after playing a flow inducing piece and a non-flow inducing piece that was nevertheless as liked as the flow piece. Relative power in the delta band was significantly higher in flow in two electrodes in the occipital area (*F*(1,43) = 5.23, *p* = .027). However, relative power in upper alpha (10-12Hz) and beta band was significantly lower in flow than in the non-flow condition (alpha: *F*(1,43) = 9.72, *p* = .003; beta: *F*(1,43) = 11.4, *p* = .002).



Topoplots of *t*-values by comparing EEG power of seven frequency bands between flow and non-flow states. Red indicates that power is higher in the flow condition while blue indicates that the power is higher in non-flow condition. Statistically significant electrodes ($p < .05$) are indicated by black dots.

Figure 3.6: Topoplots comparing flow and non-flow but equally liked conditions. Relative spectral power in the upper alpha and beta bands was higher in the non-flow condition

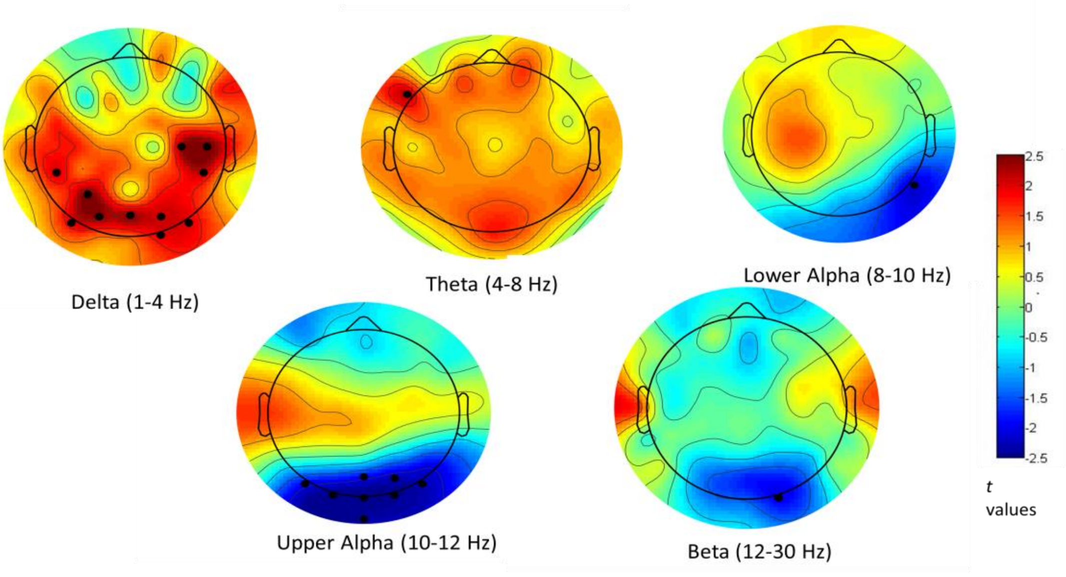
Fig 3.7 shows the relative spectral power differences between post-playing state after playing a flow inducing piece and a non-flow inducing piece that was nevertheless considered as challenging as the flow piece. However, no relative power differences were found between flow and non-flow conditions.



Topoplots of *t*-values by comparing EEG power of seven frequency bands between flow and non-flow states. Red indicates that power is higher in the flow condition while blue indicates that the power is higher in non-flow condition. Statistically significant electrodes ($p < .05$) are indicated by black dots.

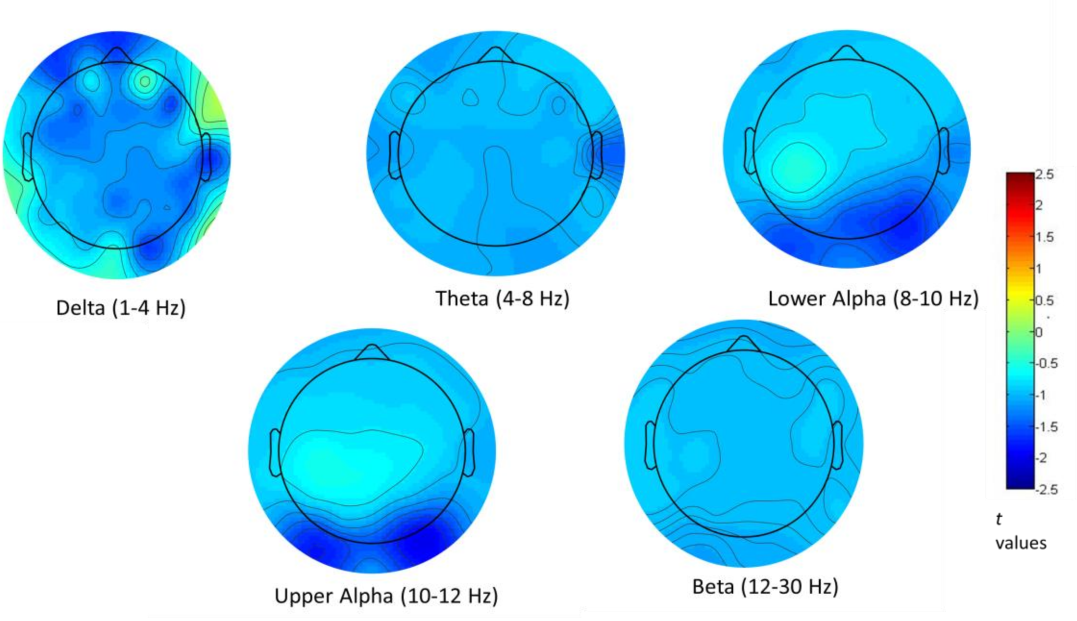
Figure 3.7: Topoplots comparing flow and non-flow but equally challenging conditions. Relative spectral power did not differ between flow and non-flow conditions

Absolute spectral values were also examined. Absolute values of delta power was higher in flow than non-flow ($F(1,43) = 7.76$, $p = .008$) while absolute occipital alpha power was lower in flow than in non-flow ($F(1,43) = 7.08$, $p = .011$). However, absolute power also did not differ between flow and non-flow but equally challenging.



Topoplots of *t*-values by comparing EEG power of seven frequency bands between flow and non-flow states. Red indicates that power is higher in the flow condition while blue indicates that the power is higher in non-flow condition. Statistically significant electrodes ($p < .05$) are indicated by black dots.

Figure 3.8: Topoplots comparing flow and non-flow but equally liked condition, using absolute spectral power



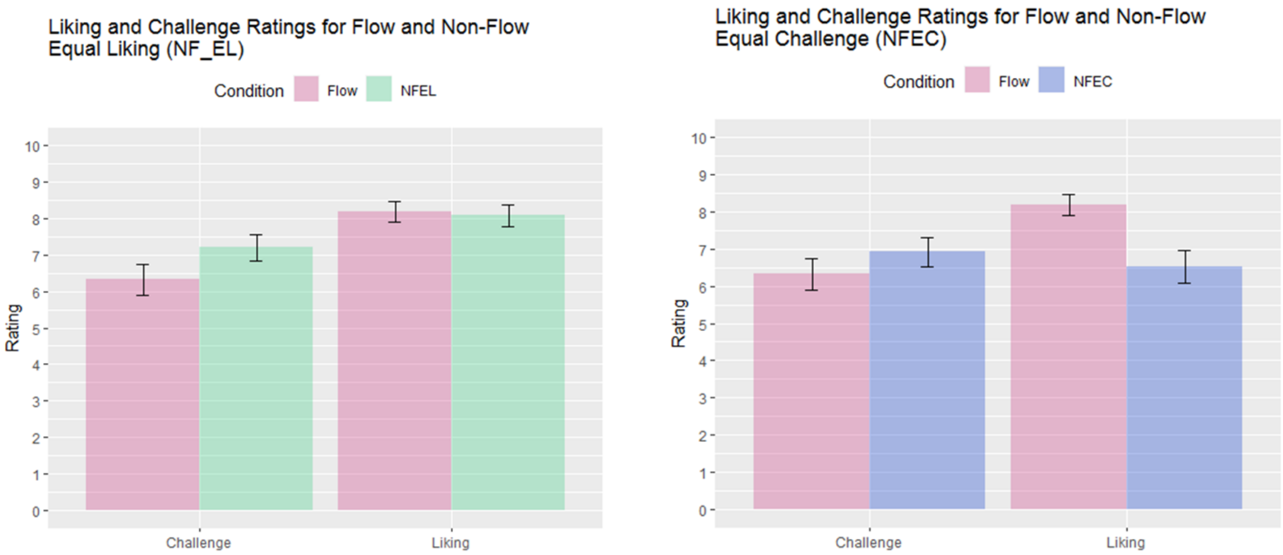
Topoplots of *t*-values by comparing EEG power of seven frequency bands between flow and non-flow states. Red indicates that power is higher in the flow condition while blue indicates that the power is higher in non-flow condition. Statistically significant electrodes ($p < .05$) are indicated by black dots.

Figure 3.9 Topoplots comparing flow and non-flow but equal challenge condition, using absolute spectral power

3. 3. 3. EEG findings part 2

After looking at the FSS scores individually, it was found that not all participants experienced highest FSS scores in the flow condition. Some had higher FSS scores in the non-flow equal liking condition while others had higher FSS scores in the non-flow equal challenge condition. Considering the possibility that the lower FSS scores in comparison to a non-flow condition meant that they did not experience flow in their flow piece, the decision was made to only examine participants who scored their highest FSS scores in the flow condition. Flow in this case, would be defined as the participants' experience of flow as it overlaps with the 9 dimensions of flow as defined by the FSS.

If we assume that lower scores on the FSS mean than participants did not experience flow characteristics in their flow pieces, we can choose to examine only the participants who scored the highest FSS scores on their flow piece.


Liking and Challenge Ratings for Flow and Non-Flow Equal Liking (NF_EL)

Liking and Challenge Ratings for Flow and Non-Flow Equal Challenge (NFEC)

Figure 3.10 Liking and challenge ratings across conditions for the participants who had highest flow scores in the flow conditions (n = 25)

As with the full sample, Liking and challenge ratings for the NFEL piece were not significantly different from the flow piece (t(24) = .287, *p* = 0.78; t(24) = -1.50, *p* = .147)but while challenge ratings for the NFEC piece were not significantly different from flow (t(24) = -1.34, *p* = .192), liking ratings were significantly different from the flow piece (t(24) = 2.87, *p* = .010).

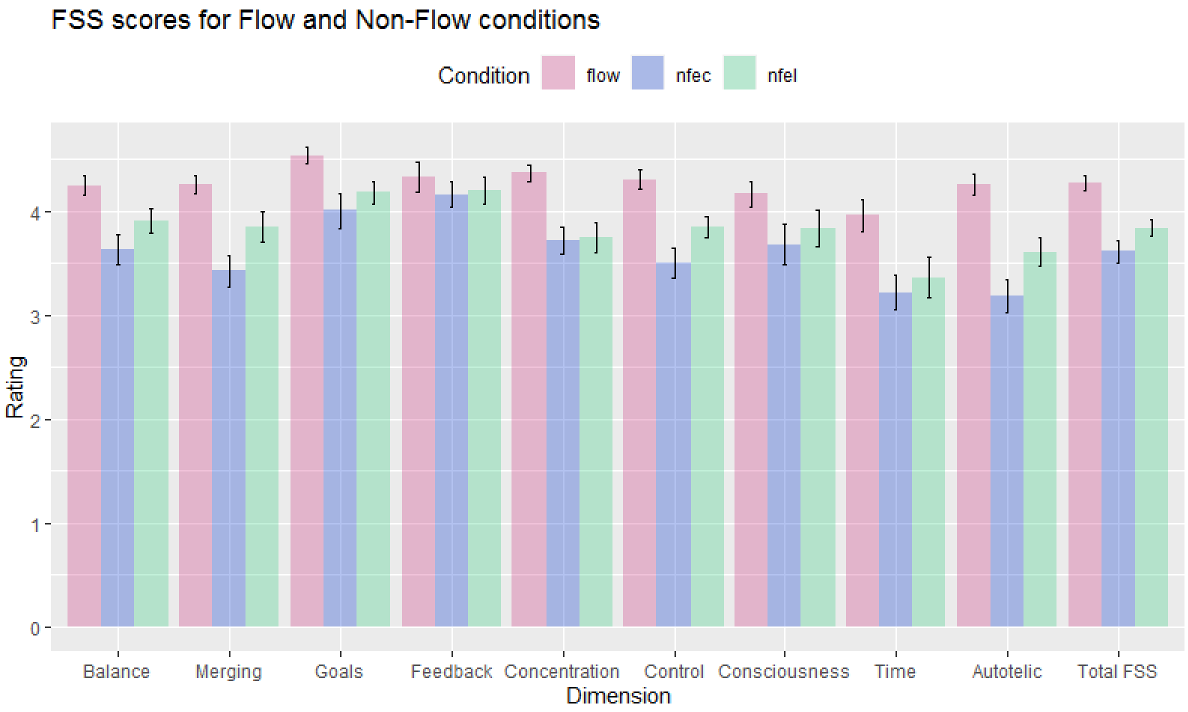


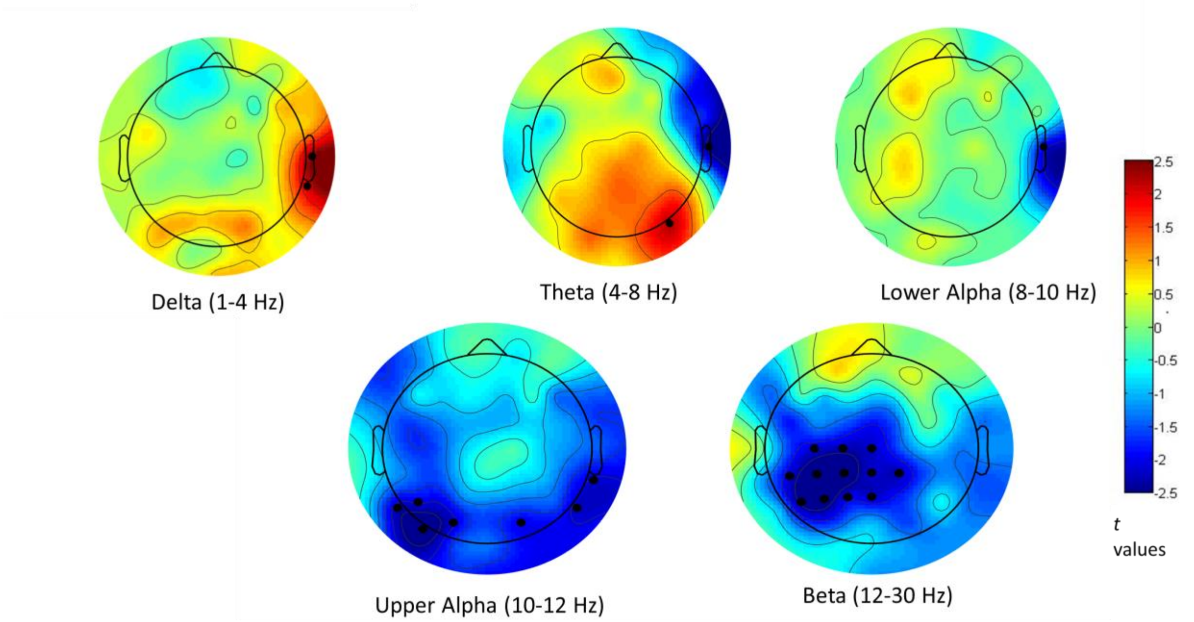
Figure 3.11 FSS scores for the subset of participants that scored highest flow scores in the flow condition (n = 25)

Behavioural results from FSS scores in the flow, non-flow equal liking and non-flow equal challenge conditions (n = 25)

Dimension	*F(2,48)*	*p*	Pairwise comparisons mean differences	
			Flow - NFEL	Flow - NFEC
Balance between Challenge and Skill	12.9	< .001	.335**	.615**
Action-Awareness Merging	18.8	< .001	.410**	.835**
Clear Goals	8.92	.001	.355**	.530**
Unambiguous Feedback	1.01	.370	.135	.170
Total Concentration	14.7	< .001	.615**	.645**
Sense of Control	20.1	< .001	.450**	.800**
Loss of Self-Consciousness	5.94	.005	.325*	.485**
Time Perception	15.9	< .001	.600**	.740**
Autotelic Experience	21.9	< .001	.645**	1.07**
Total FSS score	32.7	< .001	.430**	.654**

**. The mean difference is significant at the 0.01 level (2-tailed).

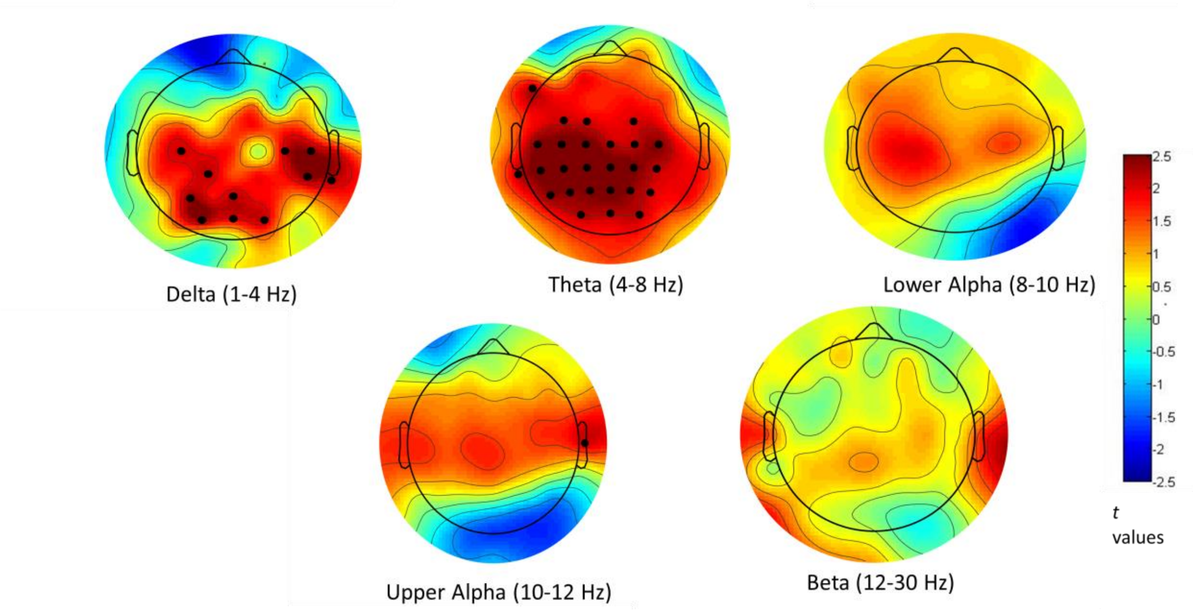
Table 3.3: Summary of ANOVA on FSS scores (total and dimensions)



Topoplots of *t*-values by comparing EEG power of seven frequency bands between flow and non-flow states. Red indicates that power is higher in the flow condition while blue indicates that the power is higher in non-flow condition. Statistically significant electrodes ($p < .05$) are indicated by black dots.

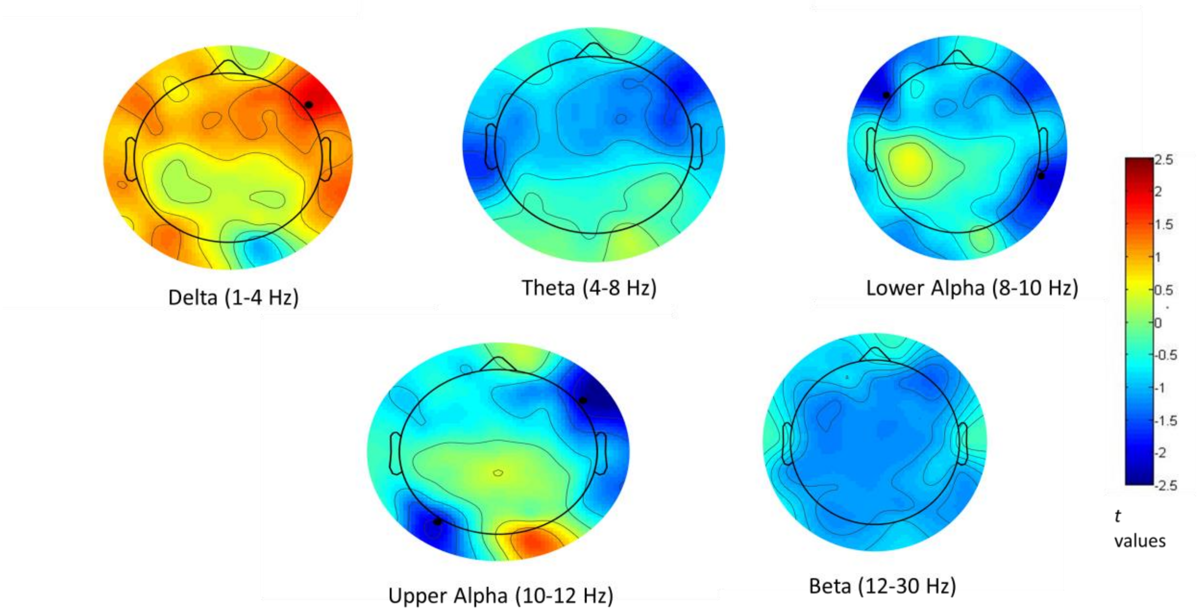
Figure 3.12: Topoplots comparing relative spectral power between flow and non-flow equal liking conditions

Relative power was still higher in the non-flow condition in the upper alpha and beta bands (upper alpha: *F*(1,24) = 7.54, *p* = .011; beta: *F*(1,43) = 8.90, *p* = .006). However, absolute power in the delta and theta band was found to be significantly higher in flow than in non-flow (delta: *F*(1,24) = 7.54, *p* = .011; theta: *F*(1,43) = 8.90, *p* = .006) (see Fig. 3.13). It would seem that in flow compared to mere liking, absolute power in the delta and theta bands increases dramatically, reducing the proportion of upper alpha and beta band power. It is also possible to observe the difference in theta band power after removing participants who did not experience flow in the flow condition



Topoplots of *t*-values by comparing EEG power of five frequency bands between flow and non-flow states. Red indicates that power is higher in the flow condition while blue indicates that the power is higher in non-flow condition. Statistically significant electrodes ($p < .05$) are indicated by black dots.

Figure 3.13: Topoplots showing differences in absolute spectral power between flow and equal liking conditions



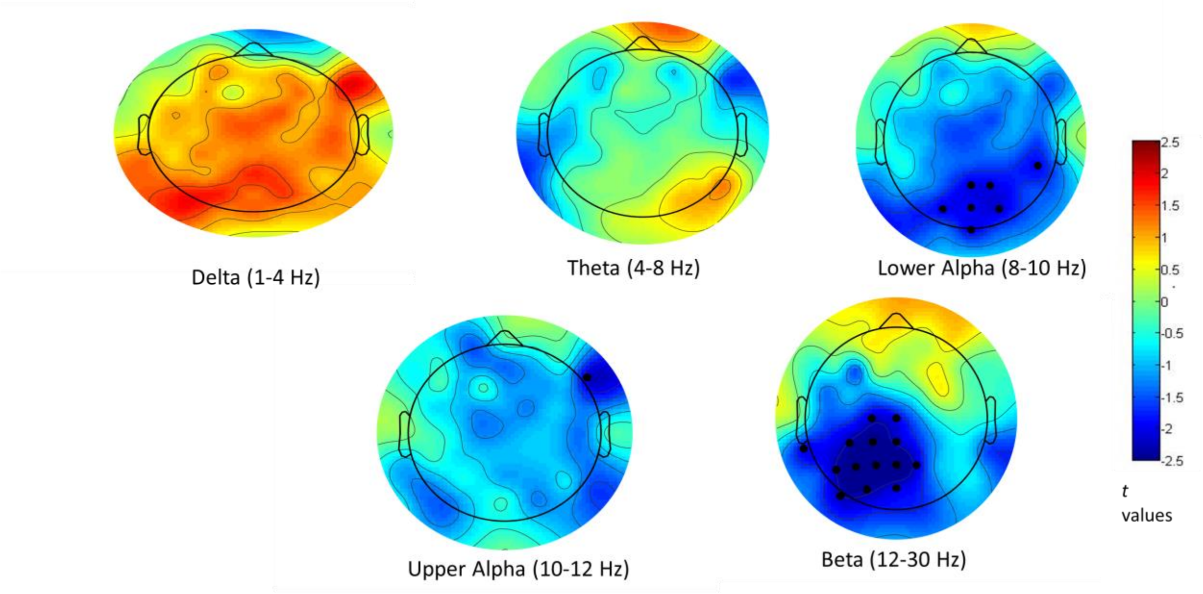
Topoplots of *t*-values by comparing EEG power of seven frequency bands between flow and non-flow states. Red indicates that power is higher in the flow condition while blue indicates that the power is higher in non-flow condition. Statistically significant electrodes ($p < .05$) are indicated by black dots.

Figure 3.14: Topoplots showing differences in relative spectral power between flow and non-flow (equal challenge) conditions

Flow and non-flow equal challenge continue to show no substantial differences in band spectral power, even in this subset of participants.

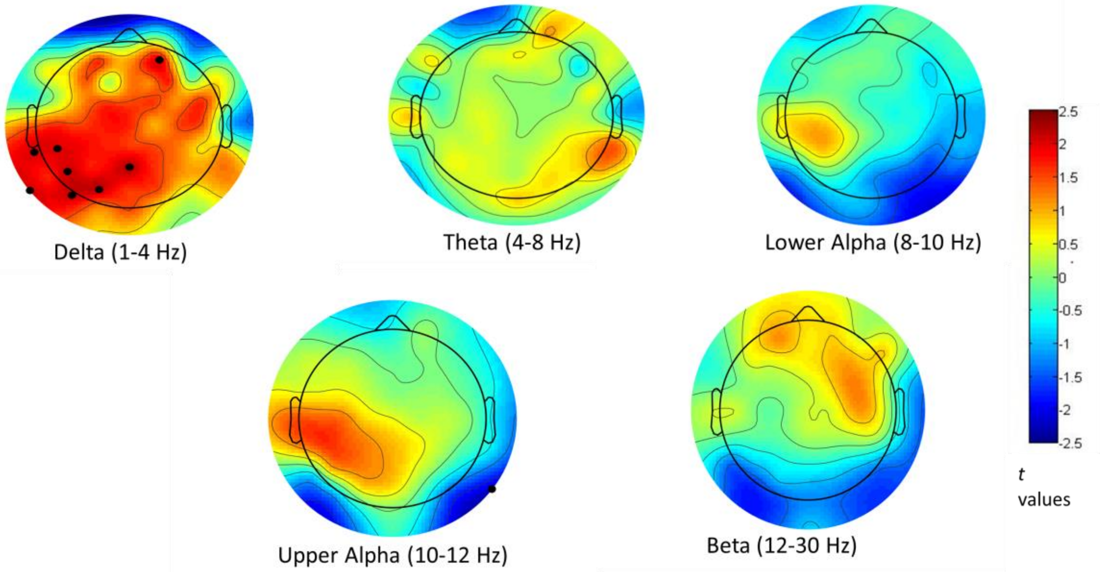
3. 3. 4. EEG findings: High flow vs Low flow

The final possible interpretation of the findings is that because both of the non-flow conditions had antecedents of flow (enjoyment for the equal liking condition and the presence of the main antecedent of flow, challenge-skill balance, in the equal challenge condition) and because of the instability of performance, we could allow that participants may not experience flow in their flow condition, but rather, that it was possible in all conditions. The appropriate analysis would then be to compare pieces with highest and lowest scores on the Flow State Scale-2. High flow turned out to have lower occipital alpha relative power and lower mid beta relative power than low flow (alpha: *F*(1,43) = 5.26, *p* = .030; beta: *F*(1,43) = 7.78, *p* = .008). High flow had higher absolute delta power than low flow (*F*(1,43) = 6.41, *p* = .015). However, using this approach, we can no longer distinguish the relative contributions of enjoyment and challenge to the neural activity associated with flow.



Topoplots of *t*-values by comparing EEG power of seven frequency bands between high flow and low flow states. Red indicates that power is higher in the high flow condition while blue indicates that the power is higher in low flow condition. Statistically significant electrodes ($p < .05$) are indicated by black dots.

Figure 3.15: Topoplots comparing relative power in the session with the highest flow score and the session with the lowest flow score



Topoplots of t-values by comparing EEG power of seven frequency bands between flow and non-flow states. Red indicates that power is higher in the high flow condition while blue indicates that the power is higher in low flow condition. Statistically significant electrodes ($p < .05$) are indicated by black dots.

Figure 3.16 Topoplots comparing absolute spectral power in the session with the highest flow score and the session with the lowest flow score

3. 4. Discussion

3. 4. 1. Behavioural data

This experiment compared flow with two different types of non-flow, one in which the piece was liked as much as the flow-inducing piece and one which was considered as challenging as the flow-inducing piece, but neither induced flow.

For the non-flow equal liking piece, mean ratings of liking and challenge did not significantly differ from that of the flow piece. For the non-flow equal challenge piece, challenge ratings did not differ but liking ratings did, suggesting that participants were able to bring a piece that they did not like as much to avoid getting into flow with a piece of appropriate challenge.

This experiment offered the opportunity to examine the within-lab stability of a flow-inducing piece. In the last experiment, participants only reported on liking and familiarity of the pieces on the day itself so there was no way to tell if their experience of the piece in the lab was a true reflection of their typical experience of the piece. Comparing ratings of pieces before and after performance in the lab showed that participants' experience of the piece often changed in the lab, sometimes in unexpected ways. Participants often liked the flow piece less in the lab. They could also find the pieces more or less challenging than expected. This offers interesting insight into the reliability of this method of flow induction.

Though this experiment tried to distinguish flow from enjoyment and challenge-skill balance, the behavioural results show that conditions are much less distinct than the first study and consequently, differences between conditions are much harder to extract and interpret. The previous study's constructs of 'flow' and 'non-flow' were easier to fit to the 9-dimensional model imposed by use of the FSS and consequently had larger differences between conditions. However, when the constructs are less differentiated, it becomes harder to rely on the FSS to differentiate these related concepts of enjoyment and equal challenge but not flow. Participants had a much more difficult task in this experiment as they could not focus solely on attaining flow in the lab. They had to differentiate a match between challenge and skill, enjoyment and flow and find comparable pieces to induce each condition. That participants still manage it to some degree is promising and more in depth qualitative research is needed to understand how they distinguished between the three conditions.

3. 4. 2. Neural data

Significant spectral power differences were only found between flow and non-flow equal liking conditions. When all participants were included, flow had lower relative upper alpha power in the occipital area and lower relative beta power in the central-parietal areas. Flow also had higher absolute delta power than non-flow equal liking. Taken together, as relative power is power presented as a proportion of the total signal, it would seem that the post-playing state after playing a flow-inducing piece is characterised by an increase in absolute delta power that drives the reduction of upper alpha and beta power as a proportion of the total signal. Increased delta and decreased beta power have been linked to hypoconnectivity of the default mode network (Hlinka, Alexakis, Diukova, Liddle, & Auer, 2010). Default mode network (DMN) activity has also been linked to an increase in occipital alpha and parietal beta (Jann, Kottlow, Dierks, Boesch, & Koenig, 2010). This would suggest that compared to a non-flow state, flow is characterised by decreased activity in the DMN. The activity of the DMN has been linked to introspection, self-referential processing and integration of cognitive and emotional processing (Greicius, Krasnow, Reiss, & Menon, 2003) and it is likely to be activated while musicians were sitting still with their eyes closed and not being engaged in any task. This aligns with the findings of Huskey et al (2018) and Ulrich et al (2016) who also found reduced DMN activity in a flow condition and linked it to reduced self-referential processing and increased task engagement (Huskey, Craighead, et al., 2018; Ulrich et al., 2016b). It is particularly promising that our experiment finds similar findings about DMN activity in musicians' flow experience and that the effect can be found in a resting state after performance. However, this interpretation of the results is based on inference from spectral power in delta, upper alpha and beta bands. One way to clarify if the DMN is involved is to conduct source space analysis to locate and analyse functional connectivity within the DMN.

Another possible interpretation of the increased delta activity in the flow condition is that increased delta reflects inhibition of sensory information that interfere with internal concentration (Harmony, 2013). As flow is a state of high concentration where attention is directed only at task-relevant information, it is possible that delta activity is involved in suppressing non-relevant neural stimuli during task performance and this mental state carries over to the post-playing resting state. This suggests that flow has positive effects on attention even after the flow-inducing activity.

Occipital alpha was found to be higher in the non-flow condition. Widespread or posterior alpha has been linked to a general state of inactivity or disengagement, as opposed to frontal alpha which may be more representative of control processes and attentional engagement (Mathewson et al., 2012). In the non-flow equal liking piece, participants may enjoy playing the piece but as it is not as well matched to their skills as their flow-inducing piece, it may have been less engaging, resulting in more occipital alpha and increased DMN activity in the non-flow condition.

In this first analysis, flow experience is assumed to be linked to the musical piece and though participants may report higher flow scores on another piece, the scores do not reflect flow as participants have already stated that they are less likely to experience flow in that piece.

After examining individual flow scores, it was found that some participants reported high flow scores in conditions other than the flow-inducing condition. As analysing all participants may mix flow experience across conditions, thereby confusing the interpretation, it was decided to exclude these participants, similar to how Yoshida et al (2014) excluded 3 (out of 20) participants who had a lower flow state scale score in the flow condition than in the boredom condition. In this interpretation, lower scores in flow compared to non-flow conditions suggest that the flow piece was unfortunately not flow-inducing in that performance and including them would result in an inaccurate picture of flow in the brain. When we decided to only look at participants that experienced highest flow scores in the flow condition, power in the delta, upper alpha and beta band show similar differences between conditions, except that upper alpha and beta differences were more concentrated in the occipital and central areas respectively. An additional difference was found in the theta band. Absolute theta power was higher in flow than non-flow equal liking conditions. Differences were mainly found in the central-parietal regions. Katahira et al (2018) also found increased theta activity in an experimental flow condition, but in the frontal areas. The increased theta was thought to reflect high levels of cognitive control and immersion in the task (Katahira et al., 2018). Widespread theta activity has also been observed during meditative states (Jirakittayakorn & Wongsawat, 2017), which have some similarity to flow in terms of attentional control. Increased theta in central regions was also found in a mystical experience in Carmelite nuns (Beauregard & Paquette, 2008). Increased theta may thus be related to the transcendent feeling sometimes experienced after deep flow (Tsaur, Yen, & Hsiao, 2013).

When we allowed for the possibility that all three conditions may have the potential to result in flow, we chose to compare states that were had the highest flow scores and states that had the lowest flow scores, regardless of their original conditions. A similar pattern in delta, alpha and beta bands was found, except that the difference was in lower alpha rather than upper alpha this round. This picture could possibly also be interpreted as reduced DMN activity in a state where the nine dimensions of flow were experienced more strongly. However, the difference in neural activity between conditions was not as clear as in the previous analyses where the participants' choice of pieces were taken into account. This calls into question the choice of relying entirely on flow scale scores as the associated neural finding is slightly different from neural findings based on participants' choice of pieces. It is also not entirely clear that there is a cut-off point by which FSS-scores can differentiate a musician in flow from a musician who isn't (Abuhamdeh, 2020). This approach also contradicts the findings of the previous experiment, which showed that participants do associate flow experience with certain specific pieces.

No neural difference was found between the non-flow equal challenge condition and flow. Yet the equal challenge piece is rated less enjoyable and there is a larger difference in FSS scores. Though flow and non-flow equal liking had more similar FSS scores, they showed more differences in EEG spectral power. This dissociation between behavioural and neural data is worrying. If participants report different subjective experiences in a piece that is equally matched in skill but the neural data does not differ between conditions, then it is possible that we cannot neurally distinguish flow from a mere match between challenge and skill, even if participants experience them as subjectively different. However, choosing a piece that was non-flow-inducing yet of equal challenge proved to be somewhat uncontrollable, given the instability of performance. An equally challenging non-flow inducing piece could suddenly be scored higher on the FSS-2 if it was a better performance on the day than the flow-inducing piece, even if in general, participants report liking the non-flow equal challenge piece significantly less than the flow inducing piece. In addition, music pieces do not have objective rankings based on difficulty so we are forced to rely only on participants' subjective reports on perceived challenge and cannot really test if they are truly as equally challenging as the flow inducing piece. A better way to test if there are neural differences between flow and a mere match between challenge and skill is using a task where difficulty can be systematically varied. In this way, we can test if participants also show this disconnect between neural and behavioural reports when a known flow-inducing stimuli is contrasted with one that is merely a match between challenge and skill. This is potentially of great importance given that many of the findings on the neuroscience of flow are based on experimental flow inductions that classify a match between challenge and skill as flow. Whilst it is noted that experimentally-induced flow is at best an abstract approximation of flow and a necessary compromise when a complex construct is brought under rigorous control in the lab (Ulrich et al., 2016c), it is important that we test that these findings still apply to people's lived experience of flow.

