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Neurocognitive mechanisms of the flow state

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Abstract

While the experience of flow is often described in attentional terms - focused concentration or task absorption - specific cognitive mechanisms have received limited interest. We propose that an attentional explanation provides the best way to advance theoretical models and produce practical applications, as well as providing potential solutions to core issues such as how an objectively difficult task can be subjectively effortless. Recent research has begun to utilise brain-imaging techniques to investigate neurocognitive changes during flow, which enables attentional mechanisms to be understood in greater detail. Some tensions within flow research are discussed; including the dissociation between psychophysiological and experiential measures, and the equivocal neuroimaging findings supporting prominent accounts of hypofrontality. While flow has received only preliminary investigation from a neuroscientific perspective, findings already provide important insights into the crucial role played by higher order attentional networks, and clear indications of reduced activity in brain regions linked to self-referential processing. The manner in which these processes may benefit sporting performance are discussed.

Keywords: attention, neuroscience, mechanisms, peak performance, zone

Neurocognitive mechanisms of the flow state

‘The consciousness of self is the greatest hindrance to the
proper execution of all physical action’

- Bruce Lee (Tao of Jeet Kune Do, 1975)

Introduction

The crucial role that attention plays in shaping the learning of sporting skills, performing under pressure and facilitating expertise is well established (Mann et al., 2007; Moore et al., 2012). However, the state of flow, something of an attentional anomaly (Bruya, 2010), provides an alternate perspective from which to examine attention during peak performance. During flow increased demands are paradoxically met with no apparent increase in effort (Csikszentmihalyi, 2000), and athletes report a laser-like task focus in the face of distractions (Jackson & Csikszentmihalyi, 1999). Flow is frequently linked to peak performances (Jackson et al., 2001; Koehn & Morris, 2012) as well as heightened enjoyment (Privette, 1983). Therefore understanding the cognitive processes responsible for this state may inform both attentional models and practical endeavours for finding peak focus during sporting performance.

Flow, or ‘the zone’, is a phenomenological state where an individual finds an effortless involvement and deep, task-related focus in the current activity. It is accompanied by a feeling of control and a loss of self, creating an intrinsically motivated, optimal experience (Csikszentmihalyi, 1975; 1990; 2000, see figure 1). Athletes in flow often report reaching the apex of their abilities and levels of fulfilment that are unrivalled in the rest of their lives (Jackson & Csikszentmihalyi, 1999). While research has described the nature of the experience and it’s antecedents in sport (Jackson, 1996; Swann et al., 2015), the underlying mechanisms of flow are not well understood. We propose that a deeper

consideration of attentional processes may be crucial to this understanding. Therefore we review current findings related to the role of attention, and the ways in which direct brain recording can inform this understanding, with the aim of proposing attentional changes as the fundamental mechanism for creating the state of flow.

In order to understand flow in the context of sporting performance (and the potential benefits it provides), findings from the sporting literature will be considered alongside neuroimaging research. Imaging findings are well established across the wider field of attention (Corbetta & Shulman, 2002; Fan et al., 2005) and will be used to highlight how attentional changes may provide beneficial outcomes for sport. We do not attempt an exhaustive review of either sporting flow or neuroimaging studies, but endeavour to give an overview of findings central to understanding attentional processes during flow.

Figure 1; Schematic representation of the focus of the article. While the experience of flow (box 3.) and its antecedents (box 1.) have been well documented, the focus of our discussion is the attentional processes (box 2.) that happen alongside, and may be responsible for, the experiential components.

1 **The Flow State**

2 Flow, the mental state of complete absorption in the present task, is traditionally
3