3. 4. 3. Limitations

Due to the nature of the activity being studied, musical performance, there were many variables that could not be systematically controlled. The experimental manipulation had unpredictable effects, perhaps due to the similarities between flow, enjoyment and challenge-skill balance. For the non-flow equal liking condition, participants could bring pieces that were of more or less challenge than the flow inducing piece, to not get into flow. A more systematic variation of liking and challenge may be necessary to properly differentiate enjoyment and challenge-skill balance from flow. Add to that the problems of the unusual performance context of a lab, the inherently evaluative nature of an experiment and the day-by-day variation in experience of a piece and it becomes difficult to definitively attribute the differences in behavioural and neural data to any one reason.

Asking participants to rate the challenge of a piece may have been insufficient as participants may view different levels of challenge as appropriate for flow. It would have been useful to include a question asking about their perception of their skills for handling the challenge. In this way, it would been possible to calculate a match between challenge and skill instead of only asking for their perception of challenge-skill balance in the FSS-2.

One major takeaway from this experiment is that flow experience is unpredictable, even in the best conditions for it. The hope is that in an experiment inducing flow, at least some participants experience flow in the expected condition and its signal can be picked out amidst the noise of other participants not experiencing flow.

3. 4. 4. Conclusion

This experiment attempted to build on the previous experiment by distinguishing flow from enjoyment and challenge-skill balance. Neural differences were largest between flow and non-flow equal liking conditions, suggesting that flow can be distinguished from enjoyment and is characterised by reduced DMN activity and features related to lower attentional engagement. No differences between flow and non-flow equal challenge were found. This study also raised the issue of handling the unexpected results of a flow induction with complex stimuli. Different ways of classifying experiences as flow and the resulting differences in analysing data was discussed. These are necessary issues to consider when examining flow outside the narrow constraints of experimentally induced flow.

Chapter 4 Interoception in musicians' flow experience

4. 1. Introduction

The previous two studies looked at differences in power spectrum and functional connectivity in states associated with flow. This study examines an event-related potential as a potential neural marker of flow.

4. 1. 1. Interoception

Interoception refers to the processing, representation and perception of stimuli originating from within the body. It is the "process of how the brain senses and integrates signals originating from inside the body, providing a moment by moment mapping of the body's internal landscape" (Khalsa & Lapidus, 2016). It has been well-linked to emotional processing but has more recently been found to be involved in decision-making, cognition and perception. Interoception interacts with cognition and emotion, modulating emotional experience, the felt experience of the body and subjective awareness, ultimately influencing behaviour (Duquette, 2017; Garfinkel, Seth, Barrett, Suzuki, & Critchley, 2015). Research on interoceptive awareness has predominantly focused on heartbeat perception and individual differences in sensitivity to cardiac signals (Herbert & Pollatos, 2012). Interoceptive awareness is related to greater sensitivity to emotion processing and responding with appropriate regulation strategies (Price & Hooven, 2018).

One of the ways to study interoception is via the heart-evoked potential (HEP), a neural feature time-locked to the heart beat. It tracks the subconscious processing of the heartbeat and reflects individual differences in interoceptive awareness. Larger HEPs are linked with better interoception (Pollatos, Kirsch, & Schandry, 2005a).

4. 1. 2. Interoception in flow

Neither interoception nor the HEP has been studied in flow before. Jackman (2017) suggests athletes report distinct perceptual changes in the body during flow but this aspect of flow has been neglected as the current nine dimensional model of flow does not include bodily sensations (Jackman, Fitzpatrick, Lane, & Swann, 2019). However, one possibility is that interoception is improved during flow. Flow features include action-awareness merging which seems to indicate a different perception of the body. Flow also includes clear feedback, that is, participants report knowing from how it feels how they are performing. It seems plausible to therefore suggest that people in flow have a better sense of signals originating from within their body to help them better perform the necessary actions. Athletes report intensified body sensitivity and attunement to their body and the environment (Chavez, 2008). Swimmers report strong perceptions of altered body sensations and awareness of their internal states during flow, including strong heartbeats (Bernier, Thienot, Codron, & Fournier, 2009). Mindfulness training to help athletes focus on cues from the environment and their internal states both enhance performance (Bernier et al., 2009) and increased flow experience (Aherne, Moran, & Lonsdale, 2011). This suggests that flow may be associated with increased interoceptive awareness and therefore larger HEPs.

While most of this work has been done in athletes, music performance is also a deeply embodied state (Nijs, 2017), where better awareness of internal states may also be a feature of flow that facilitates enhanced performance. Some support for this idea comes from a study that found that a yoga, a body-based intervention increased flow in musicians and reduced performance anxiety (Butzer, Ahmed, & Khalsa, 2016).

Interoception has also been linked to emotional regulation which is also relevant for flow experience. Emotional control was found to be a cognitive skill that was particularly important for attaining flow experience and, subsequently, optimal performance in leisure sports settings. One of these psychological skills was the use of good emotional control, which helped to explain the variation of dispositional and state flow in athletes with aged between 16 to 73 years (Jackson, Thomas, Marsh, & Smethurst, 2001). Indirect evidence also comes from studies about the effectiveness of sport training programs in the enhancement of the quality of athletic performance. Emotion regulation techniques are one of the skills commonly targeted in these interventions. Findings showed that the use of emotion self-regulation is an effective tool for the improvement of the athletes' optimal zones of performance (Robazza, Pellizzari, & Hanin, 2004). It seems plausible that better interoception during flow episodes might better enable people to cope with the demands of the situation and stay in flow.

A final clue comes from a study on neural activity during an engrossing computer game. Ju and Wallraven (2019) found increased activity in the insula correlated with increased attentional engagement in a flow-inducing activity (the computer game) and linked it to the insula's link with increased bodily self- awareness. As the insula is also been determined as a source of the HEP, this may also imply that the HEP may be larger in flow.

However, people in flow report being so absorbed in their chosen activity that they ignore bodily sensations like fatigue, hunger, thirst over time (Nakamura and Csikzentmihalyi, 2001). This would suggest reduced interoception in flow, particularly to negative stimuli. Though interoception in flow has not yet been studied, a similar experience, mindfulness, has been shown to attenuate interoception of negative stimuli (Haase et al., 2015).

The HEP also shows potential as a neural marker of flow. Several studies have explored using the auditory oddball task as a marker for attentional involvement during flow (Núñez Castellar et al., 2019; Shehata et al., 2020; Yun et al., 2017). Rare tones in a stream of sounds that are irrelevant to a task evoke a P3, which is a stimulus-locked component thought to reflect attentional processes (Polich, 2007). When players are involved in a game, less attention is being diverted to irrelevant stimuli and the P3 amplitude is reduced (Núñez Castellar et al., 2019). However, practically, a stream of irrelevant tones may be distracting and perhaps reduce likelihood of experiencing flow. An HEP on the other hand, is time-locked to the heartbeat. The heart itself becomes a built-in trigger with which to extract the HEP. As a marker, the HEP can be collected as long as ECG is being collected and synchronised to the EEG.

1.5 Aims of the present investigation

Because this is the first experiment looking at flow and interoception via the HEP, it will necessarily have to be exploratory, looking into broad differences between the three post-performance states. Using EEG, it will examine if there are systematic differences in the HEP between the post-performance states.

Hypothesis: That there are discernible differences between the HEP of the three post-performance states

4. 2. Methods

This data was collected from the participants who took part in the experiment described in chapter 3. Please refer to chapter 3 for details on participants and procedure.

4. 2. 1. Statistical analyses

The statistical analyses were conducted in IBM SPSS Statistics version 22 (SPSS Inc., Chicago, IL, USA) and in Matlab R2013b (The MathWorks, Inc., Natick, Massachusetts, USA).

4. 2. 2. EEG recording and analysis

The EEG recording was done using 64 active electrodes placed in the extended 10-20 system of electrode placement and amplified by a BioSemi ActiveTwo amplifier (www.biosemi.com). Four additional electrodes recorded vertical and horizontal EOGs, which were used to monitor horizontal and vertical eye movement. A sampling frequency of 512 Hz was used to record the data. Additional external electrodes were placed on the left and right earlobes as a reference. The ECG was recorded using two external channels, with one placed on the chest and the other grounded on the hip. The sampling frequency for the ECG was 512 Hz.

4. 2. 3. Preprocessing

EEG data was re-referenced to the average of the two earlobes. The data was high-passed filtered at 0.5Hz and because the HEP is a relative low-frequency waveform, the data was low-passed at 30Hz to remove high-frequency noise. It was then epoched from 2s before to 75s after participants stopped playing and closed their eyes. Eye-blink correction and removal of the heart artifact was done using ICA. The data was visually scanned and artifacts deleted.

4. 2. 4. ERP analysis

The QRS complex in the ECG was identified using a QRS detection algorithm based on filter banks which identifies the complex by decomposing the ECG into sub-bands with uniform frequency bandwidths. The programme was implemented in MATLAB with the code provided by the authors (Afonso et al, 1999) The ECG data was visually inspected to ensure that the R-peaks were correctly detected. Once the R-peaks were identified, the latencies of the R-peaks were imported into the EEG data structure to form epoch points for the HEP. The data was epoched around each R-peak, from 200ms before the R-peak to 600ms after it. As participants are relatively active, just coming off from playing an instrument, a longer time window would have crossed into the next R-peak. After epoching, the epochs were visually inspected and segments contaminated by large artifacts such as muscle movement and saccades were removed.

The cardiac field artefact contaminates the HEP because epoching and averaging the data on the R-peak of the ECG time-locks the data to the heartbeat, amplifying the cardiac field artefact (Dirlich, Vogl, Plaschke, & Strian, 1997). Current source density (CSD) transformation (surface Laplacian) was therefore applied to the epoched data in order to attenuate the low-spatial frequency features from the data, one of which is the cardiac-field artifact (CFA) (Tenke & Kayser, 2012). The CSD was applied using the CSD toolbox (CSD Toolbox Version 1.1, Kayser, 2009) which computes the current source density estimates by applying the spherical spline algorithm, in which the *G* (surface potentials) and *H* (current source densities) matrices are calculated based on a sphere (Kayser & Tenke, 2006). The default parameters, a smoothing parameter of 4 (*m* parameter) and a Legendre Polynomial of 10, were used.

EEGLab (Delorme & Makeig, 2004) was used to sum the ERPs across participants and electrodes, after which the relevant amplitudes (within the time window of interest 200ms to 600ms) was extracted and inputted into SPSS for analysis. The time window was selected based on prior research (Shao, Shen, Wilder-Smith, & Li, 2011).

4. 2. 5. EEG Statistical analysis

Because previous studies have yet to reach a consensus on clear features that would identify the HEP and predict its location, an exploratory method was used to determine regions of interest. The scalp was divided into three sectors, frontal, central and parietal/occipital and into two hemispheres, producing six general regions of interest. A 2x3x3 factorial (hemisphere x scalp sector x condition) ANOVA was conducted to examine possible laterality effects. This is a method frequently used in HEP research where the morphology and location of the HEP is less than robust (Montoya, Schandry, & Müller, 1993; Pollatos, Kirsch, & Schandry, 2005b; Shao et al., 2011).

4. 3. Results

4. 3. 1. Behavioural results

Summary of flow scores

	Minimum	Maximum	Mean	Std. Deviation
Dispositional flow	3.08	4.69	3.8428	0.36392
Flow (first play)	2.94	4.97	4.1016	0.44497
Flow (second play)	3.11	4.97	4.1231	0.47619
Non-flow equal liking (first play)	2.69	4.78	3.8592	0.41881
Non-flow equal liking (second play)	2.72	4.78	3.9312	0.44992
Non-flow equal challenge (first play)	2.47	4.53	3.6900	0.46384
Non-flow equal challenge (second play)	2.39	4.44	3.6862	0.53795

Table 4.1: Descriptive statistics for flow scores

Table 4.1 summarises the participants' reported state flow scores for each of the trials. The overall score for each condition was calculated by averaging between the two trials. A repeated-measures ANOVA conducted on the average scores for each condition was significant, *F* (2, 86) = 16.940, *p* <.001. Pairwise comparisons showed that the difference was mainly between Flow and the non-flow conditions. As show in **Table 4.2**, scores were higher for the Flow condition compared to both the non-flow conditions. There was a larger difference between Flow and Non-flow Equal Challenge (NF_EC) than between Flow and Non-flow Equal Liking (NF_EL). However, the difference between conditions is very small, less than 1. There was no significant difference between the two non-flow conditions.

Pairwise comparisons of average flow scores (Tukey HSD)

(I) Condition	(J) Condition	Mean Difference (I-J)	Std. Error	Sig.	95% Confidence Interval	
					Lower Bound	Upper Bound
Flow	NF_EL	.21717*	0.0905	0.047	0.0026	0.4317
	NF_EC	.42424*	0.0905	0	0.2097	0.6388
NF_EL	Flow	-.21717*	0.0905	0.047	-0.4317	-0.0026
	NF_EC	0.20707	0.0905	0.061	-0.0075	0.4216
NF_EC	Flow	-.42424*	0.0905	0	-0.6388	-0.2097
	NF_EL	-0.20707	0.0905	0.061	-0.4216	0.0075

* The mean difference is significant at the 0.05 level.

Table 4.2: Pairwise comparisons for flow scores across conditions

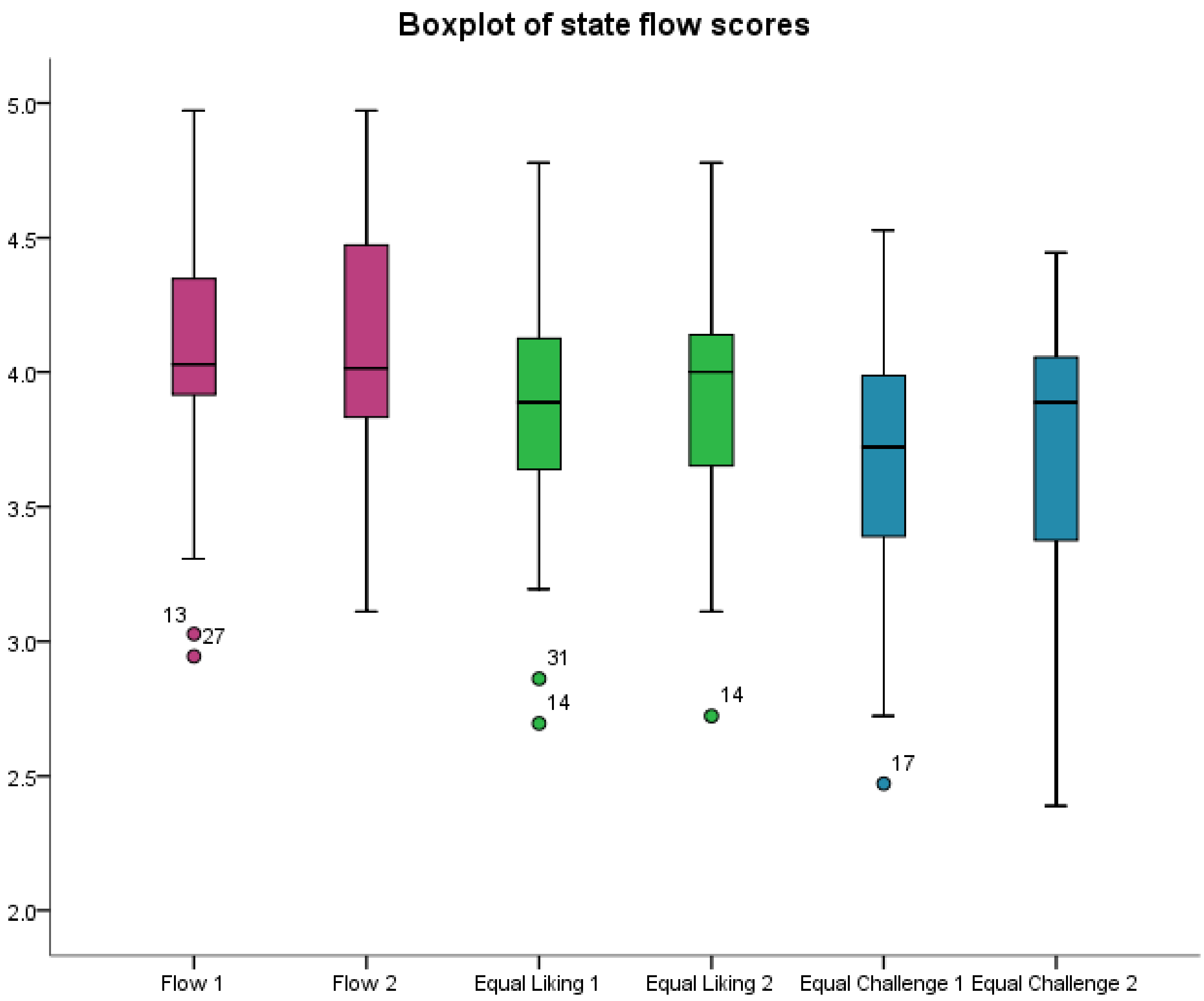


Figure 4.1: Boxplot of dispositional and state flow scores. DFS = Dispositional Flow score, F=Flow, NF_EL = Non-flow equal liking, NF_EC = Non-flow equal challenge.

4. 3. 2. ERP results

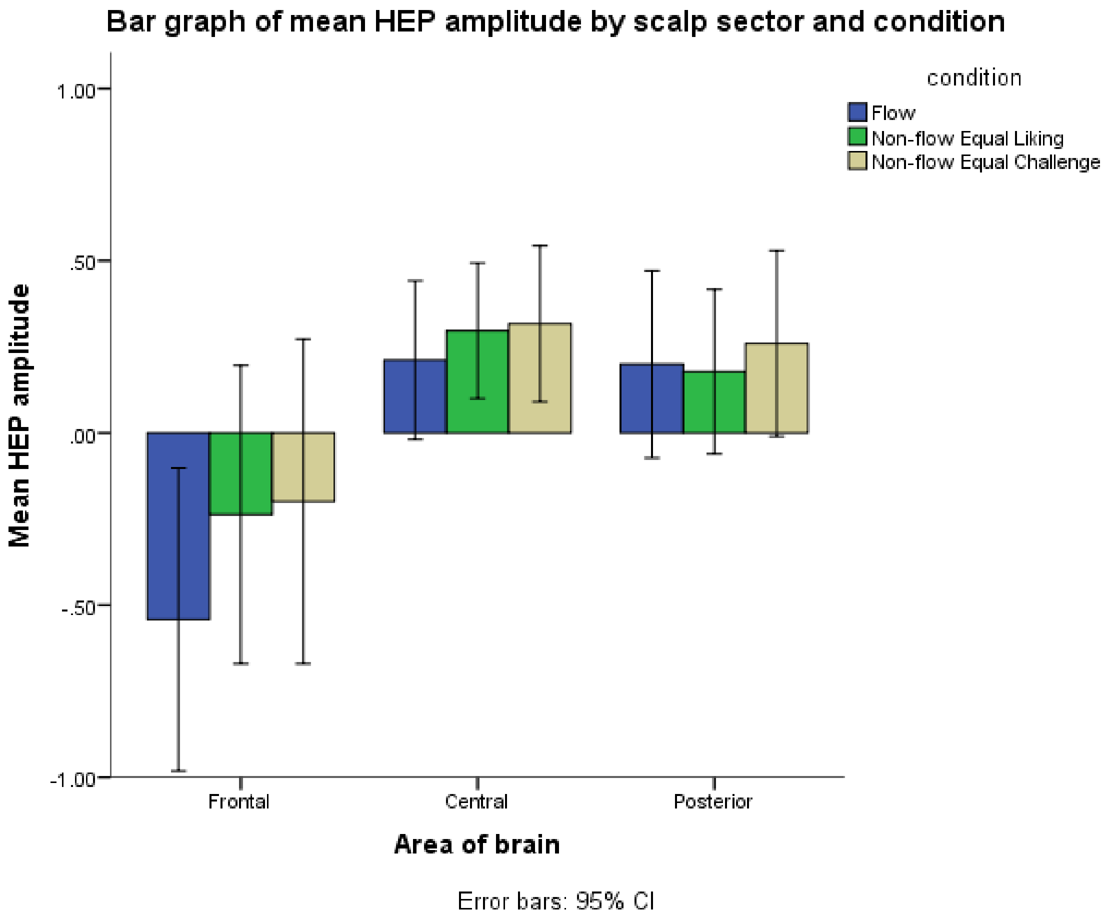


Figure 4.2: Bar graph of mean amplitude between 200ms to 600ms grouped by scalp sector. The significant interaction between scalp sector and condition seems to be driven by the large negative amplitude in the frontal regions, particularly in the flow condition.

The ANOVA found significant differences between scalp sectors, *F* (1.543, 66.347) = 5.076, *p* =.008, (Greenhouse-Geisser corrected as Mauchly's test of sphericity was significant). Results were not significantly different across conditions (*F* (2, 86) = 1.998, *p* = .142) and hemispheres (*F* (1, 43) = 1.83, *p* = .183). However, there was an interaction approaching significance between scalp sector and condition and hemisphere (*F* (4, 108= 2.332, *p* = .060). Plotting the mean amplitude (Fig 1.2) shows that the difference is mainly driven by a negative shift in the frontal areas during flow.

The ERP grand-averaged over all electrodes is shown in Fig 1.3**,** shows a broad wave form with an early negative peak in the flow condition between 0 to 100ms, earlier than the time window predicted from previous research (200ms to 600ms after the R-peak). The waveforms of the non-flow conditions are more similar to each other than to the flow wave form.

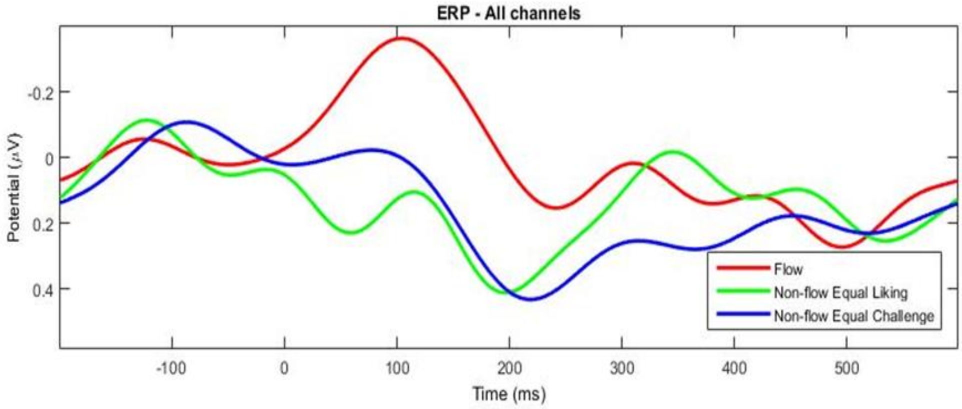


Figure 4.3: Grand-averaged ERP. By convention, the y-axis is flipped so that the negative polarity faces upwards.

4. 4. Discussion

4. 4. 1. Behavioural results

The results of the ANOVA showed a significant difference between participants' ratings of each condition but only between flow and non-flow. It showed no difference between the two non-flow conditions. Furthermore, the difference between flow and non-flow was very small, less than 0.5 on the DFS-2 and FSS-2. It raises the issue that the conditions may not have had a large enough contrast between them. This is understandable as both non-flow conditions, Equal Liking and Equal Challenge, maintained some similarities with flow, specifically the autotelicity of the experience and the challenge-skill balance respectively. It is plausible that participants were unable to separate their flow experience from the experience of being challenged and liking the piece and so found it more difficult to choose pieces that would make the distinction between the conditions. This may have reduced the contrast between the conditions, resulting in smaller differences in HEP.

This raises interesting issues about the difficulty of relying on participants' subjective experience and understanding of flow state. Unlike Klasen et al (2011) which conceived of flow in terms of performance on the game or Ulrich et al (2014) which operationalised flow as challenge-skill balance, the participants' subjective experience allows a more nuanced understanding of flow. It taps into participants who understand their flow state well enough to reliably self-induce it, allowing us to get closer to the real experience of flow. However, its downsides also came up in the experiment. This experiment depended on participants being able to conceive of their flow experience in terms of the instructions, namely as something more than simply liking the piece or finding it engaging because of the challenge. A number of participants actually chose to drop out because they could not think of their experience in those terms, specifically, that they could not imagine how they would not experience flow if they liked the piece or were very engaged with it. Hence, while it gave us the opportunity to eliminate cognitive load and emotional engagement as possible reasons for the difference between flow and non-flow neural indices, this design may require some rethinking.

4. 4. 2. ERP results

The ANOVA examining activity in different parts of the scalp in the different conditions in the time window predicted from previous research (200ms to 600ms after the R-peak) found a significant effect of scalp sector and an interaction effect of scalp sector, hemisphere and condition. Specifically, the interaction effect was driven by the large negativity in the left frontal area in the flow condition. Plotting the ERP averaged over the left frontal electrodes showed a relatively broad waveform with a negative polarity at 0 to 300ms after the R-peak in the flow condition. The HEP in the flow condition is the most negative while the HEP in the Non-flow equal liking and Non-flow equal challenge conditions are similar to each other, being smaller in amplitude and more positive in the same time window. However, the difference between conditions was not significant.

The more negative amplitude of flow would seem to indicate that interoception is better in flow state compared to non-flow state. Good heart perceivers have larger amplitude HEPs compared to poor heart perceivers (Pollatos et al., 2005a). The improved interoception in flow may explain the sense of action-awareness merging experienced in flow and the improved feedback (which includes feedback from within the body) that enables flow state. However, too little is known about both the HEP and the neural indices of flow to make this assumption. A future experiment might want to include another measure of interoception during flow and non-flow, possibly counting heartbeats without feeling for the pulse, to corroborate with the HEP (Montoya et al., 1993).

The results are not significant but do seem to show a greater negativity in flow state which may reflect greater interoception in flow. The other possibility, that interoception of negative stimuli is reduced in flow, may not have been achieved under the conditions of the lab as there are not enough negative stimuli to ignore. An interesting direction to take is to examine the effect of flow on perception of negative interoceptive stimuli. Perhaps a future study can examine if the flow modulates interoception of negative interoceptive stimuli by creating a situation where there may be negative interoceptive stimuli to ignore to see if flow experience can attenuate the experience of negative interoceptive stimuli. A possibility is an extreme stress test such as the one described in Peifer et al (2015) where participants have to prepare to give a speech in front of hostile interviewers. Extreme stress is necessary to create enough of a contrast (Peifer, Schächinger, Engeser, & Antoni, 2015). It would be interesting to see if flow attenuates interoception during a stressful event.

It would be ideal to measure HEP while participants are playing but it was found that instrumental playing sometimes interfered with the ECG signal so that the filtering function could not identify the peaks of the QRS complex. This was unpredictable, affecting some of the participants to a greater extent than others and resulting in too small a number who were unaffected and had useable data. A solution would be to drastically expand the number of participants, hopefully increasing the number whose data can be used. Salimpoor et al (2011), a similar study relying on participants' subjective experience and ability to self-induce the condition except for musical chills instead of flow, also started with a large pool of thousands before narrowing down to the small number (10) to those whose chills were most consistent (Salimpoor et al., 2011). It would be ideal do so for this experiment but it was far beyond the scope of this experiment. In fact, it would have to be even larger in scope to not only find a sizeable sample group who not only had reliable flow experiences maintained in a lab setting but also had clean data while playing.

A related point would be to analyse the HEP data in the same way as the power spectrum data was analysed, by considering the fact that some participants may not have experienced flow and including them in the analysis is blurring the contrasts between conditions.

The largest HEP differences were in the frontal regions, which aligns with previous studies that report HEP primarily at the frontal electrodes (Leopold & Schandry, 2001; Montoya et al., 1993). It is also plausible from a neuroanatomical perspective as the anterior insula has been linked to both interoception and emotion (Zaki, Davis, & Ochsner, 2012).

4. 4. 3. Limitations

It would have been worthwhile to include a self-report measure of interoception, such as the Multidimensional Assessment of Interoceptive Awareness (MAIA) adapted for measuring interoceptive awareness as a state rather than a trait (Heeter, Day, & Cherchiglia, 2020) or an alternate measure of interoceptive accuracy, counting heartbeats, to firstly check if participants did feel different interoceptive awareness between conditions.

Results in this experiment cannot tell us the direction of causality between flow and interoception. Is it that better interoception enables someone to better get into flow or that flow improves interoception? It would be necessary to have a form of manipulation to test this. For example, cardiac awareness training has been shown to improve interoception (Schandry & Weitkunat, 1990). It would be helpful to see if cardiac awareness training also improves flow experience. Alternatively, mindfulness training to help athletes focus on cues from the environment and their internal states have been found to increase flow experience (Aherne et al., 2011). It would be helpful to measure interoception before and after a treatment like that to test if its effects on flow are via improving interoception.

4. 4. 4. Conclusion

The HEP was found to be more negative in flow than the non-flow conditions. The waveforms of the non-flow conditions were more similar to each other than to flow, suggesting that flow was, from a psychophysiological perspective, a different experience from non-flow for participants. Though the results are not significant across conditions, they offer tantalising hints as to the nature of interoception during flow but much more work needs to be done before the HEP can be used as a neural marker of flow or any strong conclusions can be drawn from the HEP about interoception in flow.

Chapter 5 Challenge-skill balance in climbers

5. 1. Introduction

The two experiments described in Chapters 2, 3 and 4 relied on the self-induction of flow by musicians using stimuli they personally knew would induce flow in them. The first experiment showed that flow and non-flow can be effectively induced in this manner. The second experiment showed that challenge-skill balance played a role in flow induction. To bring a piece that they liked as much as a flow-inducing piece but not have it induce flow, participants brought pieces that were harder or easier than their flow inducing piece. This resulted in distinct neural differences between flow and non-flow conditions but it is difficult to disentangle the influence of difficulty and effort when the non-flow piece could be either easier or harder. The picture is further complicated as when participants played an equally challenging non-flow piece, no neural differences were found between flow and non-flow conditions but participants reported much less subjective flow experience.

Therefore, to clarify this discrepancy, we wanted to vary challenge systematically in this next experiment, using the established experimental flow induction paradigm which relies on challenge-skill balance as the main antecedent of flow. This could not be done with musicians as the difficulty level of any given musical piece is very subjective. Hence, we chose to study climbers. Climbing routes are rated according to an international rating system that permits a fairly accurate absolute comparative estimate of the difficulty of routes. It takes into account the most arduous move or series of moves, degree of strength and gymnastics required, size of holds and features of the wall such as shape and inclination (MacAloon & Csikszentmihalyi, 1983). Routes at the climbing centre where this experiment is conducted are rated and agreed upon by a group of climbers on the centre's staff. This makes it possible to systematically incorporate the perception of challenge-skill balance that is central to flow in an activity that is recognised to induce flow, making for an experimental task that reaches new levels of ecological validity. Furthermore, like music, as an activity with many passionate adherents, climbing is high in subjective value.

Rock-climbing has been of interest to flow researchers since Csikzentmihalyi described flow in the experience of climbers (Csikszentmihalyi, 1975). Csikzentmihalyi studied rock climbing as an example of an activity that offers no discernible external reward and furthermore involves the cost of physical danger, and yet still attracts passionate adherents. But qualitative research showed multiple ways climbing is conducive to flow experiences. Climbing offers a wide range of skill levels, control over the choice of the levels as well as an uncertainty and risk that climbers identify as intrinsic to their flow experience. There is the clear goal of getting to the top of the climb or the end of the route. The physical and mental requirements involved in staying on the rock demand an intense focused concentration, to the point of "shutting out the world". Managing the inherent risk also leads to feelings of control and competence. The risk involved also provides clear and immediate feedback via the climber's sense of control of the situation. The high focus, a demand appropriate to the climber's skill, clear and immediate feedback in the form of the sense of control over the situation can lead to such involvement that climbers report losing sense of self, as well as time. A climber described this action-awareness merging as "You are so involved in what you are doing that you aren't thinking of yourself as separate from the immediate activity... You don't see yourself as separate from what you are doing." Climbers can attain a deep flow, an ecstatic experience that is out of the ordinary (MacAloon & Csikszentmihalyi, 1983).

Research has continued to be done on flow in climbers. An experience sampling method study was conducted on climbers on an expedition to the Himalayas. It was found that flow, or a balance between higher than normal challenge and skill, was the most frequently associated experience with the expedition (Delle Fave, Bassi, & Massimini, 2003). A field experiment on climbers found that motive congruence affected flow. Climbers with a high achievement motive experienced more flow after repeating a more difficult route (Schattke, Brandstätter, Taylor, & Kehr, 2014). To date, no one has yet studied flow in climbers using physiological measurements. With portable EEG, this becomes possible (Bailey, Hughes, Bullock, & Hill, 2019). However, to collect data on the brain in flow, a state of flow must first be induced in the brain. What happens if we take the challenge-skill balance manipulation typical of most laboratory-based experiments investigating the neural correlates of experimentally induced flow out of the lab and apply it to an enjoyable, intrinsically motivating activity frequently reported to be conducive to flow?

Shamay-Tsoory and Mendelsohn (2019) suggest that lab-based experimental designs have two major limitations. The lab is an artificial decontexutalised environment and lab-based paradigms limit the active role of participants, interfering with their sense of agency and embodiment. Hence, experiments conducted on real-life behaviour will find different mechanisms from those found in controlled experimental paradigms (Shamay-Tsoory & Mendelsohn, 2019). This may be particularly true for flow. Abuhamdeh (2020) notes that in many lab-based studies on flow (which include flow neuroscience experiments), participants typically engage in an unfamiliar task in an inherently evaluative context (Abuhamdeh, 2020). The unfamiliarity of the task and the evaluative nature of the context are likely to work against the (already slim) likelihood of flow being experienced by a study participant, given that flow appears more likely to be experienced by individuals who have developed considerable skill in the activity at hand (Cohen & Bodner, 2019c; Marin & Bhattacharya, 2013; Rheinberg, 2008) and performance anxiety is not conducive to flow (Csikszentmihalyi, 1975; Fullagar et al., 2013). In this case, taking the study out to climbers in a climbing centre means that participants are engaging in a familiar task, and in particular, as an advantage over the musicians in the previous studies, in a familiar environment. This may increase the likelihood of participants experiencing flow.

The experimental flow induction rests on an established relationship between challenge-skill balance and flow experience. When challenges are far below one's skills, boredom is induced. When challenges exceed skills, frustration is induced. Flow occurs at an optimal level of challenge. This results in an inverted u-shaped curve relationship between difficulty and flow. In lab-based experiments where the conditions of boredom, flow and frustration are set up, this inverted u-shape relationship has been found between challenge and various measures of flow and intrinsic motivation (Harmat et al., 2015; Huskey, Craighead, et al., 2018; Ulrich et al., 2016c). It is remains to be seen if this relationship will hold outside of the lab in an activity high in intrinsic motivation.

A meta-analysis from Fong et al (2012) suggests that it does. The relationship between flow and challenge-skill balance is highest for leisure activities (z = 0.73), followed by personal activities and last of all, work or education. Climbing can be considered a leisure activity for the climbers at the climbing centre.

Thus, this experiment examines the effect of an experimental flow manipulation outside the confines of a lab. As is done in the lab-based experimental paradigm, participants' subjective experience will be manipulated using different levels of challenge. Participants are expected to experience highest flow scores in the condition in which most matches their skill levels. Where lab-based experiments have a session before to detect a participant's beginning skill level in an experimental task, participants will be asked for their personal climbing level at the start of the experiment.

Having participants climb at their given skill level should theoretically induce flow but studies have found that there are person-level moderators of flow induction (Moller et al., 2010). Participants high in explicit fear of failure may find it easier to experience flow in a situation where skills exceed the challenge of the activity (Engeser & Rheinberg, 2008) while someone high in action orientation can experience high demands as less effortful (Keller & Bless, 2008). Hence, similar to what was done with the musicians, the decision was made to also rely partially on climbers' knowledge of their flow states. In a second manipulation, participants were asked what climbing grade would be most inductive of their flow state. In this way, we can compare which manipulation will result in more reliable flow experiences. This is aiming towards the eventual goal of collecting neural data of flow outside the lab.

Hypothesis 1: An inverted u-shaped relationship will be observed between flow scores and difficulty levels

Hypothesis 2: Giving participants a description of flow state and asking them what climbing grade is most likely to give them the experience will result in higher flow scores than only asking them their typical climbing grade

5. 2. Methods and materials

5. 2. 1. Design

The study employs a 3 (task difficulty) x 2 (manipulation) factorial design. The within-subjects factor was task difficulty. To manipulate their subjective experience during the session, climbers climb in three conditions: easy, matched and difficult. The between-subjects factor was how the matched condition was set up. Participants provided a climbing level for the experimenter to set up easy, matched and difficult conditions described in the table below.

	Easy	Matched	Difficult
Task Difficulty	Far below skill level	At skill level	Far above skill level
Induced condition	Boredom	Flow	Frustration
Operationalised as climbing levels	At least 2 levels below the difficulty level in the matched condition	1) Self-reported climbing level 2) Level most likely to induce flow	At or above the hardest level they have ever attempted

In between-group condition 1, participants reported their personal climbing level. Climbers are well aware of the climbing grade at which they can comfortably climb and it is an effective proxy for their level of climbing skill as more skilled climbers are able to reliably negotiate higher grade routes.

In between-group condition 2, participants were given three questions from Csikzentmihalyi (1975) (refer to chapter 3) that described flow and asked if they experienced it while climbing and if they did, which level in the climbing centre would most like induce the feeling described for them.

Here, the experimenter asked each climber their climbing level based on the system used by the climbing centre. For analysis purposes, their numbers-and-letters system were converted into a numerical scale where 1 refers to the easiest climbs and 18 refers to the most difficult.

5. 2. 2. Participants

A convenience sample of 54 climbers (29 women) were recruited from members of an indoor climbing centre. 3 did not complete all conditions, leaving 24 in Condition 1 and 27 in Condition 2. Participants were between 20 to 63 years old (*M* = 34.7, *s*.d = 9.94). There was a large range of climbing skills and experience. 33% of the climbers had more than 7 years of climbing experience, 23% had climbed for a year or less, and 42% had 2 - 7 years of climbing experience. Most of them (68%) climbed once or twice a week. 11% of them climbed less frequently, once or twice a month. 21% climbed 3 or more times a week. All participants provided written informed consent. The study was approved by the local ethics committee of the Department of Psychology at Goldsmiths, University of London, and conducted in accordance with the Declaration of Helsinki.

5. 2. 3. Materials

The Flow State Scale (FSS-2) short version is a9-item version of the FSS-2 (S. A. Jackson et al., 2008) that measures the 9 dimensions of flow but was designed as a pragmatic alternative for measuring flow when practical constraints prevent use of the full-length measure. It was found to have acceptable model fit and reliability in a diverse sample of people participating in sporting activities (S. A. Jackson et al., 2008). Participants report on a 5-point scale (1 = strongly disagree to 5 = strongly agree) on the following questions - *Challenge-skill balance*: I feel I am competent enough to meet the high demands of the situation. *Action-awareness merging*: I do things spontaneously and automatically without having to think. *Clear goals*: I have a strong sense of what I want to do. *Unambiguous feedback*: I have a good idea while I am performing about how well I am doing. *Concentration on task at hand*: I am completely focused on the task at hand. *Sense of control*: I have a feeling of total control over what I am doing. *Transformation of time*: The way time passes seems to be different from normal. *Autotelic experience*: The experience was extremely rewarding.

5. 2. 4. Procedure

Participants were given a questionnaire on their climbing background before the experiment. The difficulty levels of the climbs were based on the scoring system of the climbing centre. For the first experimental manipulation, participants were asked which grade they could comfortably climb at to determine the difficulty level of the climbs for flow-inducing condition. To determine the climbing level for the difficulty condition, participants were asked about the highest difficulty level they had ever attempted. For the second experimental manipulation, participants were given the three flow questions described in Chapter 3 and asked which climbing level in the centre would most likely give them the feeling described by the questions. 5 out of the 27 report no to at least one question. To determine the climbing level for the difficulty condition, participants were asked for the highest difficulty level they have attempted.

For safety purposes, participants were allowed to warm up first. Then, based on the climbing levels reported in the pre-experiment questionnaire, participants were given a difficulty level and selected an available climb of that level to climb. For the easy condition, to induce boredom, participants were given a level at least 2 levels lower than the grade they comfortably climb at. To induce flow, depending on the between-group condition they were in, participants were given a level at the highest difficulty level they had ever attempted or the level they report most likely to induce their experience of flow during climbing. To induce frustration, participants were given a level at least as high as the most difficult climb they report attempting. With those given levels, participants chose 3 easy climbs, 3 climbs matched at their level and 3 difficult climbs. For safety reasons, participants were allowed to end a climb at any time or refuse to do any climb they did not feel safe doing. Another climb of a similar level would then be selected that the participant felt they could attempt. They were also informed that the experiment was about their experience while climbing and their performance on the climb or even completing the route was irrelevant to the experiment. Whenever they decided to end the climb, they were lowered to the ground and reported on their subjective experience during the climb by responding on the FSS-2 (short version).

The three conditions were counterbalanced across all participants within the between-group conditions. However, as the experiment was run in a popular commercial gym, due to the availability of the climbs, it was occasionally necessary to shift out of the condition and do an available climb that was part of one of the other 2 conditions and return to the planned order when an appropriate climb became available. When circumstances made it necessary to switch the order of conditions in order to complete the experiment, care was taken to find other participants to complete the counterbalancing conditions. In this way, the full counterbalancing was completed as far as it was possible under the less-than-controlled circumstances.

5. 2. 5. Analysis

A 3x2 repeated-measures analysis of variance (ANOVA) was conducted with the difficulty of the climbs (easy, matched to their skills, and difficult) as the within-subject factor and the experimental manipulation as the between subject factor. The dependent variable was the FSS-2 (short version) score, both the mean total flow score and the individual flow dimensions. Where Mauchly's test for sphericity was significant, indicating that variance of the differences between levels are significantly different and the ANOVA's assumption of sphericity is violated, Huynh-Feldt corrected degrees of freedom are reported. When results from the ANOVA were significant, Tukey's post-hoc test was used to examine the differences between within- and between-subject conditions. Statistics were conducted in IBM SPSS Statistics version 24 (SPSS Inc., Chicago, IL, USA).

5. 3. Results

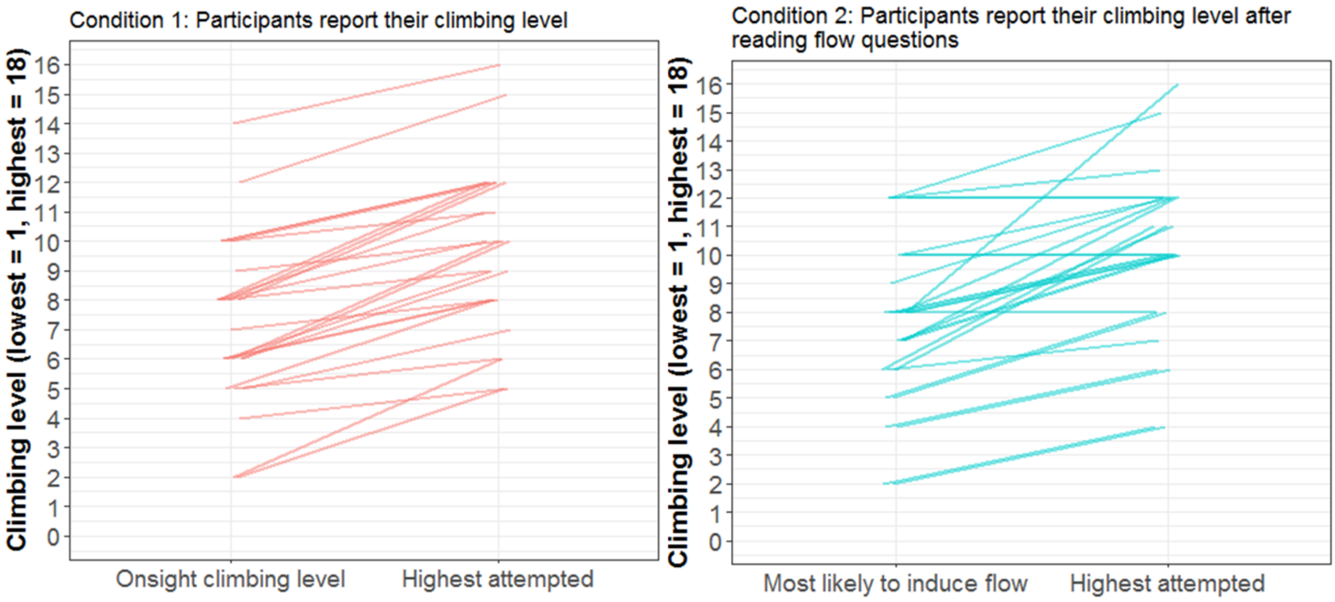


Figure 5.1: Line plots for reported climbing levels in response to experimental manipulation

Before the experiment, climbers provided their climbing levels for the experimenter to set up the conditions that were below, matched to, or above their skill level. When asked about their on-sight climbing level, participants reported levels lower than the highest level they had ever attempted. However, when they were asked for the level that would induce a flow experience, it is noteworthy that 3 participants reported that flow was more likely to be experienced in the most difficult climbs they had ever attempted.

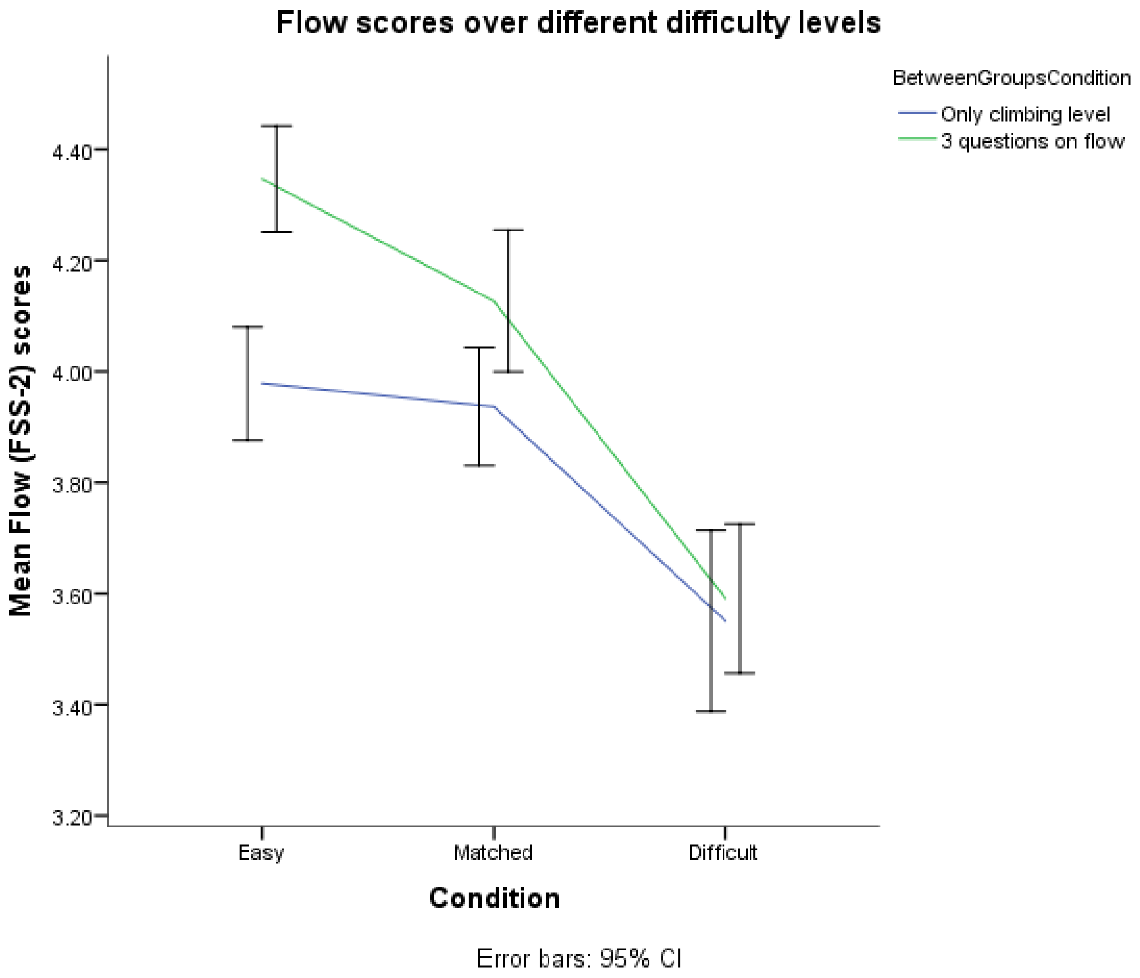


Figure 5.2: Climbers climbed routes at different difficulty levels to induce conditions of boredom, flow and frustration. Surprisingly, flow scores were not the highest at the matched condition

A 3x2 ANOVA showed that mean scores on the Flow State Scale differ significantly over difficulty levels (*F*(2,98) = 39.4, *p*< .001) and across the between group condition (*F*(1,49) = 5.04, *p* = .029). However, there was no significant interaction between difficulty levels and the between group condition (*F*(2,98) = 2.13, *p* = .125). Pairwise comparisons showed that there was a significant linear decrease in mean flow score over difficulty levels (*F*(1,49) = 56.9, *p*< 0.001). Participants whose flow inducing level was chosen with the help of the three questions on flow also scored significantly higher than those who were only asked their personal climbing level (*F*(1,49) = 5.04, *p* = .029).

For scores on the flow dimensions, most follow the pattern of linear decrease. Scores differed significantly across difficulty levels (Challenge-skill balance: *F*(1.6,74.9) = 159.9, *p*< 0.001; Action-awareness merging: *F*(1.67,81.7) = 63.9, *p*< 0.001; Clear Goals: *F*(1.76,86.6) = 33.2,*p*< 0.001; Unambiguous Feedback: *F*(1.75,85.8) = 25.8, *p*< 0.001; Sense of Control: *F*(1.89,92.6) = 75.0, *p*< 0.001; Loss of Self-consciousness: *F*(1.86,91.3) = 5.78, *p* = .004). But not across the between group condition (Challenge-skill balance: *F*(1,49) = .524, *p* = .473; Action-awareness merging: *F*(1,49) = .075, *p*= .786; Clear Goals: *F*(1,49) = 1.24, *p*=.270; Unambiguous Feedback: *F*(1,49) = 1.52, *p*=.223; Sense of Control: *F*(1,49) = 1.17, *p*=.286; Loss of Self-consciousness: *F*(1,49) = 2.11, *p* = .152). There were also no significant interactions between difficulty levels and the between group condition.

Scores on the flow dimensions of challenge-skill balance, action-awareness merging, clear goals, unambiguous feedback, sense of control and loss of self-consciousness show a linear decrease over difficulty levels.

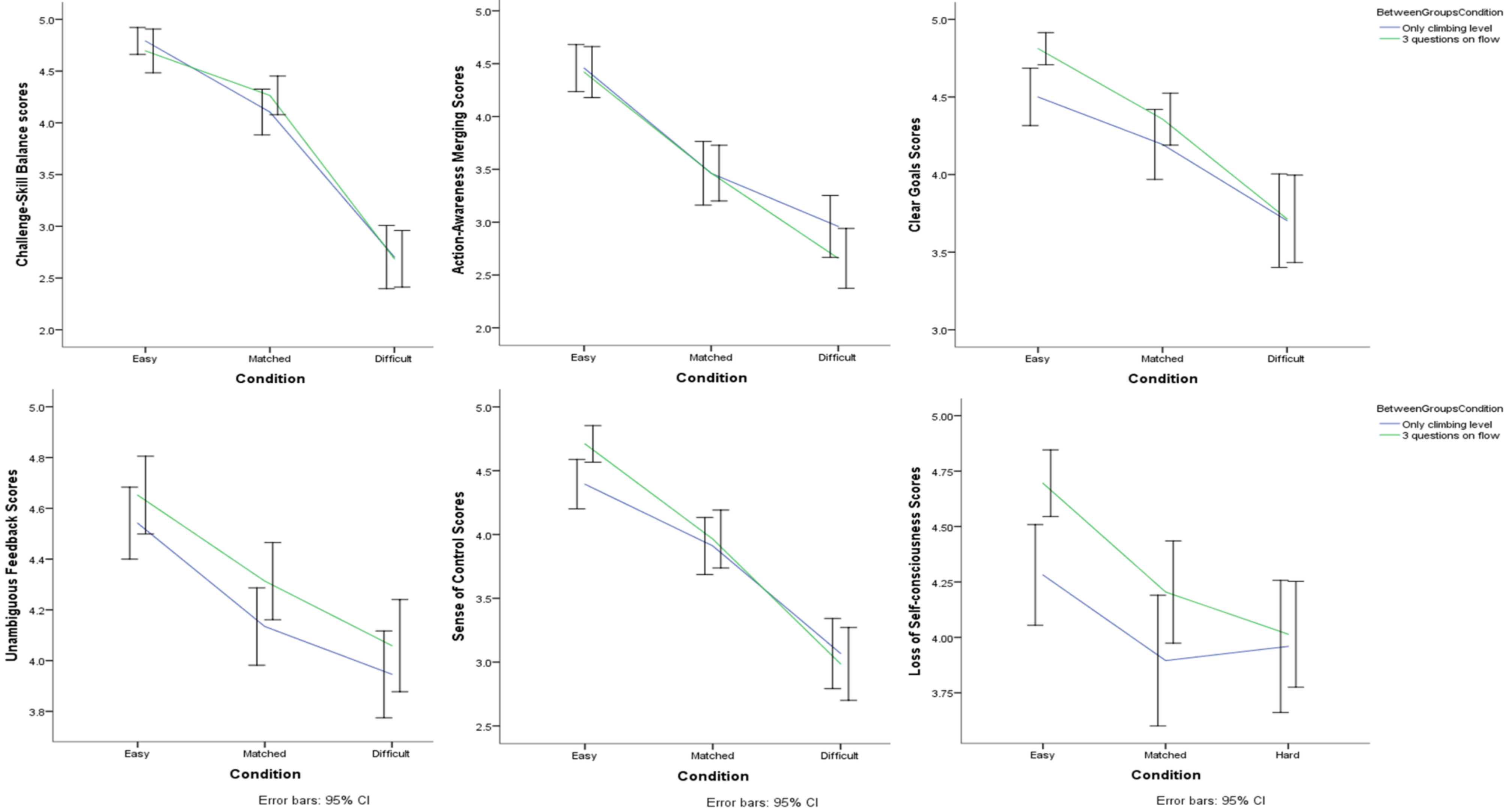


Figure 5.3 Flow scores for flow dimensions. Six of the flow dimensions: challenge-skill balance, action-awareness merging, clear goals, unambiguous feedback, sense of control and loss of self-consciousness decrease as challenge increases

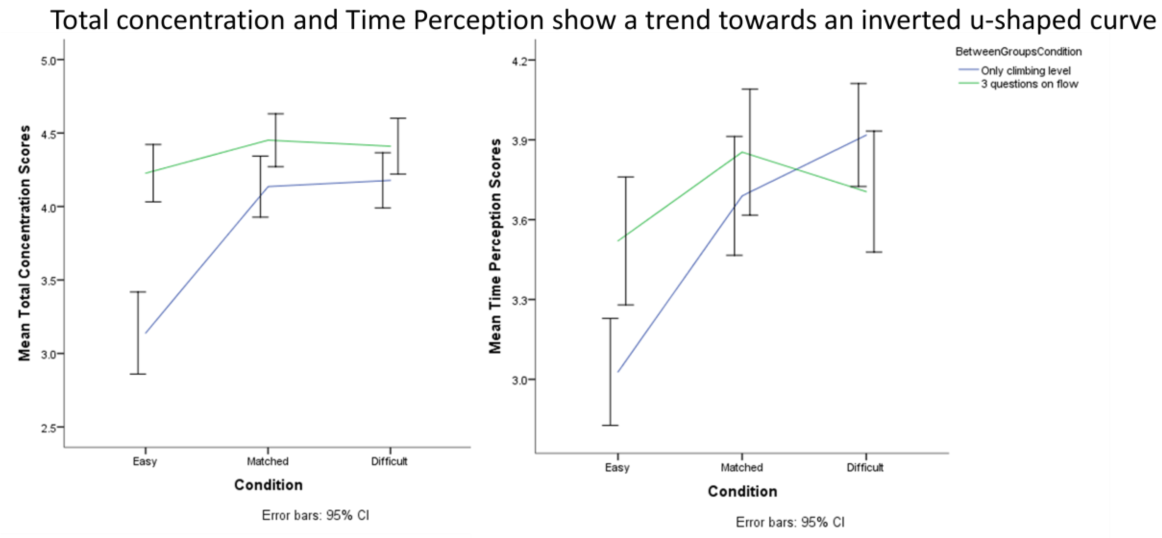

Total concentration and Time Perception show a trend towards an inverted u-shaped curve

Figure 5.4 Flow scores for total concentration and time perception. There are hints of an inverted u-shape relationship with challenge, especially in the condition where flow was brought to mind.

A 3x2 ANOVA showed that scores on the dimensions of Time Perception and Total Concentration differ significantly over difficulty levels (Time Perception: $F(2,98) = 14.5$, $p < .001$; Total Concentration: $F(1.88,92.3) = 15.5$, $p < .001$) and there was a significant interaction with experiment conditions (Time Perception: $F(2,98) = 3.94$, $p = .023$, Total Concentration: $F(1.88,92.3) = 6.76$, $p = .002$). For Total Concentration, participants also reported significantly higher scores when the flow-inducing difficulty level was determined by the three questions describing flow ($F(1,49) = 12.6$, $p = .001$). Scores on Time Perception did not differ across the between group condition ($F(1,49) = .957$, $p = .333$). For both Total Concentration and Time Perception, within subject contrasts were significant for both a linear (Total Concentration: $F(1,49) = 11.3$, $p = .002$; Time Perception: $F(1,49) = 6.73$, $p = .012$) and a quadratic relationship between flow dimensions scores and difficulty (Total Concentration: $F(1,49) = 11.3$, $p = .002$; Time Perception: $F(1,49) = 6.73$, $p = .012$).

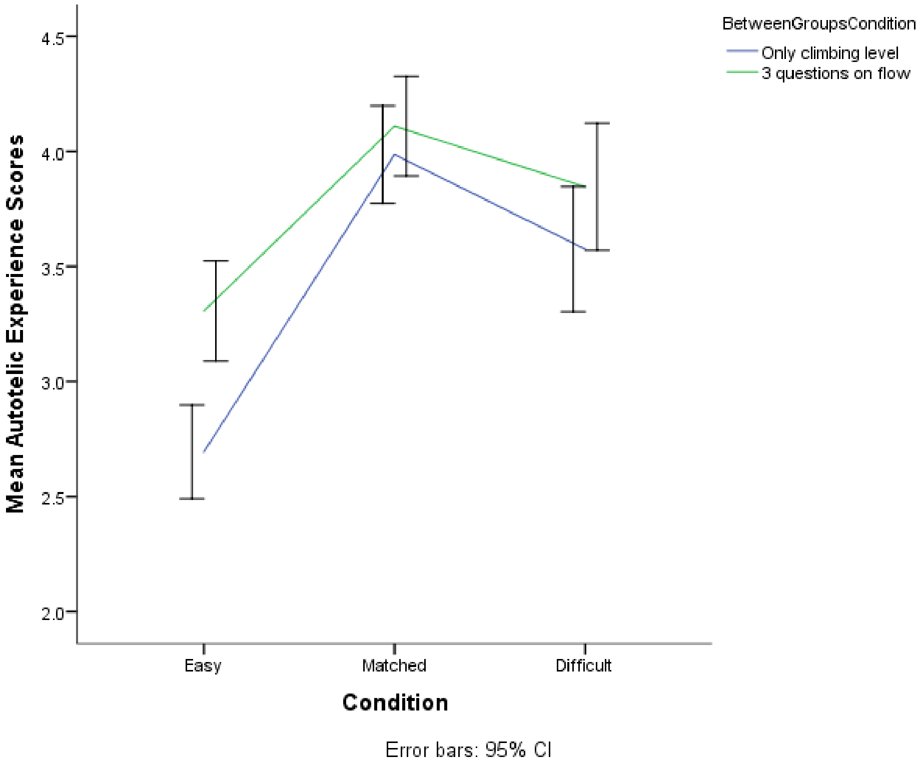


Figure 5.5 Scores for the Autotelic Experience dimension of the FSS-2 show an inverted u-shaped relation with challenge

Scores on the Autotelic Experience dimension were significantly different across difficulty levels (*F*(1.88,91.9) = 26.7, *p* < .001). There was no significant interaction (*F*(1.88,91.9) = 26.7, *p* =.287). Participants also reported lower scores in the condition where the matched condition was induced with their on-sight level(*F*(1,49) = 6.73, *p* = .012). A within-subjects contrasts showed that scores on Autotelic Experience followed a quadratic pattern (*F*(1,90) = 46.68, *p* < .001).

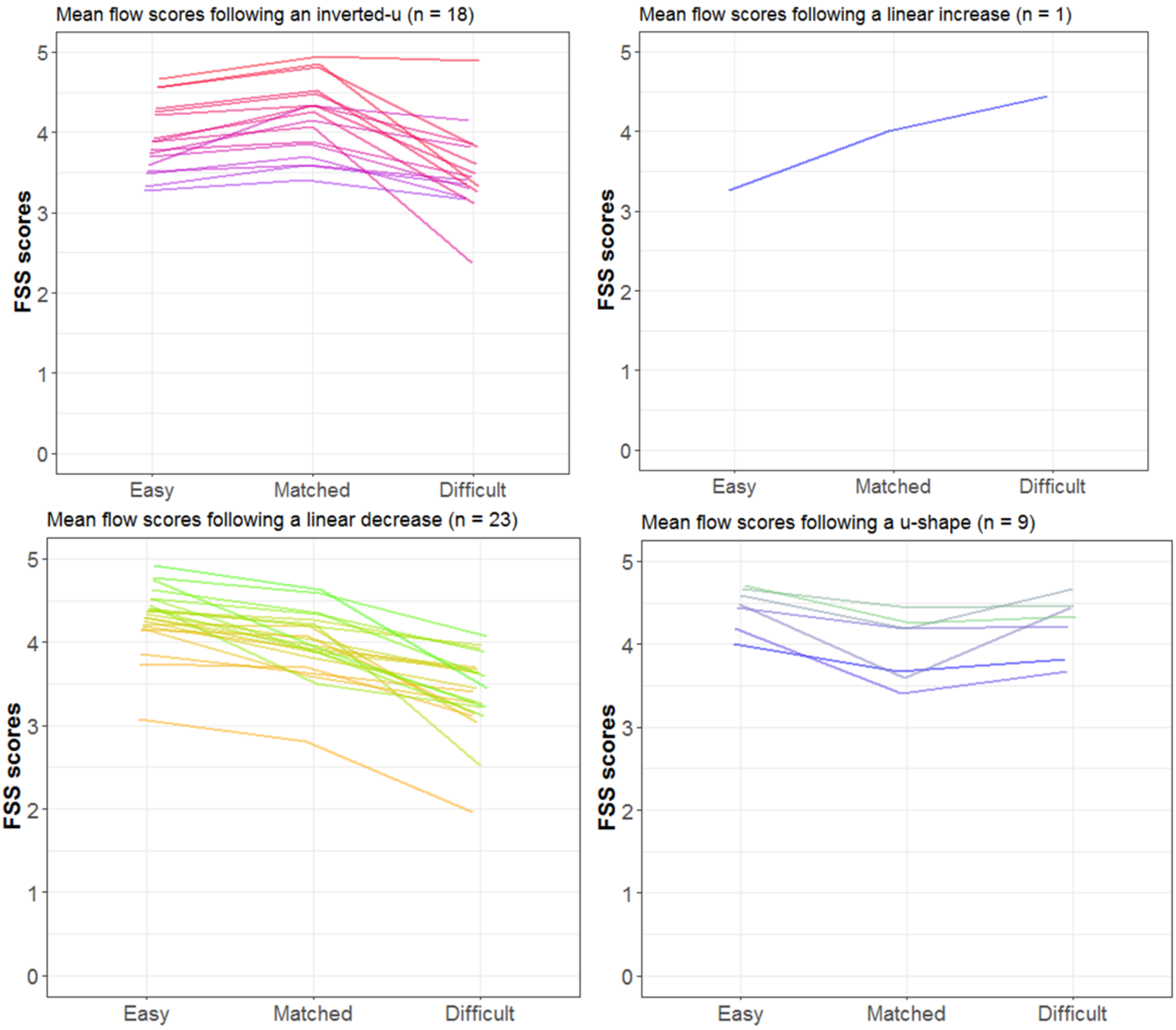


Figure 5.6: Line plots for individual participants (across between-group conditions). The majority of participants reported highest flow scores in the easy condition but 18 (out of 51) reported highest flow scores in the matched condition. A small number reported highest flow scores in the difficult condition.

When participants' scores were examined individually, it was found that while the majority of the participants (45.1%) reported highest flow scores in the easy condition, 35.3% of the participants experienced highest flow scores in the matched difficulty condition, reflecting the inverted u-shaped relationship with difficulty found in lab-based experimental flow inductions.

5. 4. Discussion

5. 4. 1. Effect of a flow induction outside the lab

This study examined the effects of a challenge-skill balance manipulation in an activity frequently reported to induce flow in a naturalistic environment with strong ecological validity. Instead of the inverted u-shape relationship with respect to challenge as expected, the highest scores were found in the easy condition and average flow scores linearly decreased with increasing difficulty.

This is somewhat surprising given that in the lab, total flow scores were often highest in the matched condition. The balance between challenge and skill is an important antecedent of flow. A meta-analysis on 28 studies found a moderate but robust relationship between challenge-skill balance and flow (Fong, Zaleski, & Leach, 2015). This relationship is even larger in leisure activities, presumably what climbing is. On the other hand, Engeser and Rheinberg (2008) found that personal task relevance, or how important a task is to a person, moderates the relationship between difficulty and flow. The inverted u-shape relationship between difficulty and flow was more likely to be observed when the task was a simple video game for a flow induction experiment, than when it was studying for an important examination. One possible way to resolve the contradiction between Fong et al (2012) and Engeser and Rheinberg (2008) is that perhaps leisure is perceived as 'less important' even though it is intrinsically motivating. Fong et al (2012) noted that leisure activities like web-surfing may be intrinsically motivating but lack a sense of challenge. It may be more appropriate to consider climbing as a 'personally relevant' activity, another category of activities Fong et al (2015)'s meta-analysis investigated. Personally relevant activities included certain leisure and work activities. The relationship between flow and challenge-skill balance is smaller in personal activities. This suggests that perhaps the inverted u-shape relationship between difficulty and flow does not hold for climbers in a climbing centre.

It is of note that Engeser and Rheinberg (2008), when looking at the effects of personal relevance on the C-S balance relationship only found the inverted u-shaped curve in the lab task, when participants were asked to play a game of Pac-Man. When it came to flow during statistics or French language, they found a linear decrease reminiscent of the one we found here too. Hence, they identified task relevance as a moderator of the relationship between difficulty and flow experience (Engeser & Rheinberg, 2008). In the highly important activity of learning statistics, flow was still high when the demand was low and a linear relationship was predominant. For the less important activity of playing the computer game Pac-Man, flow was highest when balance was present and low when the demand was too low or too high and this quadratic relationship between demand and flow was stronger the lower the perceived importance. Climbing could be said to be both enjoyable and task relevant as the climbers were recruited from regular members of the climbing gym. In this case, the linear relationship between difficulty and flow experience is actually to be expected.

A central assumption of experimentally induced flow is that flow is highest when challenge is matched to skill level. If that assumption does not hold outside the lab, in a personally meaningful activity, what are we to make of the high scores in the condition that was meant to induce boredom? There are several possible explanations for this. Perhaps in an intrinsically enjoyable activity, even low difficulty levels are enjoyable and engaging and even the easiest levels at a climbing centre are designed to be engaging. It is possible that under the inherently evaluative conditions of an experiment, perceived challenge was higher than usual for levels participants may usually considered easy. This can be seen in the Perceived Balance between Challenge and Skill dimension of the FSS-2 (short). Participants rated Challenge-Skill Balance the highest in the easy condition. It is also possible that the inherently evaluative nature of the experiment increased the challenge of the situation so that their typical or flow-inducing climbing grade was too high to induce flow and at least two levels below their current levels may not have been enough for to induce boredom.

A more intriguing possibility is the idea that someone could make a less absorbing experience a more absorbing one by shifting one's thinking about the scenario (Csikzentmihalyi, 1990). In fact, their qualitative study on flow in climbers found that climbers may re-complexify a familiar route by adding new goals to the central ones of safety and successful completion, for example, by focusing on eliminating wasted motion or a reducing their reliance on the climbing equipment (MacAloon & Csikszentmihalyi, 1983). It may be harder for one to transform a less engaging experience in the laboratory where stimuli and participants' options are rigidly controlled, but with more agency and options outside the lab, they may be able to find ways to enjoy even the easiest climbs in the climbing centre. However, given that certain dimensions of the flow experience do show the inverted u-shape relationship with difficulty, most notably autotelic experience, it may be inaccurate to consider high flow scores in the easy condition as reflecting flow.

There were also participants who experienced higher flow scores when climbing at a level that was intended to be so hard so as to induce frustration rather than flow. Should their higher flow scores in the frustration condition be considered to reflect flow? Schattke's (2019) findings suggest that climbers with a high achievement motive experience even more flow if they succeed on a too-difficult climb they had failed before. Achievement motive was not measured in this experiment so we cannot test if this was the case here. However, it is also possible that given the circumstances, this may be representing a 'clutch' state which Swann et al (2018) argues shares overlapping characteristics with flow but is distinct from flow and cannot be experienced at the same time. A 'clutch' performance has been defined as "any performance increment or superior performance that occurs under pressure situations" (Otten, 2009) Clutch states are characterised by complete and deliberate focus on the task, whereas flow state is characterised by effortless attention. Clutch states involved heightened awareness of the situation and its demands whereas flow involves positive feedback and feeling that 'everything is going to plan' and clutch states involve intense effort, in contrast to flow which is characterised as an effortless, automatic experience. But both states involve enjoyment, enhanced motivation, perceived control, altered perceptions of time and the environment, absorption and confidence and because of these overlaps, Swann (2017) suggests that flow scores can conflate the two (Swann et al., 2017).

However, one possibility that has been raised is of two different kinds of flow that are induced by the different difficulty levels instead of only one. There is evidence indicating that the optimal challenge/skill ratio differs across facets of experience, suggesting that there may be different types of optimal experience, such as a high-challenge/medium-skill one that optimizes cognitive efficiency and a medium-challenge/high-skill one that optimizes hedonic tone (Moneta, 2014). Ceja and Navarro (2012) suggest that one can experience the former until one no longer enjoys being challenged, following which, one can shift to the latter to self-soothe and experience a relaxing flow (Ceja & Navarro, 2012). It is possible that the FSS-2 scores reflect these different types of flow in the different difficulty levels. However, whether there are two different kinds of flow is still unknown (Swann, Piggott, Schweickle, & Vella, 2018). One way that neuroscience could possibly aid in answering this question is to compare sessions that differ on challenge but are scored the same on flow. If there are differences in the neural activity, it might provide some clues to explain the different flow experiences. But such experiments may need to be first conducted under the tight experimental control of the lab setting first.

5. 4. 2. Effect of the between-subject manipulation

The use of the three questions on flow and asking participants which level would best get them in flow seemed to be more effective than only asking their on-sight level. Flow scores were higher in that condition, both overall and especially in the autotelic experience. In addition, it seemed to be more inductive of the inverted u-shape relationship with difficulty, if only in certain dimensions. In keeping with the idea of flow being the result of a balance between challenge and skill when both challenges and skills are above average, in the only other study on flow in climbers , the matched condition was actually a 'challenging' condition where the difficulty level was slightly above participants' comfortable level (Schattke et al., 2014).

5. 4. 3. Limitations of the experiment

Further replication is needed before one can conclude if flow experience shows the expected relationship with challenge-skill balance outside laboratory conditions when challenge -skill balance is systematically varied in a typically flow inducing activity. One way may be to have the same participants take part in a lab-based experimental flow induction and see if they show the same pattern of behaviour.

Data was not collected on various individual differences. This is a problem if there are a number of person-level moderators of flow induction (Moller et al., 2010). There is a need to account for achievement motivation. Often found to moderate the relationship between challenge-skill balance and flow, individuals high in the implicit achievement motive of hope of success experience more flow when the demand is perceived as just right (e.g. during a task of medium challenge). Individuals high in explicit fear of failure experience less flow in this regard. Schattke (2019) has shown that it applies for climbers. Keller and Bless (2008) also found a significant interaction between action orientation and experimental manipulation of flow. Action orientation refers to the ability to stay in an action oriented mode while engaged in a task, maintain focus on the activity and persevere till the task is finished. Participants who were less action-oriented were less sensitive to the compatibility of skills and task demands (Keller & Bless, 2008). In addition, when participants read a series of questions describing flow and were asked about the difficulty level that is most likely to induce it for them, a small number reported the same level as the highest level they had ever attempted. That is, they report that flow existed at the limits of their capabilities, rather than safely within their capabilities. It is likely that this is related to personality. But without collecting data on individual differences, there is no way to test this theory.

The experiment also accepted as participants climbers with a wide range of abilities. Moneta and Csikzentmihalyi (1999) also argued that individuals of high ability or talent are expected to 'express the closest approximation to the theoretical model' of challenge-skill balance predicting flow (Moneta & Csikszentmihalyi, 1999). Without excluding the effects of person-level moderators of experimental flow induction, one cannot yet conclude that an experimental flow induction does not have the same impact outside the lab.

Currently, we cannot be certain that the higher flow scores in the second manipulation group are due to including the flow questions in determining participants' optimal climbing grade. It is possible that climbers in the second manipulation group experienced more flow than climbers in the first manipulation group because of an as-yet unmeasured factor. The between-group manipulation could have been run as a within-subject factor. That is, participants climb in 4 different conditions rather than 3: easy, personal climbing level, most likely to induce flow, difficult. That way, we could compare climbers' most-likely-to-induce-flow level to their personal climbing level as a within-subject comparison, rather than a between-subject comparison and come to a clearer conclusion on the effects of including the flow questions.

5. 4. 4. Implications for studying the neural correlates of flow outside the lab

To date, no one has yet studied flow in climbers using physiological measurements. With technological advancements such as the portable EEG, this is now possible. But based on the data collected in this behavioural study, several things need to be considered before embarking upon collection of neural data come to mind.

More work needs to be done before concluding that the inverted u-shape relationship between difficulty and challenge does not hold outside laboratory conditions. When an experiment is run in a real-world paradigm, there is less control of variables in the environment so it is possible that while the inverted u-shape relationship between difficulty and flow still holds, the increased noise made the expected inverted u-shaped curve less discernable. While some participants do show the inverted u-shaped curve, it is not seen in the majority of participants. However, this would likely correspond to a poor signal-to-noise ratio of the associated neural data.

The choice could be made to carefully select participants. If prior studies have found person-level moderators of flow induction, then it may be prudent to select participants based on these factors, for example, those of high skill, high action orientation and low explicit fear of failure (Engeser & Rheinberg, 2008; Keller & Bless, 2008; Moneta & Csikszentmihalyi, 1999).

Scores on autotelic experience and time perception do follow the inverted u-shaped curve. Participants experienced the highest autotelic experience in the matched condition. In this case, we could consider the matched skills condition the flow condition. Though it does seem to prioritise too much this one dimension over others, it is in keeping with a frequently used definition of experimentally induced flow as the highest enjoyment or intrinsic motivation in the challenge-skills matched condition (Huskey, Craighead, et al., 2018; Ulrich et al., 2016c).

However, if the inverted u-shaped curve does not hold outside of the lab, one cannot assume flow will occur simply because the antecedent of a balance between challenge and skill is met. Is the answer then to use the challenge-skill paradigm to create conditions conducive to boredom, flow and frustration, but to keep an open mind about what might be the possible outcomes? In this case, we would have to rely on the FSS scores to determine when participants are in flow. However, this is problematic when researchers have suggested that a main drawback of the flow scales is that there is no cut-off score to determine at which point someone might be in flow (Abuhamdeh, 2020). Some headway has been made in determining this crucial question. but the high number of flow episodes reported makes some question if his criteria is too generous . Based on the neural findings in Chapter 3, it is very possible that analysing the data based on the FSS scores will result in findings that differ from if the data is analysed by condition.

This experiment also raised another issue. 5 of the 27 people in the second condition, or 18.5% of the sample, reported no to at least one of the questions operationalising flow. This might be expected as Csikzentmihalyi (1997) found that 15% of people sampled do not experience flow. Their data was deemed to be fit to be included in the current analysis because participants in the other manipulation condition had not been asked if they experience flow and there may be non-flow-ers in that group as well. As Moneta (2014) noted, the FSS-2 “imposes” flow on all respondents, even if some would be classified as non-flow-ers based on the Flow Questionnaire because they do not recognise the experience (Moneta, 2014). However, if they do not recognise the flow experience, when neural data is collected, it may be necessary to discard their neural data as unrepresentative of flow, even if their FSS scores show the expected relationship with a balance between challenge and skill. If so, this attrition rate might have to be accounted for in the neural data collection.

As a consideration for future work, a means to incorporate participants' self-report of their flow experience is to film the experience and have them rate points in the climb at which they would determine themselves to have the most optimal experience. Previous experiments have had either participants or an external rater review an experience after the fact for flow (Klasen et al., 2012; Yun et al., 2017).

5. 4. 5. Conclusion

In summary, this study found that when the experimental flow induction is conducted on an intrinsically enjoyable activity outside of the lab, the expected inverted u-shape relationship between difficulty and flow was not observed. Setting the optimal challenge level at the grade participants report as more likely to induce a feeling of flow resulted in higher flow scores than when they were simply asked their personal climbing grade. The experimental procedure requires further optimization before portable EEGs can be fully utilised for examining flow in a natural environment. Nevertheless, its prospects are exciting.

Chapter 6 Investigating Links between Grit, Growth Mindset and Flow in Musicians

6. 1. Introduction

Given the unpredictability of flow experience, one effective way to study flow is via dispositional flow, or the tendency to experience flow (Ullén, de Manzano, et al., 2012). As a measure of how frequently one experiences flow in a given activity, it does not depend on reliably eliciting flow under experimental conditions. It is also of considerable interest as the state of flow is a positively-valenced intrinsically rewarding experience, while simultaneously, one may be at the peak of their performance in the chosen activity (Csikzentmihalyi, 1990). Indeed, the flow state is characterised by high intrinsic motivation - the engagement in an activity for its own sake or the pleasure and satisfaction derived from the experience but not for some external goal (Ryan & Deci, 2000). Therefore, it is not surprising that flow experience may provide a strong incentive for developing skills, facilitating the engagement with challenging performance-based activities. Indeed, studies have found that activities such as sports (Muzio, Riva, & Argenton, 2012; Swann, Keegan, Piggott, & Crust, 2012) and music-making/learning (MacDonald et al., 2006; O'Neill, 1999; Wrigley & Emmerson, 2013) are frequented with flow experiences. The aim of this study is to take a closer look at how non-cognitive skills like grit and growth mindset may influence dispositional flow in musicians.

Grit, defined as 'perseverance and passion for long term goals' (Duckworth, Peterson, Matthews, & Kelly, 2007), is a noncognitive trait that is aligned with Galton's concept of hard labour and passion (Galton, 1892) exhibited by successful individuals who keep going even when the going gets tough and rough (Cox, 1926). Grit demonstrates some predictive validity for achievement (Akos & Kretchmar, 2017; Duckworth et al., 2007; Eskreis-Winkler, Shulman, Beal, & Duckworth, 2014), especially those that are personally relevant and that require a long-term commitment. For example, a recent study (Duckworth et al., 2019) has showed that grit is the strongest predictor of completing an intensive military summer training often associated with a high attrition rate. Grit is also a significant predictor of flow proneness and practice efficiency in musicians (Miksza & Tan, 2015). The authors suggest that gritty musicians practiced more, increasing in skill and becoming more likely to perceive a balance between the challenge of the situation and their skill level, an important prerequisite of flow. This is supported by the finding that amount of practice predicted the likelihood of experiencing flow during performance in highly trained pianists (Marin & Bhattacharya, 2013).

Another non-cognitive trait contributing positively towards encouraging the investment of hard work in the practice of music is growth mindset (Davis & Persellin, 2017), which refers to the belief that an individual’s potential (e.g., intelligence, personality, talent) can be improved through effort (Dweck, 2006), right strategies and good mentoring (Dweck, 2014). A fixed mindset, on the other hand, refers to the implicit belief that one's potential is decided and cannot be improved further. A growth mindset would lead one to pursue challenging learning opportunities, in the hope of growing in knowledge or experience as one would treat setbacks, not as obstacles, but instead as opportunities to overcome. Growth mindset may thus help cultivate grit, as individuals with a growth mindset are more likely to pursue long-term goals despite setbacks. Moderate positive correlations have been found between grit and growth mindset in the context of academic performance (Wang et al., 2018; Yeager et al., 2016; Zhao et al., 2018)

In addition to a resilience to failure, a growth mindset is also conducive to intrinsic motivation. Learners with a growth mindset are more likely to be intrinsically motivated because they are focused on learning and the value placed on skill development (Aronson, Fried, & Good, 2001; Burnette, O'Boyle, VanEpps, Pollack, & Finkel, 2013). In fact, a growth mindset intervention has recently been shown to increase intrinsic interest in the subject being taught (Burnette et al., 2020). On the other hand, a fixed mindset impedes intrinsic motivation (Aronson et al., 2001; Cury, Elliot, Da Fonseca, & Moller, 2006; Haimovitz, Wormington, & Corpus, 2011). As flow is a state of high intrinsic motivation, a growth mindset may facilitate the experience of flow. Intrinsic motivation has also been found to mediate the relationship between grit and growth mindset (Zhao et al., 2018). Compared to extrinsic motivation, intrinsic motivation is more likely to lead to persistence and a better quality of engagement in the activity (Ryan & Deci, 2000).

Grit and growth mindset also share similarities to concepts that have already been found to correlate with flow. Growth mindset overlaps with the concept of an internal locus of control (LOC) or the idea that outcomes are contingent on work and effort, rather than luck or factors out of one's control. An internal locus of control has been linked to increased flow proneness in work, leisure, sports, and everyday activities (Mikicin, 2007; Mosing, Pedersen, et al., 2012; Taylor, Schepers, & Crous, 2006). High internal LOC individuals may be sensitive to factors within their control and thus are sensitive to high-challenge, high-skill situations where flow is likely to occur (Keller & Blomann, 2008). Both grit and growth mindset are positively correlated with an internal locus of control (Burgoyne, Hambrick, Moser, & Burt, 2018). Believing that one is able to take action to achieve the desired outcome, or having high self-efficacy, is linked to higher persistence in acquiring skills as well as more flow experience (Mesurado, Cristina Richaud, & José Mateo, 2016; Pineau, Glass, Kaufman, & Bernal, 2014). Grit also correlates with self-efficacy (Oriol, Miranda, Oyanedel, & Torres, 2017). The close links between growth mindset, grit and concepts related to flow, such as intrinsic motivation and internal locus of control, suggest that growth mindset is likely to correlate with both grit and dispositional flow in musicians.

But how important are non-cognitive factors like grit and growth mindset compared to other factors have been found to relate to dispositional flow in musicians? Unsurprisingly, personality plays a role. People who are more open to experience, emotionally stable, extraverted and conscientious are more likely to experience flow (Butkovic, Ullén, & Mosing, 2015; Gözmen & Aşçı, 2016; Hager, 2015; Heller, Bullerjahn, & Von Georgi, 2015; Ullén et al., 2012). Grit is often strongly correlated with conscientiousness, so much so that it has been suggested that grit is simply conscientiousness by another name (Credé, Tynan, & Harms, 2017). Would the concept of grit predict dispositional flow better than conscientiousness would? Music performance anxiety reduces the tendency to experience flow during music playing (Cohen & Bodner, 2019a, 2019c; Fullagar et al., 2013). Further, the amount of daily practice has also been found to correlate positively with the dispositional flow in pianists and singers (Heller et al., 2015; Marin & Bhattacharya, 2013). By also measuring these previously studied factors in our sample of musicians, we can test if non-cognitive factors like grit and growth mindset explain any variance in dispositional flow over and above these previously studied variables.

And finally, grit and flow may be more likely to be expressed for individuals who are highly trained in music. As higher scores of global dispositional flow were found in professional classical orchestral musicians, compared to those previously found in student musicians (Marin & Bhattacharya, 2013; Wrigley & Emmerson, 2013), it is suggested that professional musicians' higher skill levels may allow them to experience the challenge-skill balance prerequisite of flow more often (Cohen & Bodner, 2019c). Thus, we hypothesised that musical training would be correlated with dispositional flow. Long hours of practice and training over many years are required for musicians to achieve technical proficiency. As grit demonstrates some predictive validity for sustained goal commitment and retention in very varied contexts, including work, schooling and marriage (Eskreis-Winkler et al., 2014), we hypothesised that grit would also be correlated with musical training.

So, the present study intends to shed more light on the associations between grit and flow in musicians by examining the possible associations between grit, growth mindset and dispositional flow in a sample of musicians. We hypothesised that 1) grit correlates with the dispositional flow, 2) growth mindset will correlate with grit and dispositional flow, and 3) musical training correlates with both grit and flow. We also ran two hierarchical regressions – the first to examine the contribution of grit and growth mindset in predicting dispositional flow over and above relevant background traits (i.e. Big Five personality traits, musical training, performance anxiety), and the second one to examine if grit and growth mindset predicted dispositional flow over and above variables previous studies have linked to dispositional flow in musicians. Further relevant variables (i.e. musical practice) were included.

6. 2. Methods

6. 2. 1. Design

The study employed a correlational design in which we measured grit, growth mindset, and dispositional flow in a sample of musicians. We tested a model with the flow as the outcome variable, grit as the predictor variable, and growth mindset as a mediator between them. Exploratory correlation analysis was performed between grit, dispositional flow, and musical training. General musical sophistication, the Big Five personality traits, and performance anxiety were also measured and correlated with grit and the nine subscales of dispositional flow.

6. 2. 2. Participants

Participants were 162 musically trained individuals (59 males, 103 females), ranging between the ages of 18 and 57 years (*M* = 25.1, *SD* = 6.1), after removing 3 cases due to missing data. Participants were mostly Malaysians (*n* = 91), followed by individuals from the United Kingdom (*n* = 29), Asian countries (e.g., Korea, Thailand, China, etc.; *n* = 18), United States of America (*n* = 10), European countries (*n* = 10), Canada (*n* = 2), and Zimbabwe (*n* = 2).

6. 2. 3. Materials

This study included seven standardised questionnaires: participants' sociodemographic information, grit, mindset, dispositional flow, general musical sophistication, personality, and performance anxiety. These questionnaires were presented in randomised order across participants, except for the sociodemographic one that was always presented first.

Grit.The 12-item Grit Scale (Duckworth et al, 2007; α = .79) was used to measure self-reported grit in participants, comprising of questions such as "I have overcome setbacks to conquer an important challenge". Responses were recorded on a 5-point Likert scale (1 = Not like me at all to 5 = Very much like me), with six out of the twelve items being reverse scored. Higher average scores (from all twelve items) indicated higher levels of grit.

*Mindset***.** The Mindset Scale (Dweck, 2006; α = .88) includes sixteen items on a 6-point Likert scale (0 = Strongly Disagree to 6 = Strongly Agree), with eight items accounting for fixed and growth mindset respectively. These items further accounted for two separate dimensions of mindset: intelligence (first eight items) and talent (last eight items). An example of a fixed-talent mindset item was “To be honest, you can’t really change how much talent you have”; and a growth- intelligence mindset would be “No matter who you are, you can significantly change your intelligence level”. For this study, items for growth mindset (α = .88) and more specifically, growth-talent mindset (α = .85) were further taken into consideration. Scores were normalised.

*Dispositional Flow (Flow)***.** The Dispositional Flow Scale-2 (DFS-2) (S. A. Jackson & Eklund, 2002) is a 36-item instrument based on the nine dimensions of flow (Csikzentmihalyi, 1990; S. A. Jackson et al., 2008). It includes items indicating (a) balance between the challenge confronted and skill required, (b) a merging of action and awareness, (c) being clear of the desired goals, (d) having immediate and unambiguous feedback regarding the task undertaken, (E) total concentration, (f) a sense of control, and yet at the same time having, (g) loss of self-consciousness, (h) a distorted sense of time, and (i) an autotelic experience (intrinsically rewarding). Participants were required to respond in relation to their experience in musical practice (α = .95) and performance (α = .94), so the DFS-2 was administered twice under those two contexts. Items were phrased in statements such as “The way time passes seems to be different from normal” on a 5-point Likert scale (1 = Never to 5 = Always). Scores for overall flow were obtained by averaging both the DFS-2 scores from musical practice and performance.

Musical background. The Goldsmiths Musical Sophistication Index, version 1.0 (Gold-MSI) (Müllensiefen, Gingras, Musil, & Stewart, 2014) is comprised of 39 items (α = .90), with five subscales (active musical engagement (F1), perceptual abilities (F2), musical training (F3), singing abilities (F4), emotional engagement with music (F5)) and one overall measure (general musical sophistication). Responses were obtained on a 7-point Likert scale (1 = Completely disagree to 7 = Completely agree). The variable of interest, Musical Training (F3), combines years of formal musical training and practice and degree of self-assessed musicianship. Additionally, participants reported the amount of their weekly musical practice in hours. In this study, we focused on the subscale, musical training (α = .73) and the amount of daily practice (in hours) as variables.

The Big-Five Personality. The Ten-Item Personality Inventory (TIPI) (Gosling, Rentfrow, & Swann, 2003) measures the Big Five personality traits: extraversion, agreeableness, conscientiousness, emotional stability, and openness to experience. Each trait was measured by two items, with one of the items being reversed scored.

Performance anxiety. The Music Performance Anxiety Inventory for Adolescents (MPAI-A) (Osborne, Kenny, & Holsomback, 2005) is a 15-item scale (α = .90) measuring anxiety in musicians, with statements such as “Just before I perform, I feel nervous”. Responses were indicated on a 7 point Likert scale (0 = Not at all to 6 = All the time).

6. 2. 4. Procedure

An online survey set up on Qualtrics® was shared via social-media platform (Facebook) and the distribution of flyers across the campus. Several music schools in the UK were also invited to distribute the link of the online survey to their music students. One hundred and sixty-two participants, all adults and musically trained (formally or self-taught), completed the survey. It took an average of one hour to complete, and the participants were offered to enroll for a cash prize draw for their participation. The study protocol was approved by the local ethics committee of the university's Psychology Department.

6. 2. 5. Statistical Analyses

Statistical analyses were conducted in IBM SPSS Statistics for Macintosh, version 22 (SPSS Inc., IBM Corp., Armonk, NY, USA). Bivariate correlations were conducted with p-values adjusted using the Benjamini-Hochberg procedure (controlling for false discovery rate of 0.05) to control for Type I error (Benjamini & Hochberg, 1995). All correlations were set at two-tailed, at an alpha level of .05.

Two hierarchical linear regressions were run to predict dispositional flow by studied variables. Their order of entry was determined by research relevance. To examine if non-cognitive factors like grit and growth mindset predicted dispositional flow over and above other relevant background factors, the Big Five personality traits were entered in the first block. The musician-specific factors of musical training and music performance anxiety were entered in the second block. As the variables of interest, grit and growth mindset were entered last and in separate blocks to examine their separate contributions. Grit was entered in the third block and growth mindset was entered in the fourth block. In the second hierarchical linear regression, variables that have been previously linked to dispositional flow were entered first to see the effect of grit and growth mindset after controlling for variables already known to be associated with the dispositional flow. The order of entry of variables was similar to the first hierarchical linear regression except that daily practice hours was included in the musician-specific factors in block 2.

6. 2. 6. Results

Table 6.1 presents the descriptive statistics of the study's main variables. All data were screened for missing scores and outliers;3 cases were removed for missing data. Descriptives show that the variables of interest have a relatively good range of responses. Grit and dispositional flow scores are comparable to Miksza and Tan (2015)'s sample. Perhaps due to a more varied sample of musicians, the mean dispositional flow score is higher than those found in the highly trained pianists in the sample of Marin and Bhattacharya(2013).

Descriptive Statistics of Grit, Growth Mindset, Musical Training (Factor 3 in the Gold-MSI), Flow, the Big Five Personality Traits, and Performance Anxiety

	Min	Max	*M*	*SD*
Grit	1.92	5.00	3.24	0.59
Growth Mindset	0.33	1.00	0.68	0.13
Musical Training	11.00	48.00	34.54	7.95
Flow	1.90	5.00	3.52	0.51
Extraversion	1.00	7.00	3.87	1.39
Agreeableness	1.00	7.00	4.84	1.09
Conscientiousness	1.00	7.00	4.76	1.30
Emotional Stability	1.00	7.00	4.27	1.36
Openness to Experience	3.00	7.00	5.23	0.91
Performance Anxiety	4.00	90.00	49.23	17.36

Note. *N* = 162; minimum (Min), maximum (Max), mean (*M*), standard deviation (*SD*).

Table 6.1: Descriptive statistics for grit, growth mindset, musical training, dispositional flow, Big Five personality traits and music performance anxiety

6. 2. 7. Bivariate Correlation Tests

To test our three main hypotheses, we performed an bivariate correlation analysis between our main variables and summarised the results in Table 2. As previously found, grit was significantly correlated with flow (r= 0.32, p <.001). However, growth mindset did not significantly correlate with flow (r= 0.07, p = .39) or any other variables (p> 0.05). Musical training was positively correlated with flow (*r* = 0.32*, p* < .001) and with grit (*r* = 0.21*, p* = .007).

We further examined the patterns of correlations between grit and musical training with the nine subscales of dispositional flow. Grit was significantly correlated (*p* < .05) with most flow subscales except action-awareness merging and time distortion (see Table 6.3). Musical training also correlated significantly with most flow subscales except three, loss of self-consciousness, time distortion and autotelic experience (see Table 6.3).

In this sample of musicians, dispositonal flow also correlated with many of the variables previously linked to dispositional flow in musicians. Out of the Big Five personality traits, dispositional flow correlated positively with conscientiousness (*r* = 0.23*, p* = .004) and emotional stability (*r* = 0.26*, p* = .001). Grit also correlated with agreeableness (*r* = 0.23*, p* = .003), conscientiousness (*r* = 0.52*, p* =.000), and emotional stability (*r* = 0.25*, p* =.002). Performance anxiety correlated negatively with flow (*r* = - 0.33*, p* < .001) and grit (*r* = - 0.26*, p* = .001). Grit (*r* = 0.16*, p* = .048) and flow (*r* = 0.30*, p* <.001) also significantly correlated with participants' daily hours of practice.

A further analysis showed that conscientiousness and emotional stability were both found to be significantly correlated with the following flow subscales: challenge-skill balance, unambiguous feedback, total concentration and sense of control (see Table 6.3). Conscientiousness was also correlated with the subscale, clear goals, while emotional stability was correlated with the subscale, loss of self-consciousness. Lastly, performance anxiety had significant negative correlations with all flow subscales except transformation of time.

Summary of Correlations for Scores on Grit, Growth Mindset, Musical Training, Flow, the Big Five Personality Traits, Performance Anxiety and Daily Practice Hours

	1	2	3	4	5	6	7	8	9	10	11
1. Grit	-										
2. Growth Mindset	0.01	-									
3. Musical Training (F3)	0.21^{**}	0.09	-								
4. Flow	0.32^{***}	0.07	0.32^{***}	-							
5. Extraversion	0.14	0.04	-0.04	0	-						
6. Agreeableness	0.23^{**}	0.04	0.16*	0.05	-0.06	-					
7. Conscientiousness	0.52^{***}	-0.03	0.18*	0.23^{**}	0.11	0.14	-				
8. Emotional Stability	0.25^{**}	0.14	0.19*	0.26^{**}	0.05	0.36^{***}	0.20^{*}	-			
9. Openness to Experiences	0.04	-0.06	0.14	0.03	-0.01	0.14	0.03	0.11	-		
10. Performance Anxiety	-0.26^{***}	-0.06	- 0.27^{***}	-0.33^{***}	-0.19	0.01	-0.17	-0.30^{***}	-0.06	-	
11. Daily Practice Hours *(N =* 151)	.161*	0.09	.349**	.296**	0.11	0.03	0.08	0.003	0.12	-0.13	-

Note. Unless otherwise stated, *N* = 162; **p* <.05, ***p*<. 01, ****p*< .001 after controlling for a false discovery rate of .05.

Table 6.2: Summary of Correlations for Scores on Grit, Growth Mindset, Musical Training, Flow, the Big Five Personality Traits, Performance Anxiety and Daily Practice Hours

Correlations for flow subscales with grit, musical training, conscientiousness, emotional stability and performance anxiety

	Flow	Challenge-skill Balance	Action-awareness Merging	Clear Goals	Unambiguous Feedback	Total Concentration	Sense of Control	Loss of Self-Consciousness	Transformation of Time	Autotelic Experience
1. Musical Training	.315**	.385**	.299**	.330**	.364**	.243**	.242**	0.013	0.107	0.119
2. Grit	.316**	.258**	0.074	.437**	.209**	.405**	.317**	.161*	0.008	.175*
3.Conscientiousness	.228**	.213**	0.122	.356**	.157*	.239**	.249**	0.073	-0.011	0.098
4. Emotional Stability	.261**	.304**	0.093	0.152	.191*	.282**	.360**	.227**	-0.018	0.096
5. Performance Anxiety	-.325**	-.257**	-.216**	-.186*	-.209**	-.335**	-.405**	-.323**	0.070	-.218**

N = 162; **p* <.05, ***p*<. 01, ****p*< .001 after controlling for a false discovery rate of .05.

Table 6.3: Correlations for flow subscales with grit, musical training, conscientiousness, emotional stability and performance anxiety

Hierarchical Regression Analysis of Predictors of Flow Proneness in Musicians

Predictor variables		Standardised regression coefficients			
		Regression 1	Regression 2	Regression 3	Regression 4
Big Five personality traits	Openness to Experience	0.01	-0.02	-0.02	-0.02
	Conscientiousness	0.19	0.14	0.05	0.05
	Extraversion	-0.03	-0.05	-0.07	-0.07
	Agreeableness	-0.06	-0.05	-0.07	-0.08
	Emotional Stability	0.24**	0.15	0.14	0.14
Musical Factors	Musical Training (Gold-MSI F3)		0.21**	0.20**	0.20*
	Music Performance Anxiety		-0.21**	-0.18*	-0.18*
Non-cognitive factors	Grit			0.19*	0.19*
	Growth Mindset				0.03
R^2		0.10**	0.20***	0.23***	0.23***
R^2 Change			0.10***	0.02*	0.00

n = 162; **p* <.05, ***p*<. 01, ****p*< .001

Table 6.4: Hierarchical Regression Analysis of Predictors of Flow Proneness in Musicians

Hierarchical Regression Analysis of Predictors of Flow Proneness in Musicians

Predictor variables		Standardised regression coefficients			
		Regression 1	Regression 2	Regression 3	Regression 4
Big Five personality traits	Openness to Experience	0.03	-0.02	-0.02	-0.01
	Conscientiousness	0.22**	0.16*	0.12	0.13
	Extraversion	-0.03	-0.10	-0.11	-0.11
	Agreeableness	-0.07	-0.05	-0.07	-0.07
	Emotional Stability	0.23**	0.13	0.12	0.11
Musical Factors	Musical Training (Gold-MSI F3)		0.13	0.13	0.12
	Music Performance Anxiety		-0.27***	-0.25**	-0.25**
	Amount of Daily Practice		0.22**	0.21**	0.21**
Non-cognitive factors	Grit			0.10	0.10
	Growth Mindset				0.07
R^2		0.12**	0.28***	0.29***	0.29***
R^2 Change			0.17***	0.01	0.00

n = 152; **p* <.05, ***p*<. 01, ****p*< .001

Table 6.5: Hierarchical Regression Analysis of Predictors of Flow Proneness in Musicians including daily practice hours

6. 2. 8. Hierarchical Linear Regression

A regression analysis showed that on its own, grit was a significant predictor of flow (*b* = 0.27, *SE* =.0.7, *t*(160) = 4.20, *p* < .001). We ran a hierarchical linear regression to test if grit added any predictive power over and above that of other personality trait-based predictors of dispositional flow. Predictors that have been studied previously were entered first into the model, followed by the new predictors. Personality traits were entered in block 1. Music-related factors, musical training and performance anxiety, were included in block 2. Grit was then entered in block 3, and finally, growth mindset entered in block 4. The results are presented in Table 6.4. In our sample, only 2 of the Big Five, Conscientiousness and Emotional Stability correlated with flow proneness in musicians and explained 10% of the variance in dispositional flow. Musical factors such as musical training and the lack of music performance anxiety predicted an additional 10%. After adding them to the model, the personality traits of Conscientiousness and Emotional Stability are no longer significant, which suggests that they share much overlap with musical training and music performance anxiety in predicting flow proneness. When grit was added, it contributed to 2% of the explained variance, a small but significant contribution. Growth mindset, however, does not add to the explanatory power of the model. So, grit correlates with flow, and also contributes, albeit small, to predicting dispositional flow in musicians over and above other relevant personality traits,

We also ran a second hierarchical regression, similar to the first one, but after incorporating the predictor variable of daily musical practice (in hours). Interestingly, when it was included in block 2, the only factors that significantly predicted dispositional flow are performance anxiety and hours of practice (see Table 6.5). This suggests that after controlling for daily hours of practice, the predictive contribution of grit to dispositional flow becomes not significant.

6. 3. Discussion

In this study, we investigated the potential links between grit, growth mindset and dispositional flow in musicians, particularly after accounting for the effect of factors previously found to correlate with dispositional flow in musicians, namely, musical training, the Big Five personality traits, and performance anxiety. Results revealed three main findings: (i) grit was a significant predictor of dispositional flow, but it added no additional explanatory power when previous predictors were taken into account, (ii) growth mindset did not correlate with either grit or flow and (iii) musical training correlated with both grit and flow. In the remainder of this Discussion, we discuss each of these principal findings and some additional exploratory findings, followed by some remarks on potential limitations of the current study.

We replicated Miksza and Tan (2015)'s earlier finding on dispositional flow and grit and extended it further. Grit correlates with dispositional flow and explains variance, small but significant, in dispositional flow over and above other predictor variables, but only if practice hours is not included in the regression. Grit remains a significant predictor of dispositional flow when added to the model after factors that have already been related to flow proneness in musicians, namely Conscientiousness and Emotional Stability, musical training and music performance anxiety. Grit is often strongly correlated with conscientiousness (a finding that is also reflected in our sample of musicians), so much so that it has been suggested that grit is simply conscientiousness by another name (Credé et al., 2017). That it adds a small but significant explanatory power to the model even after accounting for conscientiousness, suggests that at least for musicians, grit is not simply conscientiousness by another name.

However, when daily practice hours is taken into account, grit no longer adds any additional predictive validity for dispositional flow. When practice hours is included, music performance anxiety and daily practice hours are the only significant predictors for dispositional flow in this sample of musicians, suggesting that the strongest predictors for musicians' flow experience are how you feel while playing music and how often you engage in it. Since grit only has a moderate correlation with daily practice hours, it seems to suggest that while grit may contribute to more practice, it may not be the only factor that results in more practice hours. In fact, the inclination to practice, flow proneness and musical achievement may be the result of a pleiotropic genetic influence, much as dispositional flow in general life is also has a moderate heritability (Butkovic et al., 2015; Mosing, Magnusson, et al., 2012).

Music performance anxiety was the most predictive factor of dispositional flow in this sample of musicians. Performance anxiety was also negatively correlated with grit, musical training, flow, and emotional stability. This indicates that participants who experienced more anxiety when performing music also had lower scores on grit, received less musical training, experienced less dispositional flow and were less emotionally stable. The negative correlations between performance anxiety and flow are consistent with findings from Fullagar et al. (2013) who suggest that flow and performance anxiety are opposing and contradicting experiences (Fullagar et al., 2013).When a musician is highly anxious before a performance, flow experience is unlikely. Of note, flow has been postulated as an effective tool to reduce performance anxiety (Cohen & Bodner, 2019b; Lamont, 2012; Wrigley & Emmerson, 2013).

We find that growth mindset was not correlated with either grit nor dispositional flow in musicians. The lack of a relationship between grit and growth mindset seems at odds because it is often claimed that "growth mindset and grit go together" (Duckworth, 2016,p. 181, especially based on data from college students). However, our participants, who are musicians, might not believe that a growth mindset can be beneficial for their musical training. In theory, those with a growth mindset would redouble their efforts when faced with a challenge (Dweck, 2010; Dweck & Leggett, 1988) but this might not represent the best response in every circumstance as it might be a waste of energy and resources (Burnette et al., 2013). Indeed, in some circumstances, having a fixed mindset might enable one to achievetheir desired end goal more quickly and effectively (Burnette et al., 2013). Further, the growth mindset is culture-dependent; for example, in certain cultures, creativity is considered as more fixed and less changeable (Tang, Werner, & Karwowski, 2016). Our sample is predominantly from Asia where, compared to learners from Western countries, natural talent is often perceived to be more influential than hard work (Asbury, Klassen, Bowyer-Crane, Kyriacou, & Nash, 2016; Mercer & Ryan, 2009). Future studies might explore these differences, including both context- (i.e. artistic and non-artistic achievements), and culture- (i.e. East Asians vs Westerners) specific effects of the growth mindset. Mindset may also play a smaller role than originally thought. A recent study found that the effect of mindset on goals orientation, persistence and resilience in face of failure were significantly weaker than the average effect size found in social-psychological research (Burgoyne, Hambrick, & Macnamara, 2020). Its effects may be even smaller for adults as compared to children, as found by a meta-analysis (Sisk, Burgoyne, Sun, Butler, & Macnamara, 2018).

We found significant correlations between musical training and both grit and flow. More musically trained people did experience more flow. Challenge-skill balance correlated with musical training, providing further support for Cohen (2019)'s conjecture that increased training and practice provide the skills for musicians to experience more challenge-skill balance. Previous studies have not found conclusive evidence that professional musicians experience more flow than amateurs, or that the quality of music students' flow was significantly influenced by advancement in their studies or that years of training influenced dispositional flow (Marin & Bhattacharya, 2013; Sinnamon et al., 2012; Wrigley & Emmerson, 2013). The more multidimensional and continuous measure of musical training used in this study, which takes into account years of training and practice and self-assessed musicianship, maybe a more sensitive measure to test the hypothesis that training influences dispositional flow. As for grit, it is plausible that participants who were more committed to their long-term goals were more likely to acquire musical skills and training.

The relationship between musical training, grit and flow has interesting implications for long-term musical engagement. Both intrinsic and extrinsic motivation play a role in musicians' engagement with music at any point in their development. Music is intrinsically enjoyable but early on, children may require external motivators. Parents, teachers and peers are instrumental in shaping children's self-concepts and habits and so may be considered external motivators (Sichivitsa, 2007). Professional musicians report the highest intrinsic motivation, yet are also more likely to report that their musical activities like rehearsals and performances are driven by extrinsic motivators like pay (Juniu, Tedrick, & Boyd, 1996). However, as intrinsic motivation reported to be highest in people who have engaged in it for the longest time and to the greatest depth (Appelgren, Osika, Theorell, Madison, & Bojner Horwitz, 2019), it seems intrinsic motivation is key for long-term engagement in music. Hence, the experience of flow during music, as a state of high intrinsic motivation, may serve as an intrinsic motivator for continued musical engagement. People who experience the most flow also practice the most hours (Heller et al., 2015; Marin & Bhattacharya, 2013). As grit positively correlates with intrinsic motivation and negatively correlates with extrinsic motivation, it is suggested that one is more likely to make an effort to persevere and maintain interest in an activity when one is intrinsically motivated (Zhao et al., 2018). Evidence suggests that a desire to experience flow, or an orientation towards engagement, promotes grit by encouraging sustained effort over time (Von Culin, Tsukayama, & Duckworth, 2014). In fact, Kirby et al. (2014) suggest that long-term challenge is the mechanism of grit (Kirby et al., 2014). It is through engaging with challenges over a long time that the disposition of grit can be fully expressed. Hence, grit and flow may have mutually reinforcing effects that promote long-term musical engagement and achievement.

Several limitations of this study must be acknowledged. First, we cannot assume the generalizability of our findings. The majority of participants are Malaysians so that this study may be specific to Malaysian musicians and the psychological underpinnings of their musical experiences. Future studies should include more musicians from other parts of the world. Second, the data presented are correlational rather than experimental. Thus, the causal role of any specific personality trait cannot be inferred. To increase external validity, future research may consider introducing observational tasks to test the growth mindset of participants as past research has done via intervention programs in a classroom setting (Blackwell, Trzesniewski, & Dweck, 2007; Devers, 2011; Yeager & Dweck, 2012). Finally, it should be noted that even though the hierarchical linear regression uses grit to predict flow, the correlational nature of the study means that it is not possible to distinguish the direction of causation. Longitudinal research – principally with repeated measures – will be needed to reveal the mechanisms by which grit in musical practice would lead to flow experience, and eventually to musical achievements.

In conclusion, this study offered a closer look at the claims of the effects of non-cognitive factors like grit and growth mindset in predicting flow experience in musicians. Grit, but not growth mindset, was significantly related to musicians' flow experience and demonstrated added predictive power after controlling for other personality traits, but this effect disappeared after controlling for daily practice hours. However, flow and grit were highest in those with the most musical training, offering a tantalising hint as to the effects of non-cognitive factors and flow experience in motivating musicians to undertake long years of training and practice. As research in the field of implicit theories and specifically on the growth mindset intervention continues to progress (Adams, 2019; Yeager et al., 2019), we will move closer to understanding the relationship between flow and non-cognitive traits such as grit and growth mindset, which could help musicians better position themselves to enter flow and reduce the detrimental effects of performance anxiety.

Chapter 7 Dispositional flow in resting state data: an exploration of frontal asymmetry, emotional intelligence and flow

7. 1. Emotional Intelligence and Dispositional Flow Across Domains

7. 1. 1. Introduction

The previous study investigated the links between flow and the non-cognitive factors of grit and mindset and found that they did not have any effect on dispositional flow in musicians beyond what could be explained by practice hours and music performance anxiety. But what might be the effect of non-cognitive factors on dispositional flow in other domains? Another non-cognitive factor that has been linked to flow is emotional intelligence.

Emotional intelligence (EI) is the capacity to effectively process emotional information in self and others and the ability to use this information to guide thinking and behaviour (Salovey & Mayer, 1990). Interest in it has grown in recent years as research has connected it to successful social interactions, job performance, mental health and emotional well-being. It is standard in the field to distinguish between two theoretical constructs, namely ability emotional intelligence and trait emotional intelligence (Petrides, 2011). The ability EI model posits emotional intelligence as a matter of cognitive performance in relation to emotional activities (Brackett & Salovey, 2006). It is measured by testing performance in tasks involving emotion processing. The trait EI model on the other hand, conceives of emotional intelligence as a set of emotion-related dispositions and self-perceptions measured via self-report (Petrides, 2011). Trait EI is positively associated with life satisfaction and negatively correlated with alexithymia, a deficit in emotional regulation (Baughman et al., 2011). Trait EI has also been shown to be a protective factor against stress (Mikolajczak, Petrides, Coumans, & Luminet, 2009). High trait EI in athletes is linked to lower increase of stress indicators under pressure (Laborde, Brüll, Weber, & Anders, 2011). Trait EI is a strong predictor of mental health and well-being (Petrides, 2011). Higher trait EI scores have also been associated with a lower risk for mental disorders such as depression and anxiety (Mikolajczak et al., 2009).

Though no correlation has been found between intelligence and flow (Ullén et al., 2012), emotional intelligence on the other hand, may have a role in facilitating flow. Emotional intelligence is a metacognition that may play a role in achieving flow. Metacognitions refer to information about one's cognition and internal states and coping strategies that influence both (Beer & Moneta, 2010). One main metacognitive component of the Positive Metacognitions Scale is described as 'confidence in interpreting emotions as cues, refraining from impulsive and potentially dysfunctional overreactions when experiencing negative emotions'. Indeed, Goleman (1996) posits that being able to enter flow is emotional intelligence at its best, the ultimate representation of harnessing emotions in service of performance. Wilson and Moneta (2016) also show a significant correlation between flow experience and the emotion subscale of the Positive Metacognitions Scale (Wilson & Moneta, 2016). Emotional regulation, as discussed in chapter 4, is also a psychological skill that is conducive to flow experience and enhanced performance in sport (S. A. Jackson et al., 2001).

To the best of our knowledge, the first study to examine the link between flow and emotional intelligence was Marin and Bhattacharya (2013). Marin and Bhattacharya (2013) found that trait EI predicted how prone musicians were to entering flow state. They suggest that emotional intelligence would seem to be particularly relevant to musicians' experience of flow, given that emotions play a crucial role in musical communication (Juslin & Sloboda, 2010) but conclusions could not be drawn until this relationship between trait EI and dispositional flow was examined in other domains. Thus, examining the relationship between emotional intelligence and dispositional flow will extend the findings of Marin and Bhattacharya (2013) by shedding light on whether emotional intelligence facilitates flow in domains outside of musical activities.

7. 1. 2. Methods

7. 1. 2. 1. Design

This study employed a correlational design. Measures of dispositional flow and trait emotional intelligence were collected as part of a battery of questionnaires used in various different studies. Consequently, dispositional flow scores were collected for the activities of music performance, climbing, active music listening and general daily living.

7. 1. 2. 2. Participants and procedure

The musicians sample comprised of 92 amateur and professional musicians (18 to 69, mean age = 26.84 years, *SD* = 7.531 years, 41 males, 51 females) who took part two experiments on flow in music performance. They were asked to complete the DFS-2 in relation to their experience of music performance. There were 22 wind players, 15 singers, 10 guitarists, 18 string players, 27 pianists. 23 of the participants were currently studying an undergraduate or postgraduate music performance programme at either a conservatory or a university. 35 of those who did not had graduated from a music performance course and remained active in the music scene to varying degrees. 34 had never studied music at tertiary level but played often as a hobby

The climbers sample comprised of 38 climbers responded on the Dispositional Flow Scale (DFS-2) and the Trait Emotional Intelligence Questionnaire (TEIQue) as part of an experiment on flow in climbing. Participants were between 20 to 63 years old (*M* = 31.8, *s*.d = 9.23). There was a large range of climbing skills and experience. 24% of the climbers had more than 7 years of climbing experience, 21% had climbed for a year or less, and 55% had 2 - 7 years of climbing experience. Most of them (64%)climbed once or twice a week. 13% of them climbed less frequently, only once or twice a month. 23% climbed 3 or more times a week.

37 participants in an experiment on flow in active music listening (24 females, age range of 20 years to 40 years, mean ± s.d. age: 27.43 ± 4.75 years) responded on the DFS-2 for active music listening and general daily living. They also completed the TEIQue.

7. 1. 2. 3. Materials

The short form of the Trait Emotional Intelligence Questionnaire (TEIQue-SF) (Petrides, 2009) measures global trait intelligence by collecting responses to 30 items on 7-point Likert scales (1 = completely disagree to 7 = completely agree). Other than a global emotional intelligence score, it contains four subscales: well-being, self-control, emotionality and sociability.

The Dispositional Flow Scale-2 (DFS-2) (S. A. Jackson & Eklund, 2004)comprises of 36 items referencing the nine-dimensional nature of flow and has been shown to be reliable in assessing flow in musicians (Sinnamon et al., 2012). Dispositional flow is calculated as measure of how often participants experience conditions that contribute to flow. Answers are collected on 5-point scales (1 = never to 5 = always). Participants were instructed to answer it as a general measure of their experience whenever they are playing their instrument, regardless of whether it is practice or performance.

7. 1. 2. 4. Statistical Analysis

DFS-2 and TEIQue were correlated. All correlations were set at two-tailed, at an alpha level of .05. Where the specified hypothesis was tested, Bonferroni corrections were applied to control for inflated risk of type I error. When exploratory analyses were conducted, corrections were not applied. Statistical analyses were conducted in IBM SPSS Statistics version 22 (SPSS Inc., Chicago, IL, USA) and in Matlab R2013b (The MathWorks, Inc., Natick, Massachusetts, USA).

7. 1. 3. Results

7. 1. 3. 1. Emotional Intelligence and Flow in Musicians

We were able to replicate Marin and Bhattacharya's finding on trait emotional intelligence and dispositional flow in musicians. Trait emotional intelligence correlates with dispositional flow in musicians (r = .256, p = .015).

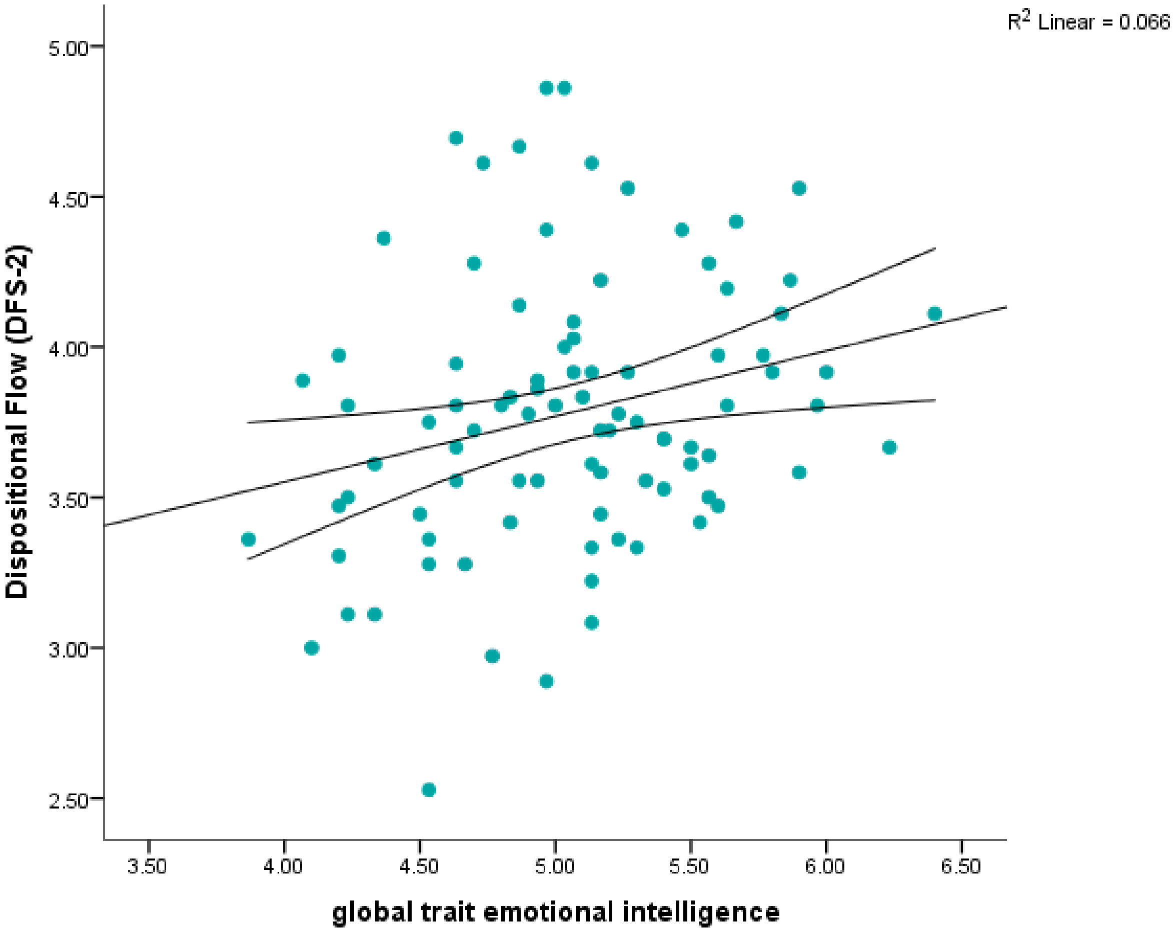


Figure 7.1: Scatterplot of dispositional flow in music performance and trait emotional intelligence (*n* = 92)

7. 1. 3. 2. Emotional Intelligence and Flow in Climbers

In an activity without purportedly emotional stimuli, does trait EI still predict dispositional flow?

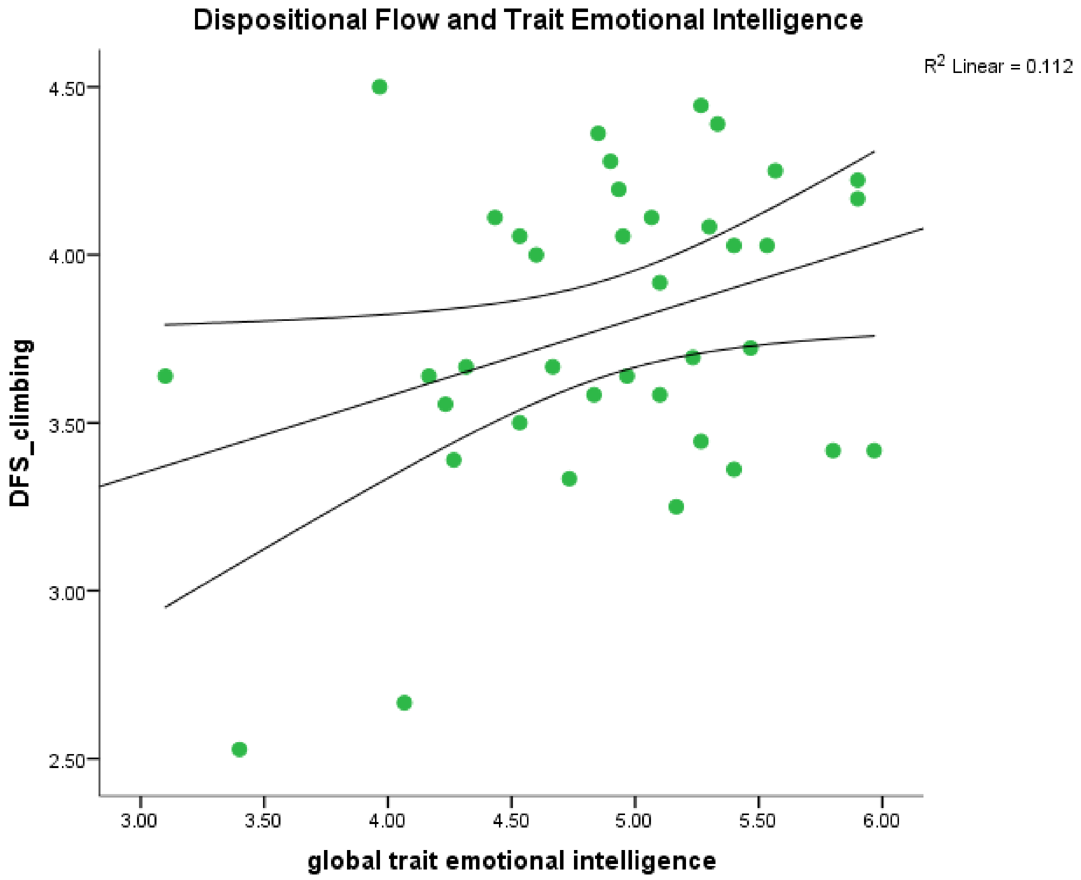


Figure 7.2: Scatterplot of dispositional flow during climbing and trait emotional intelligence in climbers (*n* = 38)

Trait emotional intelligence also predicted flow in climbers (*r* = .334, *p* = .040).

7. 1. 3. 3. Emotional Intelligence and Flow in Daily Life

Correlations between trait EI, its subscales and flow in general life (n = 36) and in music listening (n = 37)

	well_being	self_control	emotionality	sociability	Flow in general life	Flow in music listening
global trait emotional intelligence	.807** 0.000	.708** 0.000	.839** 0.000	.686** 0.000	.575** 0.000	0.254 0.129
well being		.557** 0.000	.555** 0.000	0.309 0.063	.503** 0.002	0.272 0.103
self control			.392* 0.016	0.294 0.078	.401* 0.015	-0.075 0.658
emotionality				.582** 0.000	.423* 0.01	0.265 0.113
sociability					.388* 0.02	0.308 0.064

**. Correlation is significant at the 0.01 level (2-tailed).

*. Correlation is significant at the 0.05 level (2-tailed).

Table 7.1 : Table of correlations between trait emotional intelligence (TEIQue) scores and subscales and dispositional flow in general daily living and music listening

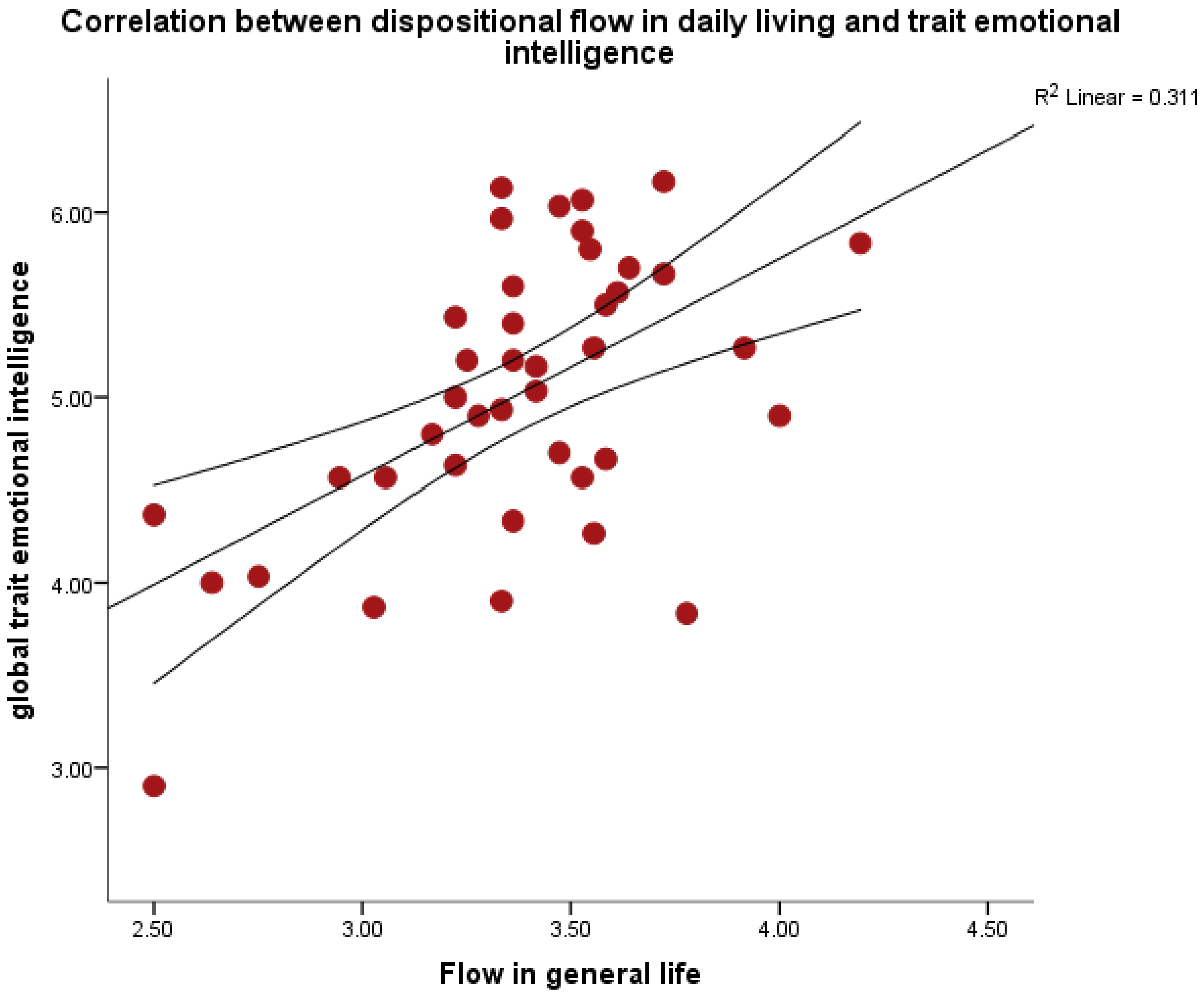


Figure 7.3: Scatterplot of dispositional flow scores for flow in general daily living and trait emotional intelligence (*n* = 37)

Trait emotional intelligence correlates with dispositional flow in daily living ($r = .575$, $p < .001$). In contrast, trait EI does not significantly correlate with flow in active music listening ($r = .254$, $p = .129$).

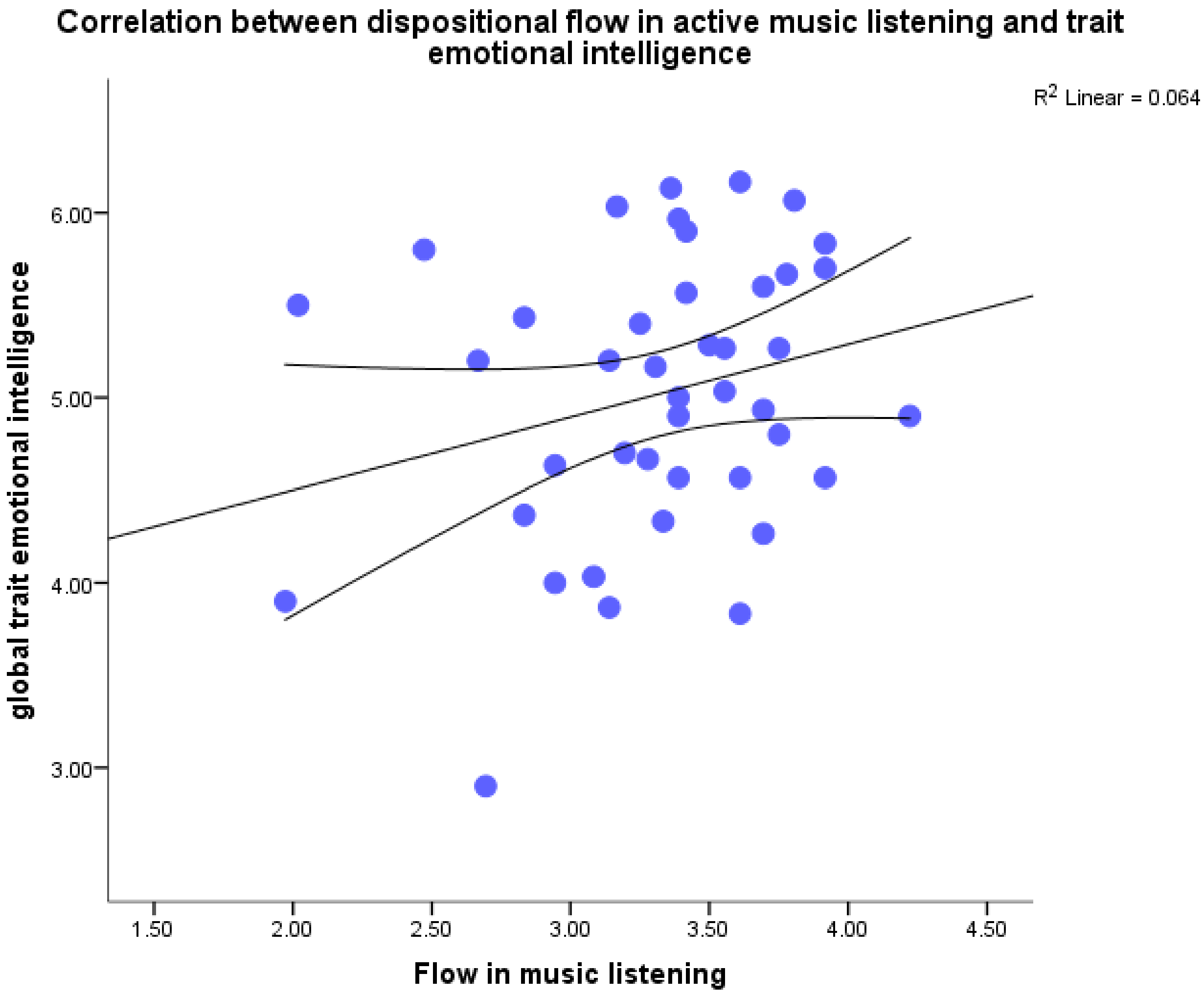


Figure 7.4: Scatterplot for dispositional flow during music listening and trait emotional intelligence (*n* = 37)

7. 1. 4. Interim discussion

We replicated an earlier finding on trait EI and dispositional flow in musicians (Marin & Bhattacharya, 2013). This is significant as it is in a more heterogenous sample of musicians than the expert pianists in Marin and Bhattacharya (2013) sample, both in terms of expertise and instrument.

In summary, the effect of trait EI goes beyond the purpose of processing music as an emotional stimuli. Though it has a moderate correlation with dispositional flow during music performance, it does not correlate with flow during music listening. On the other hand, it correlates with dispositional flow in climbing and daily living, activities that do not have obvious connections to processing music as an emotional stimuli.

It is particularly interesting that trait EI seems to be important for dispositional flow in not only musicians, but other domains. Perhaps it is not surprising as Laborde et al (2011) has linked trait EI to emotional regulation in athletes, finding that they experience less stress in response to competitive stressors (Laborde et al., 2011). As high stress is not conducive to flow (Peifer et al., 2015), being able to cope well with stress would make one more predisposed to experience flow. However, precaution should be taken when interpreting these results as sample sizes for climbing, daily living and music listening are small and more data is needed to confirm these findings, particularly for the finding in climbers. However, these preliminary findings can be used to calculate the power of the effect and predict the sample size needed.

7. 2. Frontal asymmetry, flow experience and trait EI in musicians

7. 2. 1. Introduction

Trait emotional intelligence was found to correlate with dispositional flow in three different domains. Trait EI has been linked to a neural measure known as frontal asymmetry. Frontal asymmetry, a measure of the hemispheric lateralization of frontal cortical activity, has long been associated with affect-related dispositions and behaviour (Harmon-Jones, Gable, & Peterson, 2010). Certain areas of the left prefrontal cortex comprise a circuit that is activated in approach-related behaviour and positive emotions while corresponding areas on the right prefrontal cortex are activated in withdrawal behaviour and negative emotions (Davidson, 1998). Pleasing stimuli elicits a left frontal activation while unpleasant stimuli elicit a right frontal activation (Davidson, 1992). Davidson (1993) has proposed that frontal asymmetry is a stable trait and resting state frontal asymmetry has been shown to predict emotional responses (Davidson, 1993). People with more right frontal asymmetry in resting state gave negative emotion-inducing films larger negative ratings than people with more right resting frontal asymmetry and gave positive emotion-inducing films smaller positive ratings (Tomarken, Davidson, & Henriques, 1990). There is a large body of work linking greater left pre-frontal activity at resting state with more positive biological indicators such as less cortisol (Kalin, Shelton, Rickman, & Davidson, 1998) and better immune function (Rosenkranz et al., 2003) and better recovery from negative events (D. C. Jackson et al., 2003) and higher levels of psychological well-being (Urry et al., 2004). Mood disorders such as depression and anxiety have been found to have correlates with resting frontal asymmetry. Depressed individuals show a higher right frontal activation than left (Allen, Urry, Hitt, & Coan, 2004). Because of its involvement in multiple emotion-related dispositions and behaviours, frontal asymmetry has been proposed to be related to emotional intelligence, a multi-faceted construct involving many aspects of emotion-related information processing. Mikolajczak et al (2010) found that resting state frontal asymmetry indices in the alpha band correlated with trait EI, with higher left frontal activation corresponding to higher trait EI (Mikolajczak, Bodarwé, Laloyaux, Hansenne, & Nelis, 2010). If trait EI correlates with dispositional flow, might dispositional flow also be related to frontal asymmetry?

Flow experience, an experience high in intrinsic motivation, would seem to be more associated with approach motivation and positive affect, rather than withdrawal and negative affect. Also, approach motivation was found to be more conducive to intrinsic motivation (Elliot & Harackiewicz, 1996). Hence, it seems plausible that dispositional flow may correlate with greater left relative frontal activation during resting state.

Only one previous study has related functional asymmetry with flow. Wolf et al (2015) examined frontal asymmetry in elite table tennis players and proposed that greater relative right hemispheric alpha power, i.e. a greater left frontal activation could reflect elevated approach motivation (Wolf et al., 2015).

Frontal asymmetry is often studied in resting state data. Resting-state EEG refers to EEG data collected from participants not actively engaged in sensory or cognitive processing but simply instructed to remain still, with eyes closed or open while fixating on a cross. However, the brain is never idle. Under such conditions, the brain is engaged in spontaneous activity not attributable to specific inputs nor to generation of output, but which is intrinsically generated (Rosazza, 2011) This spontaneous activity has been linked to personality and trait measures. As personality traits are theorized to reflect relatively stable and sustained cognitive and emotive processes, patterns of neural activity reflecting or facilitating these processes may be detectable in resting-state data (Jach, Feuerriegel, & Smillie, 2020). The advantage of looking for a neural correlate of dispositional flow in resting state is that it does not require inducing flow.

Only two previous studies have examined neural features in relation to dispositional flow and both related it to the dopaminergic system. Flow proneness was found to correlate with the availability of dopamine D2-receptors in the striatum (de Manzano et al., 2013) and there was a small correlation between grey matter in the right caudate and flow proneness in everyday life (Kavous et al., 2019). A third study linked trait intrinsic motivation to reduced visual evoked potentials in response to distraction (Hamilton et al., 1984) This study is the first to look at resting state EEG data in relation to dispositional flow.

The sample of musicians discussed in section 1.1.2.2 also provided eyes open and eyes closed resting state data in addition to responding on the questionnaires. Hence, we were able to explore this link between frontal asymmetry, dispositional flow and trait EI. Given Mikolajczak's (2010) finding, we decided to first test if a link between frontal asymmetry and trait EI can be found in our sample of musicians. We hypothesized that frontal asymmetry in musicians would show a similar correlation with trait EI, where higher left frontal activation correlates with higher trait EI. We also hypothesize that frontal asymmetry in musicians may correlate with higher left frontal activation.

The neural correlates of emotional intelligence have been found to differ according to gender, for example, with males showing significant correlations between alpha power measures and emotional intelligence (Craig et al., 2008; Jaušovec & Jaušovec, 2005). Hence the decision was taken to conduct analyses on the male and female subsamples in addition to the total sample. As gender differences in the neural correlates of emotional intelligence have already been found, we feel that it would be logical to expect some difference between males and females in the neural correlates of trait EI in musicians.

7. 2. 2. Methods

7. 2. 2. 1. Design

The study was a correlational design utilising cross-sectional survey methodology and includes a number of survey instruments. The purpose was to correlate trait emotional intelligence scores with frontal asymmetry indices measured from resting state EEG recording. The first part of the study was an attempt to replicate an earlier finding by Mikolajczak et al (2010) in musicians, that trait emotional intelligence is correlated to frontal asymmetry indices. The second part of the study then examines if dispositional flow is correlated with frontal asymmetry indices.

7. 2. 2. 2. Participants

The sample comprised of the 92 amateur and professional musicians (mean age = 24.25 years, *SD* = 4.076 years, 41 males, 51 females) of varying levels of skill and musical involvement described in the earlier study.

Outliers more than 3 standard deviations were removed. For Fp1_Fp2, Participant 8 is removed. For F7_F8, participant 28 is removed. For F3_F4, participant 25 is removed. After removal of outliers, all electrode pairs as well as the mean frontal asymmetry fulfil the assumption of normality as measured by the Kolmogorov-Smirnov test.

7. 2. 2. 3. Materials

Participants responded on the DFS-2 and TEIQUe described above as well as the Gold-MSI as a measure of their musical sophistication.

7. 2. 2. 4. Experimental procedure

EEG data of 5 minutes of eyes closed resting state and 5 minutes of eyes open resting state was recorded. In the eyes open resting state, participants were asked to fixate on a black cross in the middle of a white screen. After the participants finished the EEG session, they were asked to complete the questionnaire.

7. 2. 2. 5. EEG recording and analysis

EEG signals were recorded using 64 active electrodes placed according to the extended 10-20 system of electrode placement and amplified by a BioSemi ActiveTwo amplifier (www.biosemi.com). To monitor eye blinks and horizontal eye movements, vertical and horizontal EOGs were recorded using four additional electrodes. The EEG signals were recorded with a sampling frequency of 512 Hz, band-passed filtered between 0.16 and 100 Hz. The MATLAB toolbox EEGLAB (Delorme & Makeig, 2004) was used for data-processing and FieldTrip (Oostenveld et al., 2011) was used for data analysis and statistical comparisons. Statistical analyses were also conducted in IBM SPSS Statistics, version 24 (IBM Corp, 2016)

7. 2. 2. 6. Preprocessing

The EEG resting state data was re-referenced to the average of the two earlobes. The data was high-passed filtered at 0.5Hz. Eye-blink correction for eyes open data was done using ICA. The data was visually scanned and artifacts deleted.

7. 2. 2. 7. Time-frequency analysis

Eyes closed and eyes opened data was weighted then power analysis was done using Welch's power spectral density estimate for 7 frequency bands, delta (1-4 Hz), theta (4-8 Hz), alpha (8-13 Hz), beta (13-30 Hz), gamma (30–45 Hz). The data was divided into segments of 2 seconds with an overlap of 500 milliseconds.

7. 2. 2. 8. Frontal asymmetry indices

After the data was visually inspected to remove artifacts, the absolute mean spectral power in the standard EEG frequency bands (delta, theta, alpha, beta and gamma) was extracted from the resting state eyes-open and eyes-closed EEG data using Welch's power spectral density estimate. An asymmetry index for each frequency band was calculated by subtracting the log power of the left electrode from the log power of the corresponding right electrode (ie. log[right]-log[left]) and then averaging over 5 electrode pairs. The electrode pairs of interest were frontal electrodes Fp1-Fp2, F7-F8, F3-F4, FC5-FC6, FC1-FC2, which correspond to regions commonly studied in frontal asymmetry literature (Davidson, 2004; Mikolajczak et al., 2010). The calculation of the asymmetry index helps to control for the individual differences in skull thickness and voltage spread. A mean frontal asymmetry index was calculated by averaging across the 5 electrode pairs. Possible relationships between frontal asymmetry indices and gathered behavioural data were investigated by using Pearson's correlation where the data fulfilled assumptions of normality and Spearman-Rho correlations were used where the data did not fulfil assumptions of normality based on the Kolmogorov-Smirnov test.

7. 2. 2. 9. Individual alpha frequency

Individual alpha frequency was calculated by taking the peak alpha frequency as the frequency that is most depressed by the opening of the eyes (Klimesch, 1999). The peak frequency in the eyes closed condition was determined as the highest peak in the window between 7 and 14 Hz. To find the frequency that was most depressed by the opening of the eyes, the eyes open spectrum was subtracted from the eyes closed spectrum and the peak frequency of the resulting spectrum was taken as the peak alpha frequency. If the two methods gave different results, the peak frequency in the EC condition was taken. Individual alpha frequency band was taken to be 2 Hz above and below the peak alpha frequency, with the peak alpha frequency dividing the alpha frequency band individually into lower and upper alpha. Power analysis was calculated for the individual lower and upper alpha frequency bands. Frontal asymmetry indices were again calculated for the individual alpha bands.

7. 2. 2. 10. Statistical analysis

All correlations were set at two-tailed, at an alpha level of .05. Where the specified hypothesis was tested, Bonferroni corrections were applied to control for inflated risk of type I error. When exploratory analyses were conducted, corrections were not applied. Statistical analyses were conducted in IBM SPSS Statistics version 22 (SPSS Inc., Chicago, IL, USA) and in Matlab R2013b (The MathWorks, Inc., Natick, Massachusetts, USA).

7. 2. 3. Results

7. 2. 3. 1. Correlations between frontal alpha asymmetry and global trait intelligence and its subscales

No correlations were found between frontal alpha asymmetry and global trait intelligence and its subscales. In case examining asymmetries in the standard broad alpha band might have been too imprecise, a frontal alpha asymmetry index was also calculated based on participants' individual alpha frequency (IAF). No correlations were found in alpha asymmetries based on the IAF either.

Summary of correlations for trait EI and frontal asymmetry indices (n = 92)

		global trait emotional intelligence	well-being	self-control	emotionality	sociability
Frontal alpha (8-13Hz) asymmetry index	Pearson Correlation	-0.120	-0.012	-0.137	-0.106	-0.041
	Sig. (2-tailed)	0.255	0.910	0.194	0.315	0.699

**. Correlation is significant at the 0.01 level (2-tailed).

*. Correlation is significant at the 0.05 level (2-tailed).

Table 7.2: Correlations between trait EI, its subscales and frontal alpha asymmetry

Summary of correlations for trait EI and frontal asymmetry indices based on individual alpha frequency (IAF) (n = 92)

		lower alpha (IAF-2)	upper alpha (IAF+2)	broad alpha (IAF+-2)
global trait emotional intelligence	Pearson Correlation	-0.107	-0.086	-0.116
	Sig. (2-tailed)	0.309	0.412	0.271

*. Correlation is significant at the 0.05 level (2-tailed).
**. Correlation is significant at the 0.01 level (2-tailed).

Table 7.3: Correlations between trait EI and frontal alpha asymmetry indices based on individual alpha frequency

7. 2. 3. 2. Correlations between global trait EI and subscales and frontal asymmetry indices in other frequency bands

Exploratory analyses were extended to frontal asymmetries in other frequency bands.

Summary of correlations for trait EI and frontal asymmetry indices (n = 92)

		delta (1-4Hz)	theta (4-8Hz)	alpha (8-13Hz)	beta (13-30Hz)	gamma (30-45Hz)
global trait emotional intelligence	Pearson Correlation	-0.132	-0.163	-0.120	-.237*	-0.184
	Sig. (2-tailed)	0.210	0.120	0.255	0.023	0.079

*. Correlation is significant at the 0.05 level (2-tailed).

**. Correlation is significant at the 0.01 level (2-tailed).

Table 7.4: Correlations between trait EI and frontal asymmetry in classic frequency bands

There was a significant moderate inverse correlation between frontal asymmetry indices in the beta band and global trait EI scores (*r* = -.237, *p* = .023, power = 0.744).

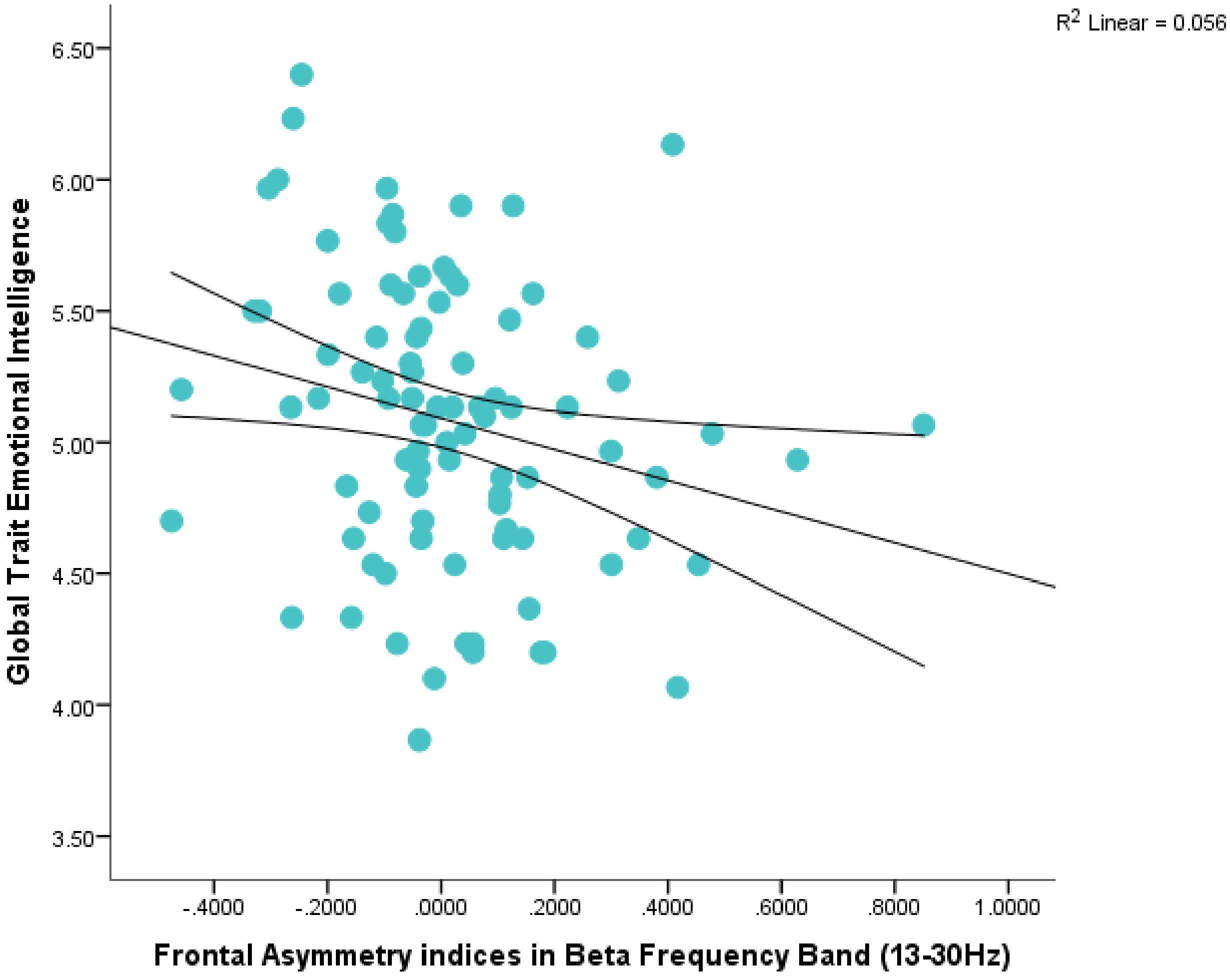
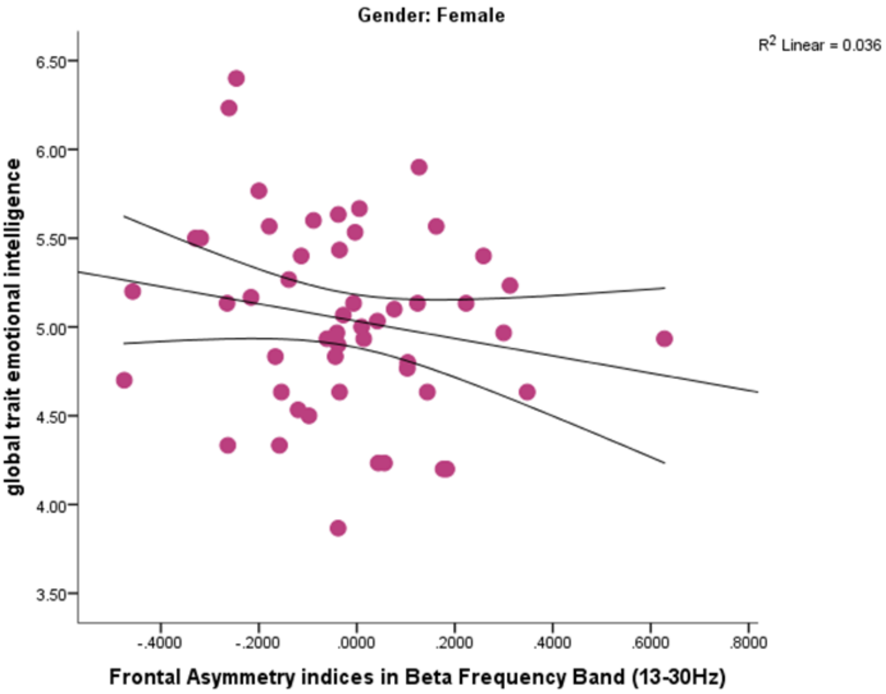


Figure 7.5: Scatterplot for frontal asymmetry indices in beta (13-30 Hz)frequency band and trait EI scores

7. 2. 3. 3. Correlations when split by gender

As previous studies have found gender differences in the neural correlates of emotional intelligence, we decided to take a closer look at the correlation between beta band frontal asymmetry indices and global trait EI, Pearson's correlations were conducted between global trait EI scores and frontal asymmetry indices in the beta band, with the results separated by gender. It was found that the significant moderate inverse correlation between beta band asymmetry indices and global trait EI scores was only found in the males when correlations were done by gender. Males showed a significant high inverse correlation between beta band asymmetry indices and reported global trait EI scores (*r* = -.333, *p* = .003). Females showed an insignificant correlation between beta band asymmetry indices and global trait EI scores (*r* = -.191, *p* = .180).

Global trait EI scores were not significantly different between males and females (*t*(46) = -.319, *p* = .751). Neither were any of its subscales. An independent samples t-test was also conducted with gender as an independent factor and the frontal asymmetry indices as dependent factors. Frontal asymmetry indices were not significantly different across gender.



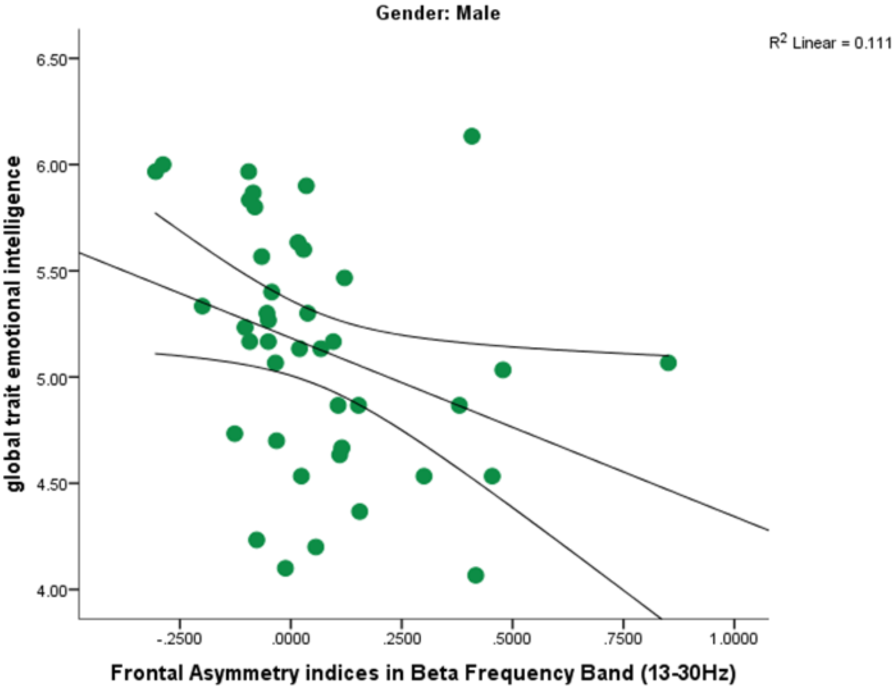


Figure 7.6 Scatterplots of frontal beta asymmetry indices and trait EI by gender

7. 2. 3. 4. Correlations between frontal asymmetry and dispositional flow and its subscales

Correlations were then conducted on dispositional flow and frontal asymmetry indices. Despite trait emotional intelligence positively correlating with dispositional flow in musicians (r = .256, p = .015), no frontal asymmetry indices was found to correlate with dispositional flow.

Summary of correlations for dispositional flow and frontal asymmetry indices (n = 89)

		delta (1-4Hz)	theta (4-8Hz)	alpha (8-13Hz)	beta (13-30Hz)	gamma (30-45Hz)
Dispositional flow (DFS-2)	Pearson Correlation	-0.081	-0.043	-0.107	0.064	0.133
	Sig. (2-tailed)	0.450	0.692	0.317	0.552	0.215

**. Correlation is significant at the 0.01 level (2-tailed).

*. Correlation is significant at the 0.05 level (2-tailed).

Table 7.5: Correlations between dispositional flow and frontal asymmetry indices

Summary of correlations for dispositional flow and frontal asymmetry indices based on individual alpha frequency (IAF) (n = 89)

		lower alpha (IAF-2)	upper alpha (IAF+2)	broad alpha (IAF+-2)
Dispositional flow (DFS-2)	Pearson Correlation	-0.126	-0.073	-0.114
	Sig. (2-tailed)	0.238	0.498	0.287

*. Correlation is significant at the 0.05 level (2-tailed).
**. Correlation is significant at the 0.01 level (2-tailed).

Table 7.6: Correlations between dispositional flow and IAF-based frontal alpha asymmetries

To check if this also applied outside dispositional flow in music performance, the same frontal asymmetry analysis was also run on eyes open and eyes closed resting state data collected from the participants in the experiment on active music listening (also described in section 1.1.2.2). However, no correlations with frontal asymmetry were found for either dispositional flow in general daily living or dispositional flow in active music listening.

Summary of correlations for dispositional flow in general daily living and music listening and frontal asymmetry indices (n = 37)

		delta (1-4Hz)	theta (4-8Hz)	alpha (8-13Hz)	beta (13-30Hz)	gamma (30-45Hz)
Flow in general life	Pearson Correlation	-0.219	-0.196	-0.041	-0.231	-0.254
	Sig. (2-tailed)	0.199	0.253	0.812	0.176	0.135
Flow in music listening	Pearson Correlation	-0.041	0.008	0.054	-0.036	-0.113
	Sig. (2-tailed)	0.810	0.963	0.751	0.830	0.505

*. Correlation is significant at the 0.05 level (2-tailed).

**. Correlation is significant at the 0.01 level (2-tailed).

Table 7.7: Correlations between flow in general daily living, active music listening and frontal asymmetry indices in classic frequency bands

7. 2. 4. Interim discussion

Though trait EI correlated with flow, and a correlation between trait EI and frontal asymmetry in the beta band was found, no correlation was found between frontal asymmetry and flow experience. Frontal asymmetry at resting state thus, does not seem to be a good neural correlate of dispositional flow.

7. 2. 5. Frontal asymmetry after playing

It is possible that state asymmetry, that is, frontal asymmetry measured during a relevant task, may be as stronger correlate of personality traits than trait asymmetry (Coan, Allen, & McKnight, 2006). Larger correlations with frontal asymmetry have been found when specific emotions like anger, fear and anxiety were induced (Stemmler & Wacker, 2010). Perhaps the main reason why no frontal asymmetry associations with flow were found was due to the fact that trait asymmetry does not reflect dispositional flow. The only previous study relating functional asymmetry with flow examined functional asymmetry during a task (imagining responding to a serve in table tennis) (Wolf et al., 2015). Wolf et al (2015) found a shift towards relative right- temporal brain activity cortex at the beginning of motor execution that positively correlated with experienced flow in elite table tennis players. However, amateurs showed a shift to left temporal brain activity instead. Expertise then, may moderate the relationship between frontal asymmetry and flow.

Since Wolf found expertise-related effects in frontal asymmetry linked with flow, it was decided to examine frontal asymmetry in the eyes closed resting state immediately after playing. Perhaps the motivation effects of flow on frontal asymmetry are larger after a relevant flow-inducing activity. It is hypothesised that immediately after a rewarding activity, frontal asymmetries should reflect an approach motivation and that this could be influenced by expertise, dispositional flow or trait EI.

7. 2. 5. 1. Methods

Frontal asymmetry was calculated from the data collected from the experiments described in chapters 2 and 3. For the first experiment, participants' resting state post playing was averaged across conditions to form frontal asymmetry after playing a flow-inducing piece and after playing a non-flow inducing piece. For the second experiment, as there were two non-flow conditions, the decision was made to take the session with the highest flow score as a flow condition and the session with the lowest flow score as the non-flow condition. Participants had also responded on the Goldsmiths Musical Sophistication Index (Gold-MSI), an instrument for assessing self-reported musical skills and behaviours ranging from no training to professional level (Müllensiefen et al., 2014). A median split was conducted on the Gold-MSI scores to form a 'high expertise' group and a 'low expertise group'. The same was done for trait EI and dispositional flow scores.

7. 2. 5. 2. Results

Musical sophistication was found to be significantly associated with frontal asymmetry in the upper alpha band (10-12 Hz) after music performance (*F*(1, 86) = 6.867, *p* = .010). This was not found in resting state data, where musical sophistication did not significantly correlate with frontal asymmetry indices (r = -.015, *p* = .888). Trait EI and dispositional flow however, were not associated with frontal asymmetry immediately after musical performance. (Trait EI: (*F*(1, 86) = .450, *p* = .504; Dispositional Flow: (*F*(1, 84) = .117, *p* = .733).

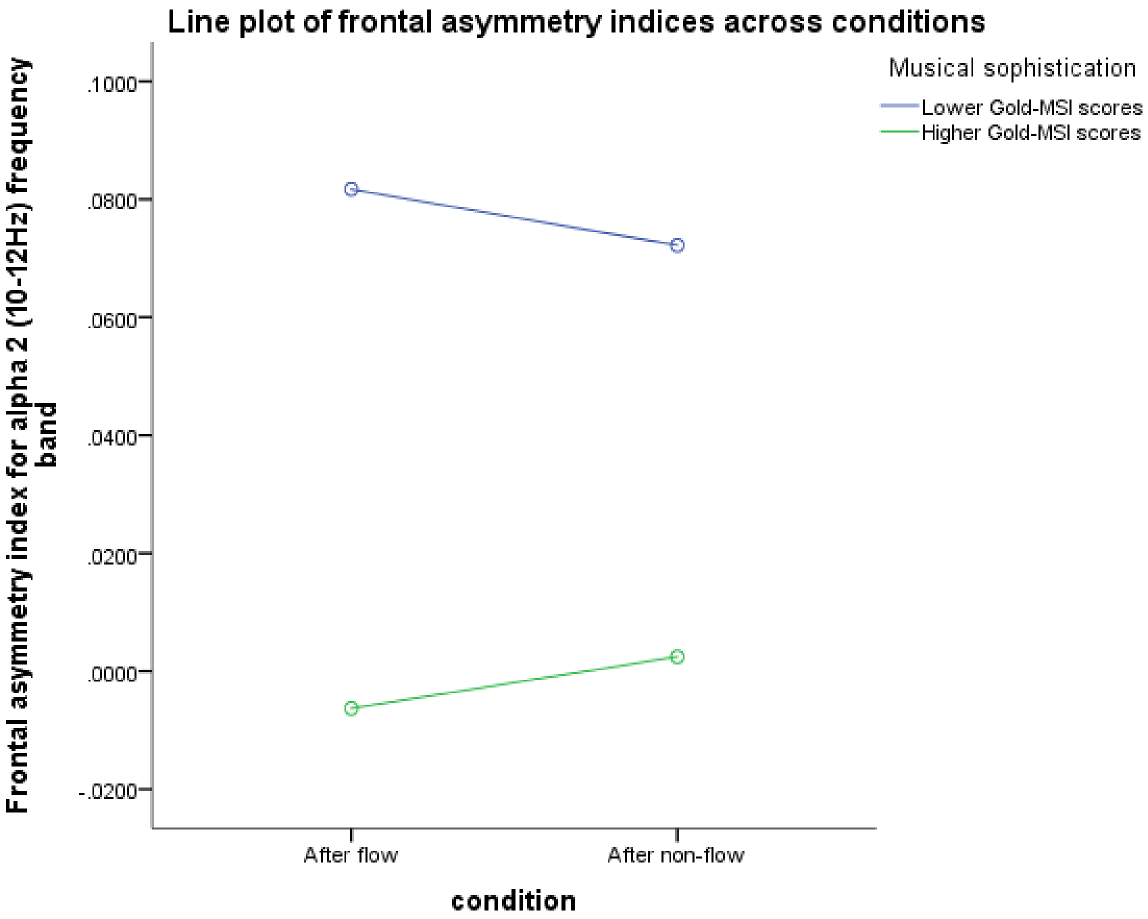


Figure 7.7: Line plot of frontal upper alpha asymmetry indices (10-12Hz) across conditions. Higher expertise resulted in a lower alpha asymmetry index, which reflects increased right frontal activity.

Though dispositional flow did not affect frontal asymmetry during playing, it does suggest that frontal asymmetry is more affected with a task than looked for in resting state data. It is also noteworthy that frontal alpha asymmetry is affected by expertise.

7. 2. 6. General Discussion

Trait EI was found to correlate with dispositional flow across a variety of activities. This is significant as it has only been related to dispositional flow in musicians before and it was unclear if it was because greater trait EI made them better at engaging with music as emotional stimuli or if emotional intelligence made one better in general at experiencing flow. That trait EI correlates with dispositional flow in climbing and daily living suggests the latter. This is perhaps unsurprising as climbers also need to manage their emotions to cope with the risk of being up on the rock.

The findings of Mikolajczak et al (2010) were not replicated in this study. Thus, we can conclude that the correlation between frontal alpha asymmetry and trait EI cannot be generalised to musicians. Whether the difference is due to musical training is difficult to clarify. Studies so far have focused on state frontal asymmetry in music-induced emotions rather than resting frontal asymmetry. Even fewer have examined the frontal asymmetry difference between musicians and non-musicians. One such study has shown that musical sophistication may result in different frontal asymmetry activity in musicians compared to non-musicians but only during the performance of a musical task (Davidson & Schwartz, 1977). However, the musician participants in this study had much lower frontal asymmetries compared to Mikolajczak et al (2010) so it is plausible to conclude that musicians may have less asymmetrical resting frontal alpha activity in general and this may have affected the correlation. Other possible reasons include a possible opaque average trend. Mikolajczak et al (2010) had preselected participants for two extremes to avoid this problem. However, after selecting the participants in this study for the two extremes (the top 30% and the bottom 30%), no significant results were found. No significant results were found when this was done for dispositional flow as well.

However, a significant correlation was found in beta band asymmetry. Beta band asymmetry was inversely correlated with trait EI and thus reached the same conclusion that higher left frontal activation correlates to higher trait emotional intelligence scores. Results in the beta band have not been explored in the trait EI research but there have been studies in other areas of emotion research where results have been found in the beta band rather than alpha band. Results in the beta band show the same affect-related cortical lateralisation found in alpha band. Pizzagalli et al (2002) found increased relative right frontal hyperactivity in the beta band in depressed participants and a significant positive correlation between right frontal beta asymmetry and severity of depression (Pizzagalli et al., 2002). Schutter et al (2008) found that frontal asymmetry results in the beta band were positively correlated with hemispheric asymmetries in cortical excitability and inversely correlated with approach-withdrawal motivation predispositions, ie. greater left activation is associated with higher approach motivational tendency (Schutter, De Weijer, Meuwese, Morgan, & Van Honk, 2008). It seems that beta band frontal asymmetry indices also reflect the frontal asymmetry model of emotion, right being associated with negative and avoidance-related emotions and left being associated with positive and approach-related emotions. Hence, it seems plausible to conclude that though musicians do not demonstrate the alpha frontal asymmetry correlation with trait EI, they do reflect the association between relatively higher left frontal activation and higher trait EI scores.

Another significant finding was the gender-specific effect in the relationship between trait EI and frontal asymmetry indices. The significant correlation between trait EI and beta band frontal asymmetry was found to be mainly contributed by males. Males showed a negative correlation between trait EI and frontal asymmetry indices while the same correlation was insignificant for females. This is unsurprising as the correlations between emotional intelligence and various measures of cortical activity have been shown to differ according to gender in previous studies (Craig et al., 2008; Jaušovec & Jaušovec, 2005). However, the earlier studies were done using measures of EI based on the ability model. This result shows that there are also gender differences in the neural correlates of trait EI. Interestingly, Jaušovec and Jaušovec (2002) also reported more significant correlations for males than females which was what was found in this study as well. However, it is also possible that the differences between the genders indicate an influence of musical training on trait EI that is specific to males. The effects of trait EI in musicians have also been shown to have gender differences. A significant correlation between the self-control aspect of trait EI and the amount of musical training was only found in males (Petrides, Niven, & Mouskounti, 2006). It is possible that this particular measure of trait EI may be more sensitive to the training effects of music in males. However, the correlations were not significantly different between gender hence, without more research, it is not possible to make any categorical conclusions about the effect of gender on trait EI and frontal asymmetry.

However, despite a significant correlation between dispositional flow and trait EI, and frontal asymmetries in the beta band correlating with trait EI, no frontal asymmetries in any frequency band correlated with dispositional flow scores. This may be due to the lack of an active task. Emotional effects are stronger with a relevant task. At resting state, perhaps there is not enough of a difference to relate to the tendency to experience flow during music. Flow is not often examined in resting state, being such an active activity. Indeed, when frontal asymmetries were examined immediately after playing, even though no neural correlates with dispositional flow was found, a relationship with musical sophistication, a measure of expertise, was found. Wolf et al (2015) did not find any effect of expertise on frontal asymmetry. However, this study unexpectedly found that participants with a lower musical sophistication score had higher left frontal activity. If this reflects approach motivation and positive feelings in response to playing music, it may be that less expert musicians were enjoying themselves more while playing in the lab than more expert musicians.

However, Wolf et al (2015) linked the shift to the right hemisphere to expertise and automaticity in elite table tennis players. It could be that the lower frontal asymmetry scores reflect increased right-hemisphere activity in more musically sophisticated musicians that is also linked to expertise and automaticity. However, they looked at temporal asymmetry in the table tennis players. Future experiments should also examine alpha asymmetry at the temporal cortex to answer this question.

Possible future analyses could be done using functional connectivity rather than asymmetry indices. The findings by Huskey et al (2018 and Ulrich et al (2016) suggest that more significant findings may be found if we focus on networks, eg. resting state networks like relating activity of the default mode network in resting state with dispositional flow (Huskey, Wilcox, et al., 2018; Ulrich et al., 2016c).

This series of studies looked at the possibility of studying the neural correlates of flow in resting state data, specifically using the frontal asymmetry index, which has been linked to motivation, which is strongly linked with flow. That no significant results related to dispositional flow was found in resting state data suggests that resting state data and dispositional flow may be less effective than studying neural activity during flow inducing activities. Future studies relating frontal asymmetry to flow may wish to focus on state asymmetry during an activity than trait asymmetry in resting state data.

Chapter 8 Inducing flow with monaural beats

8. 1. Introduction

The previous studies have explored ways to study flow by measuring state flow and neural activity during flow-inducing activities and by correlating resting state data with dispositional flow. A final way to study flow in the brain, is by modulating neural activity to influence flow experience. Not only is this of practical interest as a possible technique of increasing our experience of flow, but modulating neural activity associated with flow is crucial to test for their causality. This study experiments with using monaural beats to induce flow in music listening.

Two previous experiments have utilised brain stimulation techniques to increase flow experience and test neural features previously related to flow. Ulrich (2017) further tested the hypothesis that the medial prefrontal cortex (MPFC) plays a causal role in mediating flow experience using transcranial direct current stimulation (tDCS) to interfere with MPFC's deactivation evoked by a flow paradigm (Ulrich et al., 2018). Targeting the left prefrontal area, Gold and Ciorcari (2019) investigated whether cathodal transcranial direct current stimulation (tDCS) over the left dorsolateral prefrontal cortex (DLPFC) area and anodal tDCS over the right parietal cortex area during video game play will promote an increased experience of flow states. Compared to sham stimulation, real stimulation increased flow experience for both untrained and trained Tetris players in a first-person shooter game. Improved performance effects were only seen with untrained participants (Gold & Ciorciari, 2019).This study is the first to experiment with using auditory brain stimulation to induce neural activity favourable to flow experience.

8. 1. 1. Auditory beat stimulation (ABS)

Auditory stimulation with monaural or binaural auditory beats represents a promising new approach to influence electrical brain activity and target cognition in a reversible, non-invasive way. When two sine wave tones at slightly differing frequencies are presented, the listener perceives a beating frequency corresponding to the difference between the two frequencies. As the two frequencies come in and out of phase with each other, this phase interference produces a pulsating sound. Monaural beats are heard when a composite auditory stimulus is presented to both ears simultaneously, which is detected by the cochlear and relayed to the brain stem and auditory cortex, while in binaural beats, the beat is a subjectively perceived auditory illusion resulting from different frequencies presented to left and right ear respectively. A central assumption of auditory beat stimulation is that they can elicit an entrainment effect in the electrocortical activity of the brain, observable as an auditory steady state response (ASSR) with neural oscillations synchronising to the frequency of a repetitive acoustic stimulus that continually persists over a period of time (Gao et al., 2014).Indeed, binaural and monaural beats are found to readily entrain the cortex to specific frequencies (Draganova, Ross, Wollbrink, & Pantev, 2008; Ioannou, Pereda, Lindsen, & Bhattacharya, 2015; Nozaradan, Schönwiesner, Caron-Desrochers, & Lehmann, 2016). Monaural beats are often found to be more effective than binaural beats in entraining the cortex, with more pronounced cortical responses to monaural beat stimuli at various beat frequencies applied (Orozco Perez, Dumas, & Lehmann, 2020; Schwarz & Taylor, 2005). The differing cortical responses to beats are thought to influence cognition, mood and other aspects of subjective experience.

Auditory beat stimulation has been studied in relation to attentional processes, anxiety and mood, and cognition. Reedijk, Bolders, Colzato, and Hommel (2015) have shown that binaural beats affect how people control and monitor their visual attention. Participants listened to binaural beats while performing an attentional blink task, which assesses the efficiency of allocating attention over time. In participants with low striatal dopamine, the size of the attentional blink was considerably reduced by the binaural beats (Reedijk, Bolders, Colzato, & Hommel, 2015). Gamma (40 Hz) binaural beats bias individuals towards a narrower focus of attention (Colzato, Barone, Sellaro, & Hommel, 2017). Beta frequency stimulation for 30 minutes improved performance in a vigilance task, which assesses the ability to maintain a constant focus of attention and alertness to stimuli over long periods of time (Lane, Kasian, Owens, & Marsh, 1998). Findings from a pilot study also tentatively suggest that application of 5 Hz monaural beats may lead to a reduction in levels of mind wandering in subjects who show a greater tendency towards mind wandering (Chaieb, Derner, Leszczyński, & Fell, 2020).

Auditory beat stimulation have also been studied in relation to meditation practice, which shares with flow the concept of control of attention. Studies looking at the effect of facilitative binaural beats frequencies on meditation practice reported significant entrainment effects. Application of binaural beats at a theta frequency (7Hz) increased left temporal lobe delta power in experienced meditators, but not in the novice participant group, suggesting that experience may play a role in the effects of binaural beat stimulation (Lavallee, Koren, & Persinger, 2011). Application of a 6Hz beat for 30 minutes increased frontal midline theta and general theta power over frontal and parietal-central regions in an experimental group compared to a control group (Jirakittayakorn & Wongsawat, 2017). Participants in the experimental group also reported experiencing less tension. The authors interpret it as binaural beats in the theta band induce neural activity similar to a meditative state as increased theta power has been associated with proficiency in meditative technique and experiencing a meditative state (Aftanas 2001,2005).

Previous research also suggests that alpha and delta binaural beats reduce anxiety levels (Padmanabhan et al., 2005; Wahbeh et al., 2007a; Weiland et al., 2011).Monaural beat stimulation were also found to reduce state anxiety in healthy participants (Chaieb, Wilpert, Hoppe, Axmacher, & Fell, 2017)and since anxiety is antithetical to flow (Csikzentmihalyi, 1990), reducing anxiety may be one way monaural beat stimulation can facilitate flow.

Moreover, alpha (10 Hz) and gamma (40 Hz) frequency binaural beats have been found to affect creativity (Reedijk, Bolders, & Hommel, 2013) and cognitive flexibility (Hommel, Sellaro, Fischer, Borg, & Colzato, 2016). The studied impact of auditory beat stimulation on attention and mood as well as its possible effects on meditation and creativity suggest that it might have a beneficial impact on flow experience.

The studies described in chapters 2 and 3 have found higher alpha and theta power in flow experience in musicians. Although correlative EEG data can suggest that these brain oscillations subserve various sensory and cognitive processes related to flow, a causal role can only be demonstrated by directly modulating such oscillatory signals (Herrmann, Strüber, Helfrich, & Engel, 2016). As studies by Katahira et al (2016) and Nunez Castellar et al (2019) have also implicated alpha and theta activity in experimentally-induced flow states, monaural beats designed to modulate activity in these frequency bands seemed appropriate to test these findings. Gao et al (2014) observed increases of relative power in theta and alpha bands and decrease in beta band during delta and alpha binaural beat stimulations (Gao et al., 2014). One study found that exposure to a 6-Hz binaural beat for 30minutes resulted in widespread theta activity within 10 minutes of exposure (Jirakittayakorn & Wongsawat, 2017). However, an intracranial EEG study found decreases of theta power due to stimulation with monaural 5 Hz beats, but found enhancements of alpha phase synchronization related to application of monaural 10 Hz beats (Becher et al., 2015).It is possible that the lack of a theta response is due to a much shorter stimulation time (5 seconds) in Becher et al (2015). Thus, it seems plausible that sufficiently long exposure to monaural beats at delta, theta and alpha frequencies could lead to increase in neural activity in these frequency bands, which have been previously linked to increased flow experience. If they play a causal role in our experience of flow, entraining the brain to increase neural activity in these frequencies should result in more frequent or more intense flow experiences.

8. 1. 2. Flow in music listening

To avoid interference of neural activity associated with a second task, the decision was made to test the effect of monaural beats in influencing flow in music listening, specifically, listening to the music the monaural beats in this study were embedded in. Compared to flow in music performance and music composition, much less work has been done in flow in music listening (Chirico et al., 2015). However, this may be a consequential oversight by flow researchers as a survey of expert pianists found that they experienced significantly more flow states during music listening than during performance (Marin & Bhattacharya, 2013). Csikszentmihalyi (1990) noted the potential for focused and deliberate music listening to induce a flow state, writing that

> *"Music, which is organized auditory information, helps organize the mind that attends to it, and therefore reduces psychic entropy, or the disorder we experience when random information interferes with goals. Listening to music wards off boredom and anxiety, and when seriously attended to, it can induce flow experiences. (p. 109)"*

Music listening has been recognised to result in altered states and strong emotional experiences (Lamont, 2011). Interviewing students about their strong experiences with music, Lamont (2011) found descriptions reminiscent of flow, particularly in terms of the high engagement and loss of attention to surroundings. Participants typically referred to “being lost in the music”, focusing on the musical experience to the exclusion of everything else.

However, if, like other activities, a balance between challenge and skill is the antecedent to experiencing flow, what would challenge and skill refer to in the context of music listening? 'Skill' may be characterized as skills in attention or discrimination, and 'challenges' with the likelihood that a particular stimulus might be interesting enough to warrant an adequate level of engagement (Diaz, 2013). Weber et al posit that linear media, like books, films and video games require mastery of mental models: video games require a level of skill that increases as one progresses, and films require an understanding of the characters and the narrative (Weber et al., 2009). It is suggested that these contribute the challenge, which in addition to pleasurable engagement, coincides with activations of the brain regions necessary to achieve flow. Music too, may pose a challenge by requiring listeners to draw on mental models. Building on this concept, Ruth et al (2017) found that, depending on the musical skill or listening modes of the recipients, the complexity of the music radio programs could be associated with higher or lower flow experiences, which in turn had an influence on positive listener appraisal. The complexity of the music had a positive effect on liking via flow experience for participants who were highly musically skilled, but a negative effect for participants who had low musical skill. There was also a negative effect of complexity on liking via flow for listeners who preferred to move, sing or dance to music, rather than listen with an analytical evaluative attitude. It was suggested that younger nonanalytic recipients listening to a complex music program experience less flow because they are over-challenged and feel no enjoyment in analysing a musically challenging radio program (Ruth, Spangardt, & Schramm, 2017).

Other than Ruth (2017), to the best of our knowledge, only one other study has investigated flow in music listening. Diaz (2013) investigated the effects of a brief mindfulness meditation induction technique on perceived attention, aesthetic response, and flow during music listening. Verbal responses from participants indicate that they experienced decreased mental distraction, increased awareness of musical characteristics, and improvements in focus. It is suggested that engaging in mindfulness prior to music listening might enhance attentional skills, and thus affect the overall response characteristics of flow or other heightened affective experiences (Diaz, 2013)DD. Given that auditory beat stimulation has been found to have positive effects on focused attention, it could also, like mindfulness, be facilitative of flow in music listening.

This experiment aims to investigate the impact of monaural beats embedded in music on behavioural, neural and autonomic responses in healthy human adults. During the experiment, behavioural (subjective ratings and self-reported measures), brain (high density EEG signals) and cardiac (ECG signal) responses were recorded from healthy human adult participants (*N* = 37) while they were listening to musical excerpts with delta-theta (1-6.5 Hz) monaural beats, with alpha (8-12 Hz) monoaural beats, and to musical excerpts without any beats as a control. We examine if behavioural, neural and autonomic responses differ between the three conditions to see if monaural beats induced changes in neural oscillations which resulted in increased flow experience during the task.

8. 2. Materials and Methods

8. 2. 1. Participants

Thirty-seven healthy adults (24 females, age range of 20 years to 40 years, mean ± s.d. age: 27.43 ± 4.75 years) participated in this experiment. All participants were neurologically healthy, had self-reported normal hearing and normal or corrected to normal vision. They gave their written informed consent before the start of the experiment. The experimental protocol was approved by the Local Ethics Committee of the Department of Psychology at Goldsmiths, University of London, and the experiment was conducted in accordance with the Declaration of Helsinki. All participants received a fixed incentive for taking part in the study.

8. 2. 2. Materials

All participants completed a set of questionnaires before the start of the experiment as follows:

(i) Goldsmiths' Musical Sophistication Index (Gold-MSI) to validate participant's self-reported musicality (Müllensiefen et al., 2014),

(ii) Depression Anxiety Scale short version (DASS-21; Lovibond & Lovibond, 1995) to evaluate trait anxiety and also to evaluate whether beat related effects depend on the presence of absence of symptoms of depression and anxiety,

(iii) modified Dalbert Emotions Scale (modified DES; Dalbert, 1992) to evaluate mood states (both positive and negative),

(iv) State-Trait Anxiety Inventory (Spielberger, 1983) to evaluate anxiety levels and to discriminate the participants' trait anxiety (STAI-T) from the state anxiety (STAI-S), i.e. between a general anxiety level from the current anxiety level,

(v) Sleep Condition Indicator (Espie et al., 2014) to estimate the degree of sleep insomnia,

(vi) Pittsburgh Sleep Quality Index, PSQI (Buysse, Reynolds, Monk, Berman, & Kupfer, 1989) to provide an estimate of the quality of the sleep,

(vii) short version of Big-Five Personality measure (TIPI) (Gosling et al., 2003).

After each block, participants answer the following questionnaires:

(i) short 9-item version of the Flow State Scale (FSS-2) to measure if there are beat-related effects on the experience of the 9 dimensions of flow during music listening (S. A. Jackson & Eklund, 2004),

(ii) Depression Anxiety Scale short version (DASS-21; Lovibond & Lovibond, 1995) to evaluate trait anxiety and also to evaluate whether beat related effects depend on the presence of absence of symptoms of depression and anxiety,

(iii) modified Dalbert Emotions Scale (modified DES; Dalbert, 1992) to evaluate mood states (both positive and negative)

8. 2. 3. Beat Stimuli

The musical excerpts were created by Jukedeck. In brief, the process started with the creation of what was internally referred to as a “style”. This describes a collection of virtual instrument patches, FX chains, audio routing architectures, and a bank of settings which dictate the way various parts of our system work together to create a piece of music. These systems included the composition engine (which composes melodies, harmonies, rhythms, accompaniments, etc.), the arrangement creator (which decides on the overall contour of the piece, and arranges the musical material across parts and over time), and the production engine (which selects palettes of sounds and banks of processing, and renders all the audio). For this project, a specially modified style was created which contained a software synthesiser whose two oscillators were controlled by a purpose-written script. This script took the input from an exposed “hook” into the style, and precisely tuned the two oscillators to produce a monaural beat with the desired beat frequency and carrier frequency. This approach allowed us to reproduce the same track across multiple beat frequencies. With this style, a large batch of tracks was generated, from which we selected a subset of musical excerpts. From this point, a suite of scripts (custom built for this project) were executed which generated the final batch of tracks, from our selections, taking advantage of the specially created “hooks” into the style which allow us to manipulate beat frequency, beat volume and BPM. We have three groups of musical excerpts: (i) musical excerpts with delta/theta monoaural beat, (ii) musical excerpts with alpha monoaural beat, and (iii) musical excerpts without any beat. Table 1 lists the properties of the selected excerpts.

Monoaural Beat Condition	Beat Frequency (Hz)	Tempo (BPM)	Carrier Frequency (Hz)
Delta/Theta	1	64.56	246.94 – 329.63
	1.5	63.64	220 – 246.94
	3	64.68	233.08 – 349.23
	4	64.56	246.94 – 277.18
	5	62.86	277.18 – 311.13
	5.5	63.23	233.08 – 349.23
	6	63.59	207.65 – 277.18
	6.5	63.95	329.63 – 392
Alpha	8.5	64.17	246.94 – 293.66
	9	65.36	277.18 – 311.13
	9.5	65.73	233.08 – 349.23
	10	64.18	207.65 – 277.18
	10.5	63.92	233.08 – 277.18
	11	66.82	233.08 – 277.18
	11.5	66.01	233.08 – 277.18
	12	67.55	277.18 – 369.99
No Beat	-	64.17	246.94 – 293.66
	-	65.36	277.18 – 311.13
	-	63.64	220 – 246.94
	-	61.09	207.65 – 277.18
	-	63.92	233.08 – 277.18
	-	66.82	261.63 – 392
	-	66.01	233.08 – 277.18
	-	67.55	

Table 8.1: Musical stimuli belonging to three conditions (i) delta/theta monoaural beat, (ii) alpha monoaural beat, and (iii) no beat. For each condition, there are eight musical excerpts and each excerpt has a duration of approximately 3:30 min.

8. 2. 4. Experimental Procedure

All experimental recording sessions were performed in a quiet room. Before the experiment began, participants provided written informed consent. Subsequently the EEG cap and electrodes were placed, and during this period, participants completed a set of questionnaire (Gold-MSI, DASS-21, modified DAS and STAI as mentioned earlier). Subsequently, participants were instructed to sit in an upright but relaxed position in front of a computer monitor. They were informed of the task instructions by watching a short presentation on the monitor. There were 3 experimental conditions: (i) delta/theta monaural beat, (ii) alpha monaural beat, and (iii) no beat. For each of the three conditions, participants were presented with eight short musical excerpts belonging to the specific condition. Musical excerpts were presented through in-ear headphones, and the volume of the musical stimuli was self-adjusted *a priori* by each participant and was kept at the same level throughout the experiment. After listening to each musical excerpt, participants reported the following on a 7-point Likert scale (higher values indicate higher ratings): (a) their liking of the music, (b) their felt arousal, (c) their flow during listening to the music, (d) their eagerness to listen to the music tomorrow, and (e) their willingness to pay (in pence out of a budget of £1) to buy the track of the excerpt. Participants were provided with a description of flow and then asked whether: (1) they were familiar with the description; and (2) they had experienced the phenomena while listening to music. The description of flow provided for participants was: ‘a mental/emotional state partially characterized by the feeling of being fully immersed, focused, and involved in a given task’. This procedure and definition of flow in music listening was tested by Diaz (2013) and found to be clear to participants and suitable for collecting rapid unobtrusive judgments of flow while listening to music.

After each condition (i.e. after listening to the eight excerpts belonging to the specific condition), the participants completed the STAI-S, modified DES, and the 'short' version of the Flow State Scale (FSS-2). A brief break was provided between conditions to prevent carryover effects.

Some studies do not find any effect of binaural or monaural beats on neural entrainment or behavioural findings like mood (Gao et al., 2014; Goodin et al., 2012; López-Caballero & Escera, 2017; Vernon, Peryer, Louch, & Shaw, 2014). This could possibly due to differences in beat stimulation durations and methodological approaches. Hence, care was taken to ensure the participants were exposed to the monaural beats for a sufficiently long period (at least 25 minutes for each condition). Hence, a block randomized design was used, i.e. for each block, all musical excerpts belonged to the specific condition and the blocks were counterbalanced across participants; the sequence of musical excerpts for each specific condition was randomized for each participant. The total duration of the experimental session was a little over 3 hours. Participants were debriefed at the end of the experiment.

8. 2. 5. EEG Recording and Preprocessing

EEG signals were recorded by sixty four active electrodes placed according to the extended 10-20 electrode placement system. Additional electrodes were placed above and below the right eye, and at the outside corner of each eye to record vertical and horizontal eye movements, respectively. The EEG signal was amplified by a Biosemi ActiveTwo® amplifier and sampled at 512 Hz. Biosemi amplifier has two electrodes – active CMS (common mode sense) electrode and passive DRL (driven right left) electrode – that together form a feedback loop representing the online reference (see Biosemi link, http://www.biosemi.com/faq/cms&drl.htm for details on the Biosemi referencing and grounding procedures). EEG signals were algebraically re-referenced to the average of two earlobes. A high pass filter at 0.5 Hz was applied to remove slow baseline drifts and a notch filter at 50 Hz with a 2 Hz bandwidth was applied to remove line noise. Independent component analysis (ICA) based method was applied to the EEG data to remove large blink related artifacts. Next the ICA-cleaned EEG data was visually inspected for the identification and subsequent removal of any remaining artifacts.

8. 2. 6. EEG Analysis

EEG signals were principally analyzed in terms of the constituent oscillatory components. Therefore, we computed periodograms, i.e. the power spectral density based on Welch method, by using a 2 seconds long window with a 1 second overlap. The periodogram was estimated for each electrode and condition for each participant.

For calculating neural entrainment, i.e. the brain's steady state responses (SSR) to the monaural beat, we estimated the spectral power at the monaural beat frequency. For broadband analysis, the EEG spectral power values at each electrode for each condition was divided into five standard EEG frequency bands (Ioannou et al., 2015): delta-EEG (< 4 Hz), theta-EEG (4-8 Hz), alpha –EEG (8-13 Hz), beta-EEG (13-30 Hz) and gamma-EEG (30-48 Hz). The spectral power values within each of these frequency bands were averaged. The no-beat condition was used as a baseline condition, and the spectral power values for the delta/theta- and alpha- monaural beat conditions were normalized with respect to the spectral power values for the no-beat condition. The normalized spectral power was expressed in dB.

8. 2. 7. ECG Recording and Analysis

ECG signals were recorded in a bipolar fashion by placing two electrodes, one over left chest and the other over right abdomen. The sampling frequency was 512 Hz, and was amplified by Biosemi amplifier along with EEG signals. The ECG signals were preprocessed using MATLAB® based custom scripts for the analysis of heart rate variability according to the recommended standards for HRV measurements (Malik et al., 1996). QRS complex was first identified using a QRS detection algorithm based on filter banks which enable the identification of the complex by decomposing the ECG in sub-bands with uniform frequency bandwidths (Afonso, Tompkins, Nguyen, & Luo, 1999), and the interbeat R-R interval was subsequently calculated. Any outlier or glitch in the R-R sequence was identified by investigating the residuals of a forward and backward autoregressive fit and was subsequently replaced by spline interpolation (Lee & Bhattacharya, 2013). For R-R interval sequence related to each musical excerpt excluding the first 8 sec as transients, we calculated the following HRV indices: (i) the mean of R-R interval, (ii) the standard deviation of R-R interval (both PNS and SNS activity contribute to this measure, and it represent short term variability (Kuusela, 2013)), (iii) the skewness of R-R interval, (iv) the proportion of the number of pairs of adjacent intervals differing by more than 50 ms, pNN50 (it is usually related with PNS activity (Umetani, Singer, McCraty, & Atkinson, 1998), (iv) the square root of the mean of the sum of the squares of differences between adjacent intervals, rmSSD (it is related to the inter-beat variance and could provide an estimate of the vagally mediated changes reflected in the HRV (Shaffer, McCraty, & Zerr, 2014)), (iv) the mean spectral power in the LF band (0.04-0.15 Hz) (this frequency range is termed as the baroreceptor band as it usually reflects baroreceptor activity at rest (Goldstein, Bentho, Park, & Sharabi, 2011)), (v) the mean spectral power in the HF band (0.15-0.4 Hz)(usually associated with respiratory sinus arrhythmia because it reflects the heart rate variations coupled with respiratory cyle, and is usually associated with PNS activity (Akselrod et al., 1981; Grossman & Taylor, 2007)), (vii) the LF:HF ratio (usually reflecting a balance between PNS and SNS activities – a low value reflecting a parasympathetic dominance while a high ratio indicating sympathetic dominance (Pagani et al., 1984); however, recent findings have raised doubts about these interpretations (Billman, 2013; Shaffer et al., 2014). The first four indices are based in time domain, and the latter three are based in frequency domain (Shaffer & Ginsberg, 2017).

The spectral power in the HF power reflects the activity of the parasympathetic nervous system which is crucial for reducing anxiety, while the spectral power of the LF power reflects the activity of the sympathetic nervous system which is crucial for increasing arousal.

8. 3. Results

8. 3. 1. Behavioural Ratings

After each musical excerpt, participants provided various ratings, and Fig. 1 shows the mean ratings of liking, felt arousal, felt flow, and the reported eagerness to listen it again for the three conditions. Four separate within-subjects ANOVAs revealed no significant differences between the 3 conditions (liking: $F(2,72) = .71$, $p = .49$; arousal: $F(2,72) = .29$, $p = .75$; flow: $F(2,72) = .53$, $p = 59$; re-listening: $F(2,72) = .23$, $p = .79$).

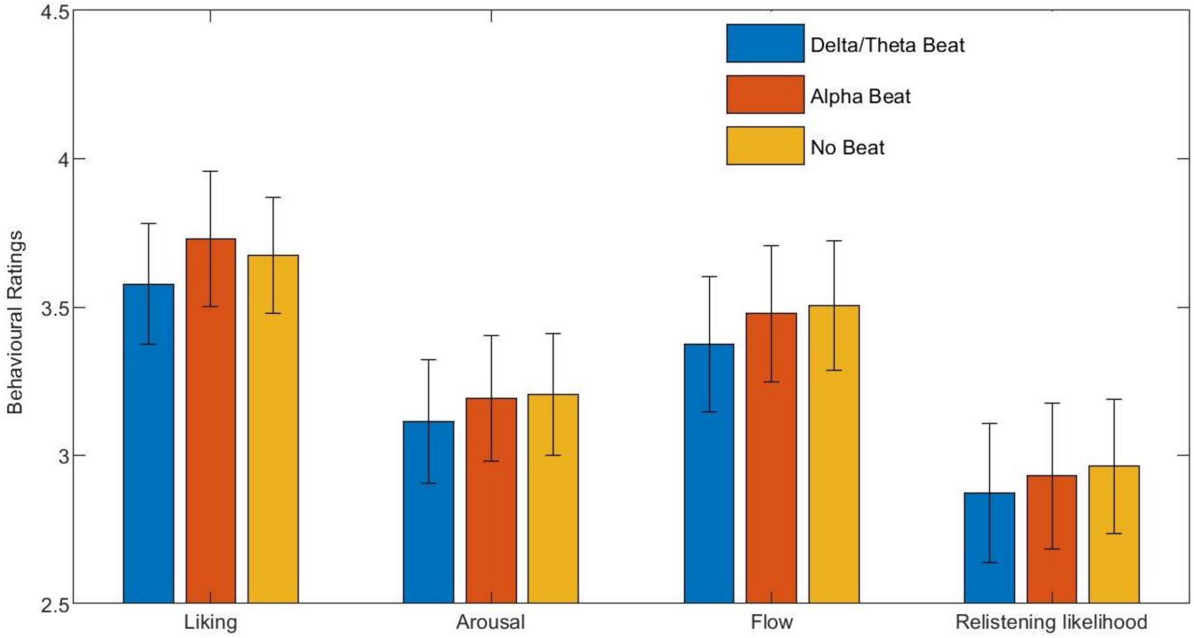


Figure 8.1: Behavioural ratings of musical excerpts belonging to three conditions: alpha monaural beat, delta/theta monaural beat, and no beat. Four ratings are shown: liking of musical excerpt, felt arousal, felt flow experience, and the re-listening likelihood (all on a 7 point scale). Values were averaged over eight musical excerpts belonging to each condition. Error bars represent s.e.m.

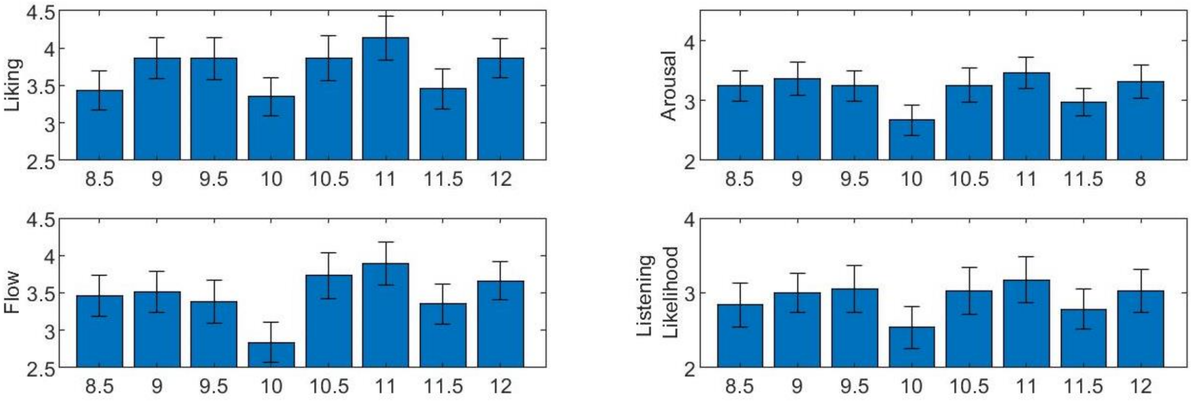


Figure 8.2: Behavioural ratings of eight musical excerpts with monoaural beat belonging to the broad alpha band (8-12 Hz). The values on the y-axis represent the beat frequency in Hz for the corresponding musical excerpt. The values are averaged over participants, and the error bars represent s.e.m

Interestingly, there were substantial variations across musical excerpts belonging to a specific condition. For example, Fig. 2 shows the mean ratings for eight musical excerpts with beat frequency belonging to the alpha band.

After each condition, participants completed the 9-item short version of the Flow State Scale (FSS-2) (S. A. Jackson et al., 2008), reporting experienced flow via the nine dimensions of flow**.** The average (s.d) state flow score for three conditions are 3.34 (0.10), 3.40 (0.10), and 3.27 (0.09). An one-way within-subjects ANOVA showed that the flow scores did not differ significantly between the three conditions (F(2, 72) = 1.10, *p* = 0.337). No significant effects were observed for pairwise comparisons.

8. 3. 2. Neural: EEG Results

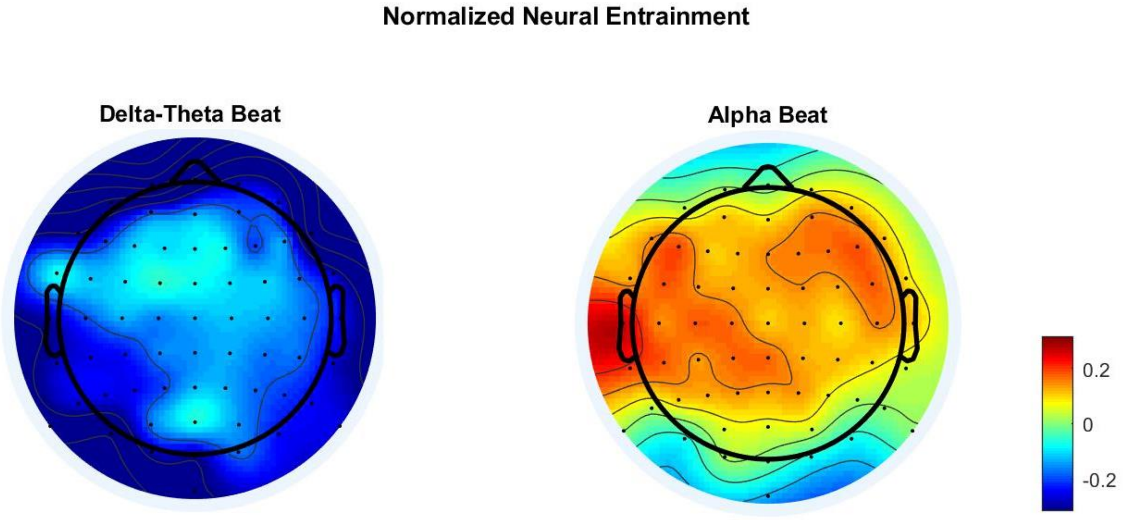


Figure 8.3: Neural entrainment to monaural beat stimuli represented as the scalp maps of the neural entrainment as distributed over the scalp (red or brighter colours representing larger degree of entrainment). Left panel shows the results averaged over 8 musical excerpts with delta-theta monaural beat, and the right panel the same but for alpha monaural beat. Neural entrainment was measured as the steady state responses elicited by monaural beat and normalized subsequently by the same frequency band specific power against no-beat excerpts.

8. 3. 2. 1. Neural Entrainment and Neural Oscillations

Though the presence of monaural beats, whether in the alpha or delta/theta conditions, did not induce significant changes in flow experience during music listening, we examined the neural data to see if neural entrainment to monaural beats resulted in neural oscillations associated with higher flow experience. First, we analyzed the normalized SSRs for both delta/theta monaural beats and alpha monaural beats averaged across all electrodes and all beat frequencies within a specific condition, and Fig. 3 shows the scalp distribution of the normalized SSRs. It is clear that the musical excerpts with monaural beats belonging to the traditional alpha band (8-12 Hz) elicited a more robust neural entrainment distributed over multiple brain regions, including the bilateral temporal cortex. On the contrary, similar neural entrainment was almost absent when the monaural beats were in the delta/theta (1-6 Hz) frequency range. So while monaural beats in the alpha band were effective in increasing alpha oscillations, monaural beats in the delta/theta band did not increase delta and theta oscillations.

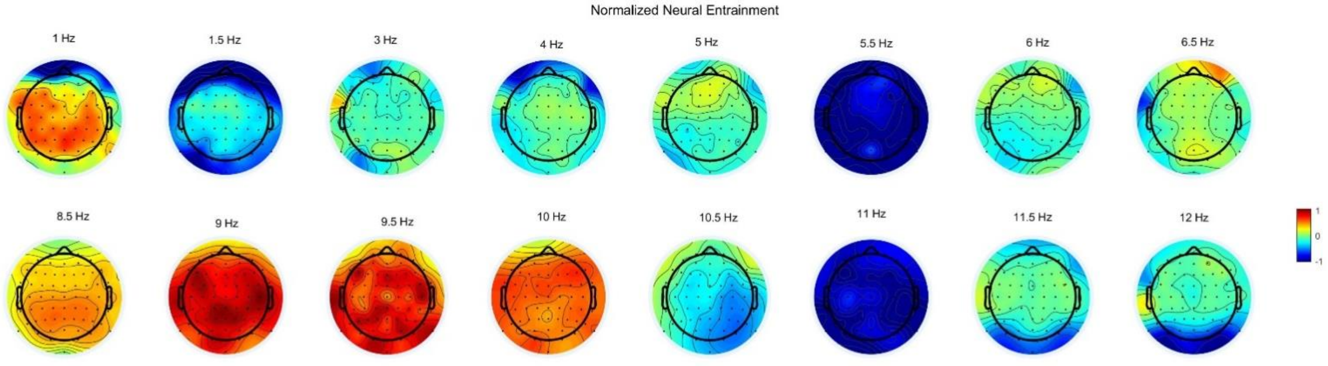


Figure 8.4: Neural entrainment for each of the eight musical excerpts belonging to delta-theta (upper row) and alpha (lower row) monoaural beat condition condition. For each excerpt, entrainment was normalized with respect to the specific control (i.e. same musical excerpt but without the beat) stimulus

When the analysis was repeated at the individual musical excerpt level, Fig. 4 shows the scalp maps of neural entrainment at each of the sixteen chosen monaural beat frequencies. Substantial variations were observed across musical excerpts. However, as expected, more beat frequencies belonging to the alpha band showed larger and conspicuous increase of auditory SSRs, and this effect was pronounced when the beat frequency was in the lower alpha range, i.e. close to the usual peak at 10 Hz of spontaneous alpha oscillations. Surprisingly, when the monaural beat was at the upper alpha range, i.e. between 10-12 Hz, we observed a sharp decrease in the neural entrainment. Similarly, the strength of auditory SSRs was minimal when the monaural beat was in the delta/theta range except at the beat of 1 Hz.

Next, we extended our analysis to include other classical EEG frequency bands. Fig. 8.5 shows the normalized power in five EEG frequency bands at the global level (i.e. averaged across all electrodes, and over eight excerpts for each monaural beat condition). Compared to the no beat condition, delta/theta monaural beat was associated to event-related desynchronization, i.e. decrease of spectral power, at the global brain level. However, alpha monaural beats was associated with increase of spectral power over a broad range of frequencies with the largest increase was observed at the theta band at the global brain level.

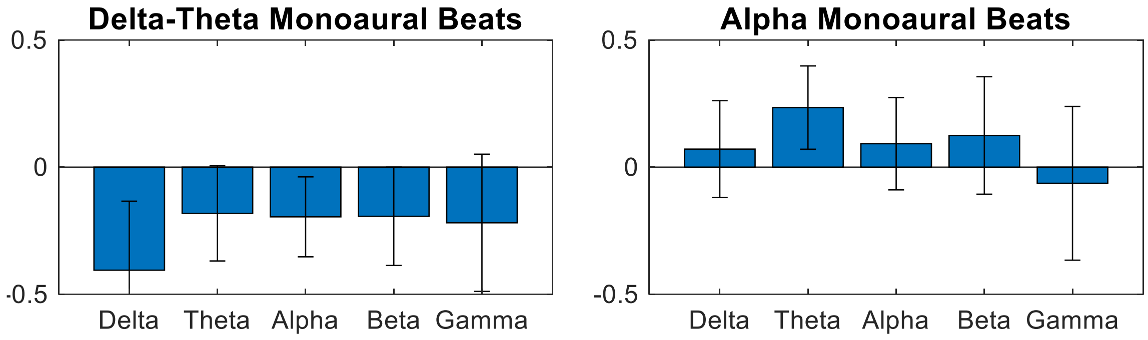


Figure 8.5 Normalized power in the five EEG frequency bands (delta, theta, alpha, beta and gamma) during delta/theta and alpha monoaural beats stimulation. Spectral power was normalized w.r.to the no-beat condition. Spectral values were averaged over all 64 electrodes, thereby indicating spectral power changes at the global brain level. Error bars indicate s.e.m

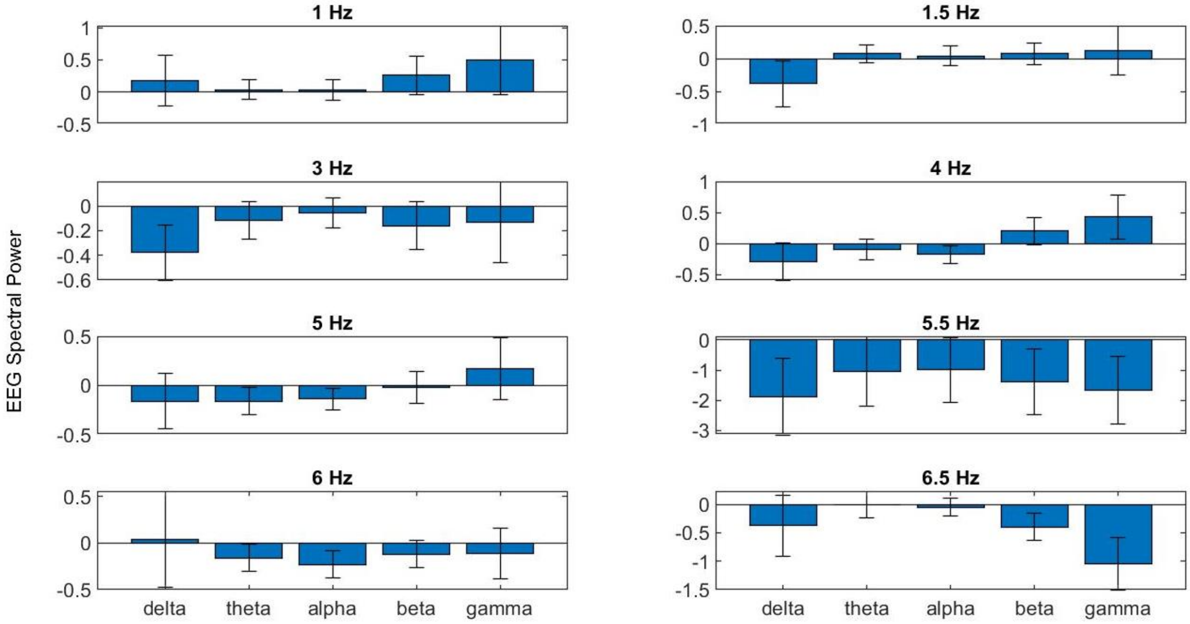


Figure 8.6: Normalized spectral power in the five EEG frequency bands (delta, theta, alpha, beta and gamma) for each of the eight musical excerpts with monoaural beat belonging to the delta/theta band. Spectral power was normalized w.r.to the no-beat condition. Spectral values were averaged over all 64 electrodes, thereby indicating spectral power changes at the global level. Error bars indicate s.e.m

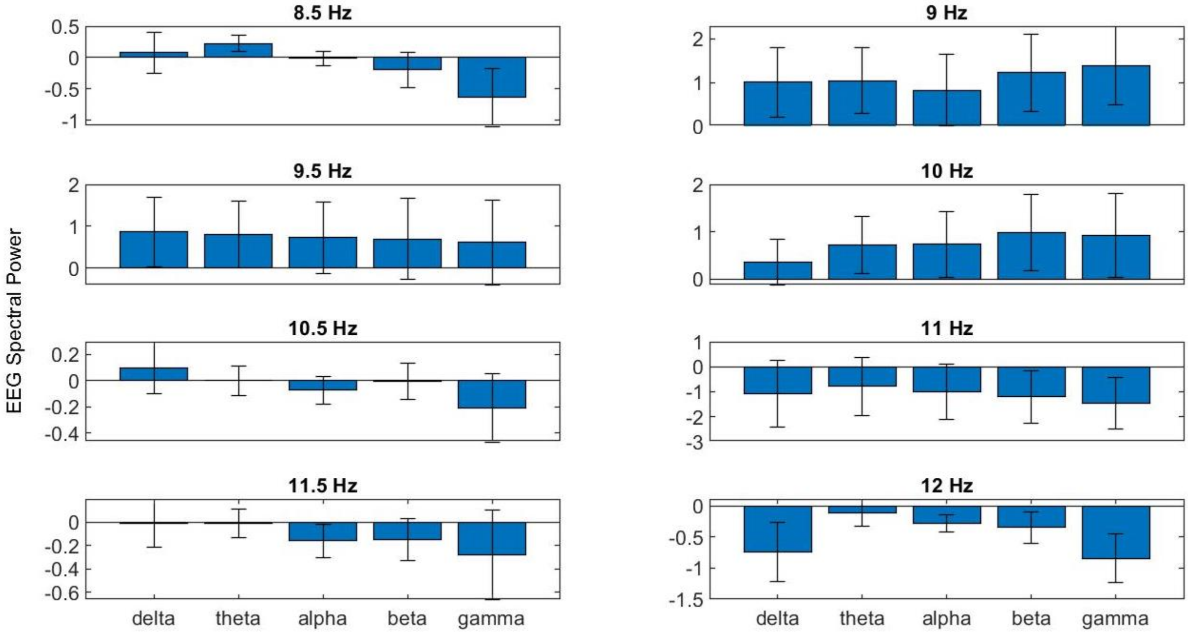


Figure 8.7: Normalized spectral power in the five EEG frequency bands (delta, theta, alpha, beta and gamma) for each of the eight musical excerpts with monaural beat belonging to the alpha band. Spectral power was normalized w.r.to the no-beat condition.

Figures 8.6 and 8.7 show the spectral power changes in the five classical EEG frequency bands associated with individual musical excerpts belonging to the delta/theta (Fig. 8.6) and the alpha (Fig. 8.7) beat condition. There are several noteworthy points. First, like in auditory SSRs, musical excerpts with monaural beats at the lower alpha range also produced larger increases in the broadband EEG power at the global brain level. Second, monaural beat at 1 Hz was associated with an increase spectral power with a large effect in the high frequency gamma band, and a similar trend was observed for monaural beats at 1.5 Hz, 4 Hz, and at 5 Hz. Third, gamma band synchronization was also associated with monaural beats at 9 – 10 Hz, while gamma band desynchronization was observed for monaural beats at 10.5 – 12 Hz.

In summary, we identified two types of oscillatory responses: (i) auditory steady state responses suggesting a type of neuronal entrainment or a linear association to the monoaural beat frequency, and (ii) broadband or cross frequency responses suggesting more widespread effects in frequency bands outside the monaural beat's target frequency. While monaural beats in the alpha band increased alpha oscillations at the global brain level, a closer look at individual musical excerpts with specific beat frequencies shows that the neural entrainment effect is at the lower alpha band (8-10 Hz). Neural entrainment was minimal at the upper alpha band (10-12 Hz) which was more associated with flow than the lower alpha band. There was little neural entrainment at the delta and theta band. However, theta band power increases were found in the alpha condition. It seems that monaural beats have unpredictable effects when influencing the brain and do not have a clear impact on flow in music listening.

8. 3. 2. 2. Differences between high and low flow

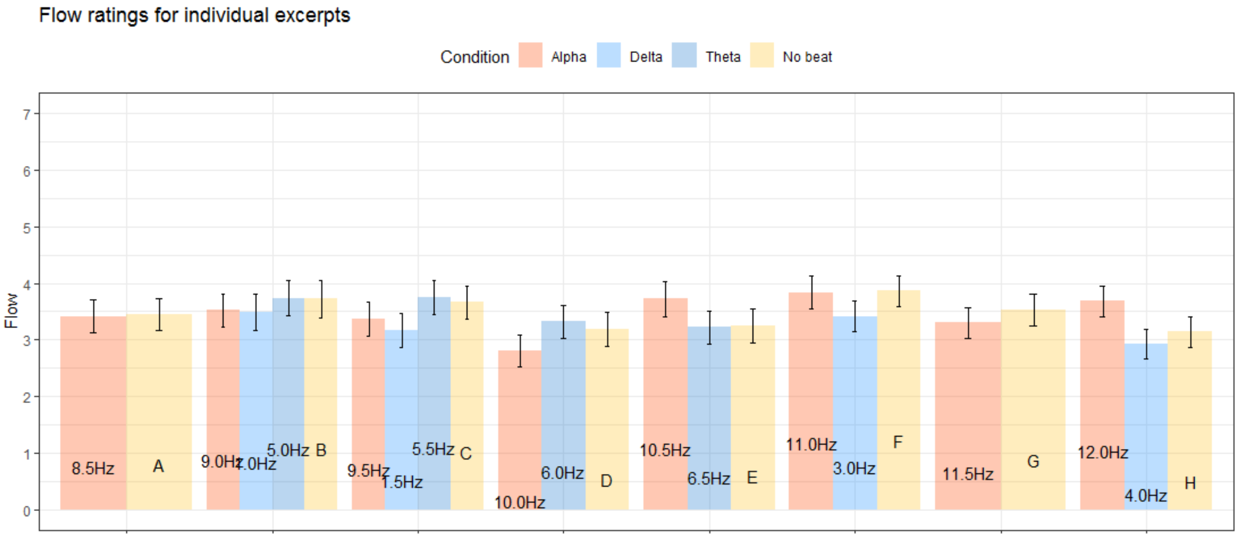
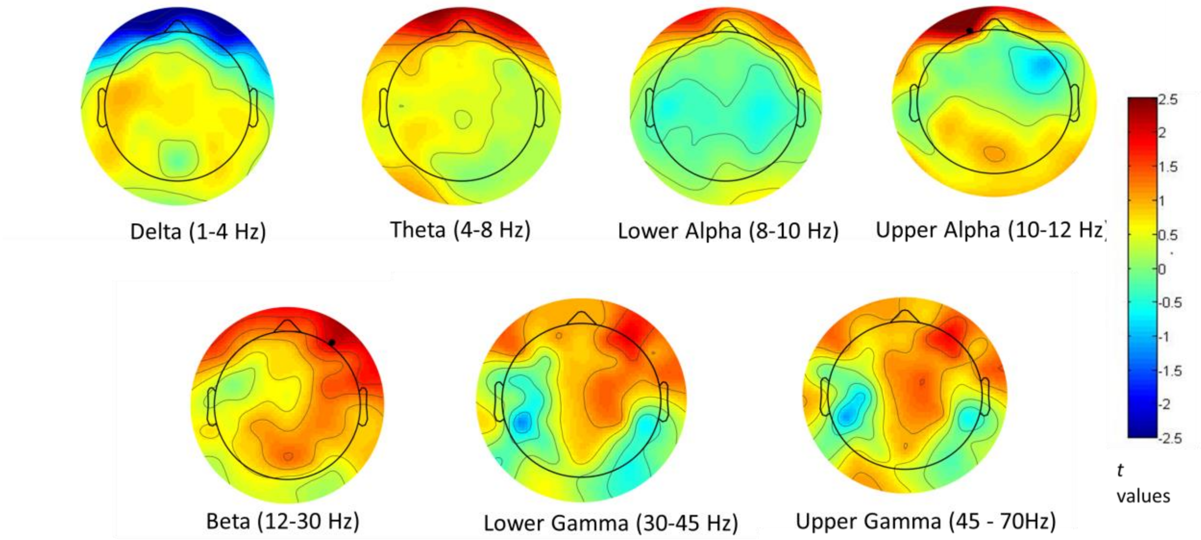


Figure 8.8 Average flow ratings for individual excerpts. Excerpts with beats are grouped with their control no-beat excerpt (labelled alphabetically)

However, even though there were few significant behavioural, neural and autonomic differences across conditions, there was substantial variations in reported flow experience across musical excerpts belonging to a specific condition. Hence, we decided to examine pieces by their flow ratings rather than by condition. For each participant, a median split was taken of flow scores across conditions. Excerpts rated higher than the median were deemed 'high flow' while excerpts rated lower than the median were deemed 'low flow'. Normalised spectral power during these excerpts were averaged and compared across high and low flow conditions for each electrode.



Topoplots of *t*-values by comparing EEG power of seven frequency bands between flow and non-flow states. Red indicates that power is higher in the flow condition while blue indicates that the power is higher in non-flow condition. Statistically significant electrodes ($p < .05$) are indicated by black dots.

Figure 8.9: Topoplots of t-values comparing EEG power in high flow and low flow conditions

Compared to those rated lower in flow experience during listening, musical excerpts rated higher in flow experience did not show a large difference in relative spectral power across multiple electrodes. However, there are some intriguing hints of a difference in the frontal regions. Musical excerpts rated higher in flow had higher upper alpha and beta relative power in the frontal regions.

8. 3. 3. Autonomic: HRV Results

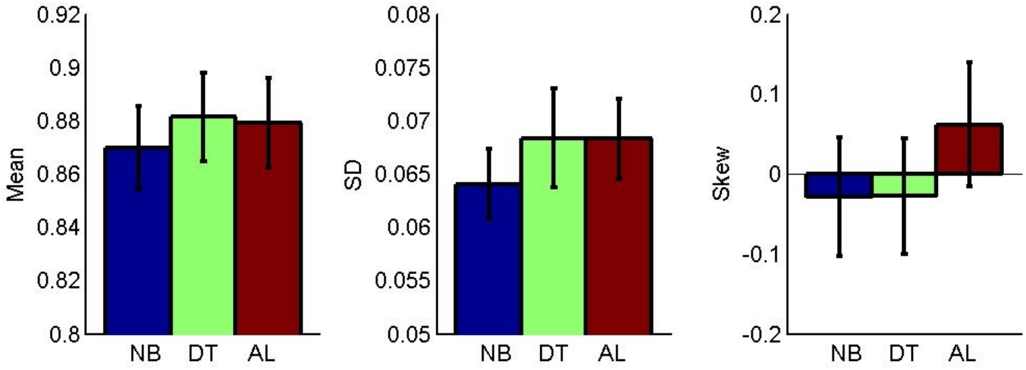


Figure 8.10: Values of mean, standard deviation and skewness of R-R interval sequences corresponding to three conditions: NB (musical excerpts without beat), DT (musical excerpts with delta-theta monoaural beats), AL (musical excerpts with alpha monoaural beats). Values were averaged across eight excerpts within each condition. Error bars denote SEM.

Fig. 8.10 shows the mean values of three time domain measures, mean R-R, SD, and skewness for three conditions. In terms of mean R-R interval (i.e. inverse of heart rate), there was a slight increase in mean values from no-beat condition to the two beat conditions (both DT and AL), a one way within-subjects ANOVA revealed no statistically significant differences between the conditions (*F*(2,70) = 1.03. *p* = .36). For the SD measure, the beat-variability increased, on average, from the no-beat condition to monoaural beat conditions, but the effect was only marginal (NB vs DT and AL combined: *t*(1,35) = 1.70, *p* = .09). For skewness measure, an one-way within-subjects ANOVA revealed a marginally signficant difference between the three conditions (*F*(2,70) = 2.37, *p* = .10), and this was primarily driven by the higher skewness for alpha monoaural beat condition as compared to the no-beat (*t*(1,35) = 1.73, *p* = .09) and delta-theta (*t*(1,35) = 2.40, *p* = .02) beat conditions.

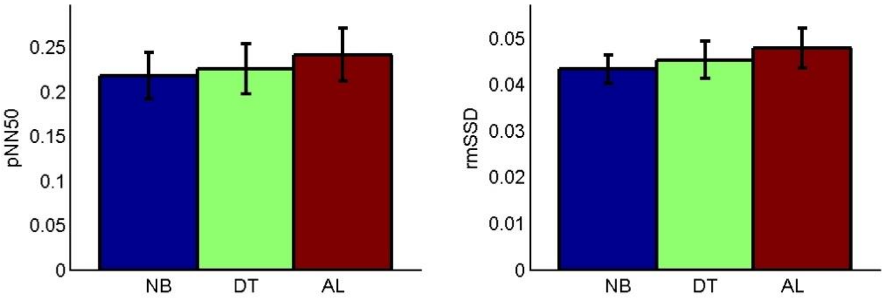


Figure 8.11: Values of pNN50 and rmSSD of R-R interval sequences corresponding to three conditions: NB (musical excerpts without beat), DT (musical excerpts with delta-theta monoaural beats), AL (musical excerpts with alpha monoaural beats). Values were averaged ac ross eight excerpts within each condition. Error bars denote SEM.

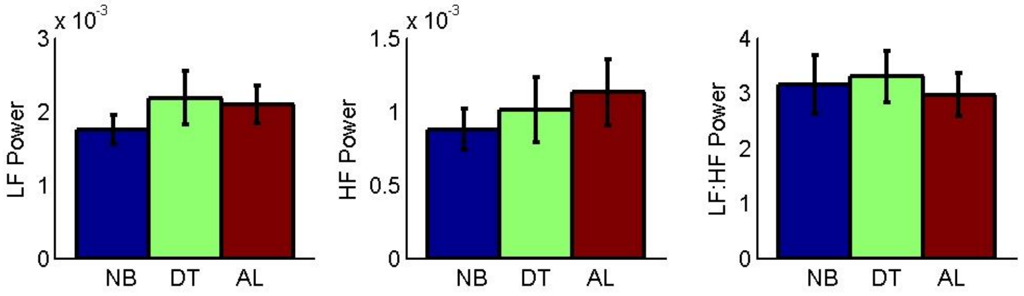


Figure 8.12: Values of LF power, HF power, and LF:HF ratio of R-R interval sequences corresponding to three conditions: NB (musical excerpts without beat), DT (musical excerpts with delta-theta monoaural beats), AL (musical excerpts with alpha monoaural beats). Values were averaged across eight excerpts within each condition. Error bars denote SEM.

Fig. 8.11 shows the mean values of two other time domain HRV indices, the pNN50 and rmSSD. A within-subjects ANOVA revealed no significant difference between the three conditions (pNN50: *F*(2,70) = 1.19, *p* = .30; rmSSD: *F*(2,70) = 1.30, *p* = .28); however, both measures were marginally higher in the alpha monaural beat condition than in the no beat condition (pNN50: *t*(1,35) = 1.53, *p* = .13; rmSSD: *t*(1,35) = 1.81, *p* = .07).

Fig. 8. 12 shows the mean values of three frequency domain based HRV indices, LF power, HF power, and LF:HF ratio. Beat related conditions showed marginally higher LF values than no-beat condition (DT and AL combined: *t*(1,35) = 1.81, *p* = .07) but the difference between delta-theta and alpha beat conditions was not significant (*p*> .7). For HF power values, we observed an increasing trend from no beat to delta-theta to alpha beat condition, and a statistically marginal effect was observed between no-beat and alpha beat condition (*t*(1,35) = 1.80, *p* = .08). No significant differences were observed between the three conditions in terms of LF:HF ratio (*p*> .45).

Although no statistically significant findings on the impact of monaural beats on HRV was found, the higher heart variability, higher mean R-R interval and skewness, higher rmSSD and pNN50 and lower LF:HF ratio could indicate that autonomic nervous system responses during the alpha monoaural beats condition suggest a physiological state which is more relaxed and less stressful.

8. 4. Discussion

In this study, we explored the effects of monaural beats on flow experience during music listening. Reported flow experience did not significantly differ across the conditions of monaural beats in the alpha (8.5 - 12 Hz) band, monaural beats in the delta and theta (1.0 - 6.5 Hz) and the same music without any beats. When neural oscillations were examined, enhanced neural entrainment was primarily found in the lower alpha band (8.5 - 10.0Hz). However, monaural beats at the upper alpha band (10.5 - 12.0Hz) and at delta and theta bands mainly caused a decrease in entrainment. Neural oscillations were also not significantly different between excerpts rated high in flow and those rated low in flow. No statistically significant findings on the impact of monaural beats on HRV were found.

8. 4. 1. Effects of monaural beats stimulation on flow experience

The robust findings of enhanced neural entrainment for monaural beats in the lower alpha band aligns with a previous EEG study on binaural beats (Ioannou et al., 2015) where it was reported that the alpha band EEG power was significantly increased during stimulation by binaural beats belonging to the alpha band (8-12 Hz). The alpha oscillations are the dominant oscillations in the spontaneous neuronal actitives, and have widespread functional roles in perception, memory and cognition including both task-directed and internal information processing. Alpha monaural beats also had the largest impact in terms of cross-frequency responses. Interestingly, we observed that the spatial locations of these effects are not necessarily confined to the auditory cortices, instead distributed over multiple brain regions, thereby demonstrating the efficacy of specific monoaural beats in engaging brain at a global level.

This is the first study, to the best of our knowledge, investigating the autonomic responses to various types of monoaural beats embedded in musical excerpts. Little is known about the impact of binaural beats on the HRV measures as scant evidences are based on studies with poor sample size (N = 5, Palaniappan, Phon-Amnuaisuk, & Eswaran, 2015), no control condition nor any statistical analysis (N = 10, Casciaro et al., 2013). Two recent studies (N=14 in López-Caballero & Escera, 2017; N = 31 in Rashkin, 2018) reported no statistically significant effects of binaural beats, as compared to a control condition with no beats, on heart rate variability.

Although we did not find statistically robust findings of the impact of monoaural beats on time- and frequency domain measures of HRV, the features taken together point towards an interesting hidden pattern. The heart rate during alpha monoaural beats showed a consistent trend towards higher variability, higher mean R-R interval and skewness, higher rmSSD and pNN50 and lower LF:HF ratio. A recent meta analysis suggests that the opposite pattern of features, i.e. lower mean R-R, higher rm-SSD, pNN50 and lower RF:HF ratio, is usually associated with induced mental stress sessions (Castaldo et al., 2015). Lower heart variability is also often related with stress/anxiety (Brosschot, Van Dijk, & Thayer, 2007).Therefore, it could be concluded that the autonomic nervous system responses during the alpha monoaural beats suggest a physiological state which is more relaxed and less stressful and thus may be more conducive to flow.

However, no clear effects of alpha or delta/theta beat stimulation on flow during music listening was found. There may be several reasons for this. Binaural beat stimulation at 5 Hz for 15 min, twice a day for 2 weeks, significantly increased the number of words recalled during testing and after stimulation (Ortiz et al., 2008). Hence, the effect of monaural beats may take several weeks to develop.

Findings also suggest that the effects of binaural beat stimulation may depend upon the experience and skill set of the individual. Lavallee et al. (2011) reported that theta binaural beat stimulation (7 Hz) increased left temporal lobe delta power in experienced meditators but not in novice practitioners. Beta (15 Hz) frequency stimulation increased gamma power in novice meditators, not in the experienced group (Lavallee et al., 2011). Ioannou et al (2015) found more differences in musicians' brains compared to non-musicians in response to a binaural beat stimulation. Whether expertise helps or hinders flow during music listening in response to auditory beat stimulation is still unknown. tDCS seemed to benefit people with low flow in Ulrich (2017) while Gold (2019) found increased flow for both untrained and trained participants but only increased performance for untrained participants (Gold & Ciorciari, 2019; Ulrich et al., 2018).

As the desired frequencies, particularly in the theta and upper-alpha band were not induced by the monaural beats, it is not yet possible to draw any conclusions on their causative relation to flow experience. As a tool for modulating neural activity at the frequency level, monaural beats had unexpected effects. Effects were distributed over multiple brain regions and activity in other frequency bands were influenced. While theta monaural beats reduced theta entrainment, alpha monaural beats increased theta power alongside alpha entrainment. Though auditory beat stimulation is more convenient and easily applied compared to the tDCS used in Ulrich (2018) and Gold and Ciorcari (2019), it is less targeted and more unpredictable in its effects. Much more research on the use of neural stimulation to induce brain states beneficial for flow is needed as studies so far have found unpredictable effects. Ulrich (2018) only found effects on participants with low flow while Gold (2019) found increased flow for both untrained and trained participants (Gold & Ciorciari, 2019; Ulrich et al., 2018). The effect may also be very small. Scores in Gold's study only seemed to differ in terms of 0.3 - 0.4 on the FSS-2 (Gold & Ciorciari, 2019). well-powered studies may be needed to reliably detect it.

While this study looked at selected frequencies in the alpha and delta/theta band, other frequencies could also be tested. It is an open question which beat stimulation frequencies are best suited for cognitive enhancement. Colzato et al. (2017) proposed that low frequency binaural beats stimulation is more likely to be associated with mental relaxation and high-frequency beats with processes relating to attention and alertness (Colzato et al., 2017). Given that flow is characterised by 'effortless attention' (Bruya, 2010), it may be the case that either high or low frequency beats would be appropriate at different times, low frequency when one has to be brought back down to the optimal level of arousal to experience flow or high frequency when one has to raise attention to induce flow. While this experiment tested low frequency beats, future experiments should also test the effects of higher frequency beats like gamma (40Hz or 80Hz) and also the conditions they work best under.

8. 4. 2. The neural correlates of flow in music listening

Though the presence of the beats did not predict more flow during music listening, there was wide variety in the reception of the different musical excerpts. Hence, we thought to examine the difference in neural response between excerpts that were rated high in flow and excerpts rated low in flow. No statistically significant neural differences were found between the excerpts rated high in flow and those rated low in flow. However, the hints of an effect in the frontal regions recall the findings on the first study on flow in music performance described in Chapter 2. Again, the difference is in the upper alpha (10-12 Hz) and beta (13-30 Hz) frequency band and again in the frontal areas. However, compared to flow during performance, a strong effect isn't observed. There may be several reasons for this.

The perceived benefits of music listening are stronger when people are allowed to choose their desired music (North, Hargreaves, & Hargreaves, 2004). Participants preferred playlists they created rather than automatically curated content (Kamalzadeh, Baur, & Möller, 2012) and those who chose the music they were listening to reported enjoying it more (North et al., 2004). Furthermore, with greater control on the choice of music selection, individuals reported becoming more positive, more alert and more focused on the present (Sloboda, O’neill, & Ivaldi, 2001). Focused listening to self-chosen music provides a means to engage in reminiscence, catharsis, calming, and other intellectual outcomes associated with high levels of engagement, a scenario closer to what Csikzentmihalyi described as having the potential for flow (Lamont, 2012; Tekman & Hortaçsu, 2002). However, this experiment examines flow during music listening to a novel musical stimuli. Music was newly composed to include the auditory beat stimulation. Though this allowed for extremely well controlled stimuli, it is possible that the lack of personal meaning prevented participants from experiencing high flow.

Moreover, because they were designed as a delivery mechanism for monaural beats for neural stimulation, musical variability was not a priority. This may have resulted in a lack of complexity to induce flow during music listening. Ruth (2017) found that challenge-skill balance was an important aspect for flow during radio listening and that depending on the musical skill of the recipients, the complexity of the music could be associated with higher or lower flow experiences (Ruth et al., 2017). It is possible that the excerpts were not challenging enough to induce high flow during music listening.

While flow experience as a function of condition was measured using the short version of the FSS-2, flow scores for individual pieces were rated using a definition of flow from Diaz (2013). The advantage of this system is that a single score can be quickly obtained in response to the piece heard without much disruption. However, a single dimension may not capture the full effect of flow during music listening. Diaz (2013) also notes the possibility that the uni-dimensional definition provided to participants may have been confounded with similar constructs, such as concentration or attention (Diaz, 2013). Compared to the componential form of flow, this may be inadequate.

8. 4. 3. Monaural beats in music to aid flow

Finally, given the lower engagement of the musical stimuli and also the fact that many ABS studies have examined the effect of ABS on cognitive tasks, rather than examining the effects of monaural beats on flow during music listening, a more effective way to study the effect of monaural beats on flow experience may be to examine if ABS affected flow during a cognitive task.

Demetriou et al (2016) suggests another context in which music-induced flow may occur outside the absorbed focused listening Csikzentmihalyi describes. Pointing to the fact that music listening is a common occurrence in everyday life, yet rarely the sole focus of an activity, they posit that individual music selections function as a means to achieve various emotional, motivational, or cognitive effects that will help in the accomplishing of various activities (North et al., 2004).Recalling Csikzentmihalyi's description of music to "ward off boredom and anxiety", music becomes a tool that a listener may use to achieve the internal state necessary to accomplish their goal, rather than an end unto itself (Demetriou, Larson, & Liem, 2016). During tasks in which boredom is likely, more arousing music may be selected. By diverting attentional resources to the music, the challenge of the task increases, as it now requires attention to be paid to both the activity and the music. As such, music that is more likely to be arousing either by resulting in responses from the brain stem (e.g., loud, frequently changing, or dissonant song selections) or causing prediction errors (e.g., less familiar, familiar and causing anticipation, or more complex) may be more suitable. During tasks that are challenging or otherwise cognitively engaging, music that is likely to be less arousing either by resulting in less brain stem activation (e.g., relatively un-changing or consonant) or being predictable without anticipation (e.g., somewhat familiar and somewhat liked, more simple songs) may be more suitable. This use of music as a tool for self-regulation parallels the use of auditory beat stimulation at different frequencies for different purposes discussed earlier. Some research in this vein already exists. Pates (2003) looked at flow in netball players and found that the use of asynchronous background music resulted in increased flow experience for two of the three participants in the intervention. It is suggested that flow in sport may be induced by music interventions (Pates, Karageorghis, Fryer, & Maynard, 2003). Future experiments with monaural beats embedded in music would add another dimension to such research on how music leads to and moderates flow state. It also dovetails nicely with research beginning to examine how brainwave entrainment could help athletes' performance (Abeln, Kleinert, Strüder, & Schneider, 2014).

8. 4. 4. Conclusion

This experiment is the first to study the use of monaural beats in influencing neural activity to encourage flow. Though no significant effects on flow experience were reported and the neural entrainment shows unexpected effects, heart rate variability data suggests that monaural beats particularly in the alpha band may induce a more relaxed state that could be conducive to flow. Possible future experiments could examine flow experience in a task while listening to monaural beats or after a brainwave entrainment session.

Chapter 9 Discussion

9. 1. Summary of findings

This thesis explored three main ways to study the neural correlates of flow. They can broadly be defined as investigations into state flow, dispositional flow and the induction of flow with neural stimulation.

The first involved examining neural correlates of state flow, specifically those induced in an activity participants recognise a flow state in. To this end, flow was studied in music performance and indoor rock climbing, two activities that have been recognised as inductive of flow. More than that, people pursue these activities to experience flow and are thus, often familiar with their experience of flow. Hence, the decision was made to allow participants to self-induce their flow. In Chapter 2, musicians brought a flow-inducing piece and a non-flow inducing piece to the lab. Post-playing, relative power in flow was higher in upper alpha and beta bands compared to non-flow. The finding in upper alpha in particular aligned with studies in experimental flow, which suggest that it could be due to reward-related processing, attentional processes, or a manageable working memory load (Katahira et al., 2018; Núñez Castellar et al., 2019). The finding in beta band power was novel and could reflect the increased movement involved in music performance compared to simple computer games or mental arithmetic. However, as little was known about participants' definition of flow, a second experiment described in Chapter 3 set out to first provide a check on their definition of flow and then try to distinguish enjoyment and challenge-skill balance from flow. Instead of a flow inducing piece and a non-flow inducing piece, participants brought three pieces: a flow inducing piece, a non-flow inducing piece that was as liked as the flow piece, and a non-flow inducing piece that was of equal challenge. Flow was indistinguishable from the equal challenge non-flow piece, even as participants rated it lower on the Flow State Scale-2. However, flow was found to differ from the equally liked non-flow piece. Spectral band power in delta, alpha and beta band suggest reduced default mode network activity (DMN) in flow compared to mere enjoyment, which matches earlier studies finding reduced DMN activity in experimental flow (Huskey, Craighead, et al., 2018; Ulrich et al., 2016c). That some of these findings on musicians' self-induced flow overlap with findings on experimental flow is reassuring. However, much more research is needed before any firm conclusion can be drawn on relating the neuroscience of experimental flow with the neuroscience of self-induced flow.

Using a similar paradigm, in Chapter 4, an event-related potential (ERP) was investigated as a possible neural correlate of flow. The heart-evoked potential (HEP) is thought to index interoception, of the awareness of signals originating from within the body. Though bodily sensations during flow are not as well-researched, there is cause to believe that interoception may differ in flow. The HEP was found to be larger in flow compared to non-flow conditions, implying that interoception is greater in flow. However, findings did not reach significance so further investigation is needed into this interesting possible neural marker of flow.

In Chapter 5, an attempt was made to apply the experimental flow paradigm to an activity people frequently experience flow in. Rock climbing was chosen for the objective classification of climbing routes by difficulty, which offers a way to systematically vary challenge in relation to individual skill level. The intent was to test if the inverted u-shape relationship between difficulty and flow experience held true for an experiment conducted outside the rigorous experimental control of the lab in an intrinsically motivating activity.

However, climbers unexpectedly showed a linear decrease in flow scores instead, with the highest scores in an easy condition rather than a matched condition.

Given the unpredictability of flow induction, the second line of investigation centred on dispositional flow. Chapter 6 investigates the effect of grit and mindset on dispositional flow in musicians and found that dispositional flow depended more on hours of practice and music performance anxiety than grit and mindset. Chapter 7 extended this line of research by examining the relationship between trait emotional intelligence and dispositional flow, not just in music performance, but in climbing, music listening and general daily living. Trait emotional intelligence was found to correlate with dispositional flow in music performance, climbing and general daily living but not music listening. Chapter 7 also explored if dispositional flow could be linked to frontal asymmetry, a neural correlate in resting state EEG that correlates with trait emotional intelligence. While frontal asymmetry in resting state did not correlate with dispositional flow, frontal asymmetry in the post-playing data was found to be impacted by expertise.

Finally, neural correlates associated with flow can be tested for causality by modifying these neural activity and observing corresponding changes in flow experience. Monaural beats were tested as a way to entrain the brain to a more conducive state for flow. While they were unsuccessful at reliably entraining the brain in the frequency bands of interest (delta, theta, alpha) and they did not significantly influence flow experience during music listening, monaural beats in the alpha frequency band seem to induce a more relaxed state which could be conducive to flow. As a final look into the neural correlates of music-induced flow, no clear spectral power differences were found when musical excerpts that were rated high in flow were contrasted with musical excerpts rated low in flow.

In summary, this thesis took a three-pronged approach to shed light on the neural correlates of flow, producing three main takeaways. Flow induction with typically flow-inducing activities is unpredictable. Yet despite the elusive nature of flow, inducing it using typically flow-inducing activities is more fruitful than examining dispositional flow in resting state data. And finally, a reliable way of influencing neural activity to a more conducive state for flow not only holds value as a way to increase flow experience, but as a way to test if discovered neural correlates have a causal relationship to flow.

9. 2. Limitations

With the exception of the flow in music listening experiment, EEG data discussed here were either resting state data collected before the activity or immediately after the activity. While they show differences between conditions and shed light on the brain in flow, it is not the same as examining the brain during flow in an activity. EEG during an activity suffers from movement artifacts and noise but luckily, with new techniques of data cleaning such as Artifact Subspace Reconstruction (ASR), it may be feasible to salvage data from during music performance or during climbing.

Coping with complex flow-inducing stimuli in the form of musical performances and climbing routes at a climbing centre meant that these experiments are not as controlled as lab-based experimental flow inductions. Consequently, there may be confounding factors influencing results.

Some of the findings lacked sufficient sample size, reducing their generalisability. A larger sample size is needed to replicate the finding of trait emotional intelligence correlating with dispositional flow in climbers, music listening and general daily living.

9. 3. The future of neuroscience of flow research

Extensive work has been done on the neural correlates of experimentally induced flow, but many researchers have noted that it is as yet unknown if their findings apply to flow experience in other flow inducing activities. Hence, the challenge is now to extend the findings of experimental flow to the experiences of flow people get doing their favourite activities, and perhaps even deep flow. What the experiments in this thesis have shown is that as we start to look at real activities people experience flow in, things get exponentially more complex. Flow-inducing stimuli vary by more than one experimental parameter and interindividual differences abound. This thesis has made but a scratch on exploring how to handle these issues and here, we discuss several relevant approaches.

9. 3. 1. Scalable experiments

As neural experiments on flow move from simple computer games to more complex activities, the loss of experimental control is accompanied by a reduction in interpretability of results. One way to approach this issue is with scalable experiments linking lab-based research to research in actual flow activities. Complex activities and phenomena should be linked to a lab-based equivalent. It would help even more if the same participants can do both lab-based and flow activities.

Fig 9.1 depicts Parada's concept of scalable experiments (Parada, 2018). In brief, it lays out the tradeoffs involved in designing an experiment to capture a phenomena that cannot be easily reduced to a lab setting. Designed for mobile brain/body imaging experiments, it is surprisingly easily adaptable to flow contexts. Structured experimental designs are characterised by high internal validity at the cost of ecological validity. For example, a micro version of a complex task can be implemented under laboratory conditions. The simple computer games used in flow experiments come to mind. Semi-structured experimental designs are characterised by providing participants with some control over experimental variables and more behavioural and cognitive degrees of freedom. More real life behaviour is allowed in exchange for reduced internal validity and experimental control. But even with a complex task, given the semi-structured nature of the design, data analysis and interpretation can be relatively straightforward. The studies on musicians and climbers described in this thesis are examples of such semi-structured designs. Unstructured experimental designs are nearly real-life situations where brain/body datasets are collected. Participants have high behavioural and cognitive degrees freedom at the cost of internal validity and interpretability of results. The most important point Parada (2018) makes not that one design approach is better than another, but rather than they have tradeoffs that must be acknowledged. Moreover, it is not recommended that researchers have to stay within one approach. The idea of the continuum is to be able to move comfortable across approaches. Experiments can be designed to be scalable across this continuum, allowing for exploration of neural correlates of flow based on robust findings under structured and controlled conditions, testing these results in semi-structured complex, yet still fairly controlled, experiments, pushing new hypotheses into complex unstructured settings and returning to a more structured setting if necessary.

With regards to studying the neuroscience of flow, I have added two related concerns. The first is physiological signal-to-noise ratio. This refers to two things. One is the use of different neuroimaging modalities to observe brain activity. While fMRI can access deeper brain structures like the amygdala and dorsal raphe nucleus, which have been persuasively linked to the flow experience (Ulrich et al., 2016a), and allows more accurate views of functional network activity (Huskey, Wilcox, et al., 2018), it cannot be brought out of a lab and flow-inducing activities that are explorable within it are limited. The limited mobility might also suggest the difficulty of inducing deep flow. On the other hand, EEG can only reliably measure activity from the cortical surface though promising work is being done with source-space analysis which allows projection to deeper brain structures. But it has the temporal resolution to measure rapid changes in neural activity, which might be necessary in studying complex activities. And more importantly, it can be brought out of the lab where more flexible conditions allow recreation of the conditions that help people get into their flow. However, as the experiments described in this thesis discovered, the increased flexibility can result in unexpected experimental outcomes that can be hard to interpret. Data collected outside the confines of the laboratory is not only messier in the sense that it is harder to interpret, but because of participants' increased freedom of movement, there are more artifacts. But a more flexible, naturalistic environment might mean higher likelihood of flow. Hence, flow neuroscience research needs to get to grips with scalable experiments.

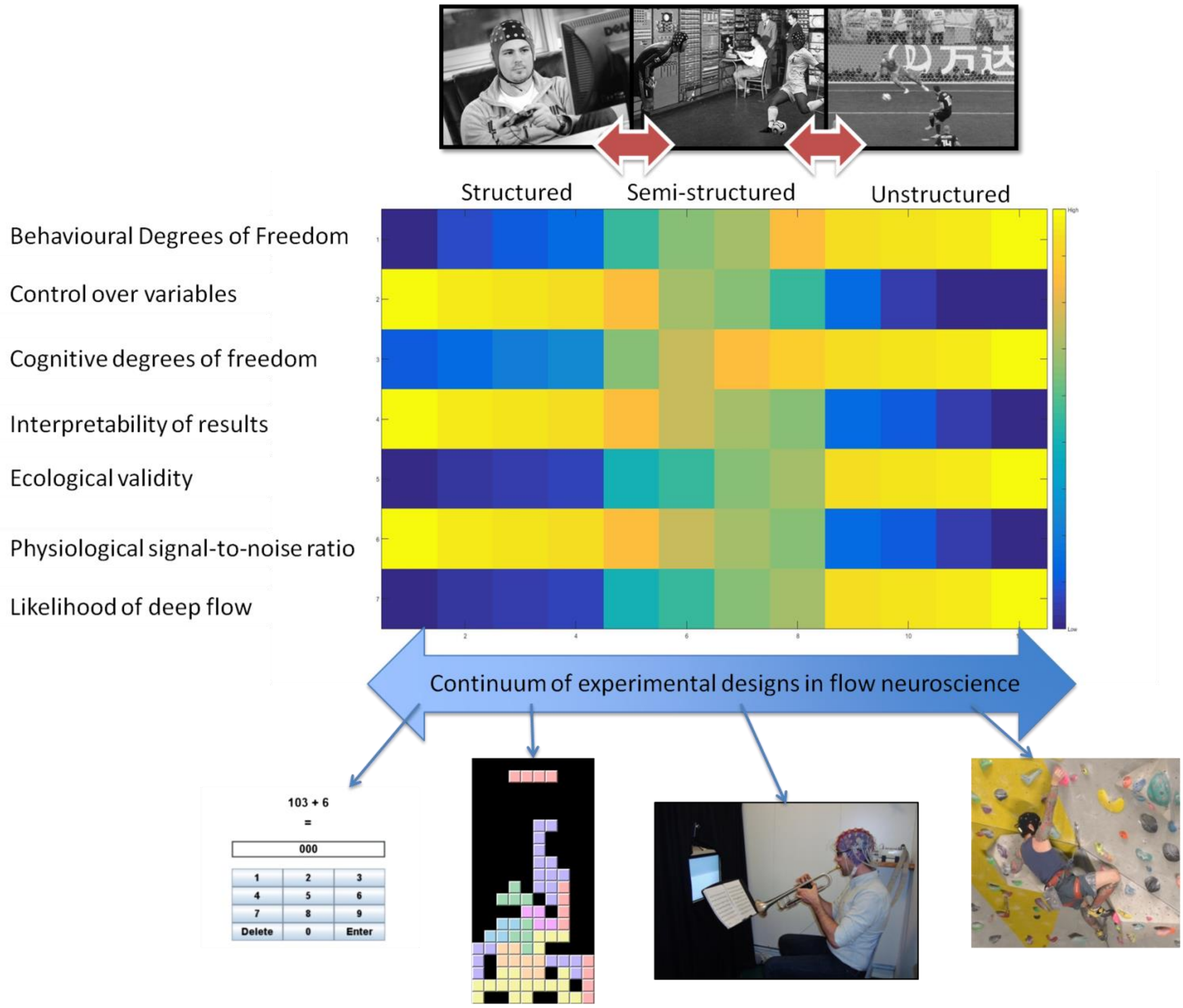


Figure 9.1: Flow neuroscience experiments on a continuum from structured to unstructured experimental designs, with the impact of design decisions on dimensions such as ecological validity and interpretability of results. Adapted with permission from Parada (2018)

In the context of flow research, a simple approach that immediately comes to mind is testing the AEP probe paradigm of Nunez Castellar et al (2019) and Shehata (2020) in an activity outside the lab to see if the attenuation of the response to the auditory oddball occurs in an engaging activity, possibly in combination with an experience sampling methodology. With technology like mobile EEG and transparent EEG rapidly ushering in a new world of real-world neuroscience (Matusz, Dikker, Huth, & Perrodin, 2019), the opportunity to collect data that reflects people's actual flow experiences seems more possible every day. Some studies have already attempted to collect physiological data under real-world circumstances (Gaggioli et al., 2013; Schmidt, Gnam, Kopf, Rathgeber, & Woll, 2020). Schmidt et al (2020) is particularly interesting in that cortisol was collected during an e-sports tournament. It is possible that the real stakes of the competition could lead to higher incidence of flow experience (Csikzentmihalyi, 1990). In designing for structured and unstructured experiments, flow neuroscience also has an advantage as unlike other fields of neuroscience, research studying flow outside the lab already exists in the form of Experience Sampling Method studies. Flow neuroscience has a rich array of studies to draw on to design experiments to effectively study flow outside the lab.

9. 3. 2. A reliable way of identifying flow

When discussing the importance of a reliable flow manipulation in facilitating the exploration of the neuroscience of flow, Moller et al (2010) wrote "it is infeasible, at the moment , to attach a high-resolution brain scanner...to an athlete or artist's head and have him or her wander around until an episode of flow sets in" (Moller et al., 2010). This slightly tongue-in-cheek description may soon become a reality as the technology of mobile EEG advances to the point that it becomes feasible to collect neural data from people going about their daily activities. But then, our problem would be to determine what constitutes flow.

We can discuss the problem of laboratory conditions on flow induction or the difficulties and unknowns associated with flow induction, but a related problem that has not been solved is the problem of *recognising* flow when it happens. For example, if, as argued in Chapter 3, circumstances may require sorting data by flow scores, there is no cut-off score for determining if someone was in flow or not at a certain point. Some early work has been done on using the FSS scores to judge if someone has been in flow. However, taking anyone with a general score higher than the midway point suggests an unrealistically high number of flow experiences, so more work needs to be done (Kawabata & Evans, 2016).

One solution may be to use multimodal recordings and derive flow from multiple physiological markers like heart-rate variability, electrodermal activity, neural response to an oddball etc. However, we are still far from established physiological markers of flow.

9. 3. 3. Methods of flow induction

When an experimental flow induction involving systematically varying the challenge of a task in relation to a participant's skill level was conducted in a climbing centre, no overall effect of the inverted u-shaped relationship between flow and difficulty was observed. However, when examined individually, some climbers showed the expected inverted u-shaped curve. If there are person-level moderators of the effect of experimental flow induction, such as achievement motivation (Engeser & Rheinberg, 2008; Schattke et al., 2014) and action orientation (Keller & Bless, 2008), the relevant information should be collected before a neural study is run with this paradigm. Studies on the neuroscience of flow have yet to include a systematic look into the effects of personality. This is where research into dispositional flow will help greatly. Studies into factors predicting the likelihood of experiencing flow in a given activity can be extended predicting the likelihood of experiencing flow under experimental conditions and participants can be selected to maximise the chance of capturing neural activity of flow.

However, if we are moving towards studying the neuroscience of flow in intrinsically enjoyable activities that have meaning for people, it is worthwhile to ask if flow is really such a rare thing when people are allowed to do the things they enjoy on their own volition and out of the lab. It may be possible to work closely and extensively with people who really understand their flow state, possibly with repeated sessions, with their experiences and movements recorded on film and with multiple measures, including self-report and electrophysiology.

Finally, Chapter 8 raised the possibility of using neural entrainment to alter brain states to experience flow. Though the experiment did not find effects of neural entrainment on flow experience, more research can be done with beats at other frequencies in different contexts. Part of the idea behind neural entrainment is putting the brain in an optimal state, depending on whether the desire is for mental relaxation or alertness (Colzato et al., 2017). Being able to induce a state conducive to flow will also help increase chances of experiencing flow. Beyond the fact that more flow is desirable, increased chances of experiencing flow also increase the chances of studying its neural correlates.

9. 3. 4. Hyperscanning

Hyperscanning, or the simultaneous imaging of two or more brains, may be a tool that will be frequently used to study flow in the future. A hyperscanning set-up allows the study of interactions between two or more people. Flow was reported more in social than solitary situations (Csikzentmihalyi & Csikzentmihalyi, 1988). Flow may thus be more likely in a hyperscanning set-up than a task done alone. Studies in flow neuroscience have already begun looking at activity during team games, such as couples tennis on a computer game (Labonte-Lemoyne, 2016), joint improvisation (Noy, Levit-Binun, & Golland, 2015) and a music rhythm game (Shehata et al., 2020). Not only can data be collected from one brain but interactions between brains in flow together can be elucidated.

9. 4. Conclusion

Most research into the neuroscience of flow has considered tasks like mental arithmetic, that are less engaging and when conducted in the controlled environment of a lab, do not reflect the conditions under which flow is usually experienced. Here, we suggest an alternative framework to study flow by studying people who are engaged in a complex activity they find intrinsic enjoyment and meaning in, and argue that this represents a valid, if technically challenging, opportunity to collect neurophysiological data under conditions conducive to flow and reflect an experience more recognisable as the optimal experience often described as flow. Studies in Chapters 2 and 3 show that self-induced flow in musicians is neurally distinguishable from non-flow, even in the moments after the activity. Some findings, like differences in the theta and alpha band align with findings on experimental flow. Others, like findings in the beta band do not. The pattern of delta and beta band power suggest that flow is characterised by reduced activity in the default mode network, a finding that fits well with fMRI studies on flow. However, analysis needs to be conducted in the source-space to draw firmer conclusions.

A recurrent theme is the unpredictablity of flow. In both the studies on musicians and climbers, flow state scores were not always highest in the condition that was supposed to be most conducive for flow. In Chapter 3, playing a flow-inducing piece did not always result in the highest flow scores. In Chapter 5, in an experimental flow induction conducted in a climbing centre, climbers did not show the expected inverted u-shaped relationship between flow and difficulty. When there is a discrepancy between flow scores and conditions, it raises the related problem of the uncertainty of determining when someone is in flow.

The unpredictability of flow may be solved with more research into what influences dispositional flow, or someone's tendency to get into flow. Research into the effect of non-cognitive factors like grit and mindset on dispositional flow found that they did not predict flow beyond what would be predicted by practice hours and music performance anxiety. Trait emotional intelligence however, not only correlated with dispositional flow in music performance but also with dispositional flow in climbing and daily living. But when looking into resting state data for neural correlates of flow, frontal asymmetry was found to correlate with trait emotional intelligence but not with dispositional flow.

Finally, neural entrainment using monaural beats was investigated as a way to alter brainwaves to a state more conducive to flow. However, monaural beats were found to have unpredictable effects, entraining lower alpha frequencies (8 - 10Hz), rather than theta or upper alpha frequencies which have been linked to flow experience. Hence, it was not possible to test if altering these frequencies, which have been found to correlate with flow experience, changed flow experience. No effect on flow experience during music listening was found but heart rate variability data suggests that monaural beats at the alpha frequency band induced a more relaxed state that may be more conducive to flow.

This thesis offers but a scratch on the surface that is the neuroscience of flow, or the brain in its optimal state. Many of the findings, though intriguing, await further confirmation and elaboration, but they represent an effort to study the neuroscience of flow as it is experienced in activities that people do to experience flow. If, as Abuhamdeh (2020) states, flow is a rare and discrete phenomenon, it does not then follow that research into flow neuroscience has no recourse. It will require sensitive experiment design and appropriate tools. It is not unlike filming wildlife. A lot of preparation is needed along with knowledge of where to look. Unobtrusive data collection techniques capture more behaviour. A keen understanding of the subject and knowing how to recognise it is key. The desired behaviour is rarely on demand. But wildlife cameramen still manage to obtain footage of rare elusive animals. Similarly, despite the difficulties, knowledge of the brain in its optimal state is a worthy goal to strive for.

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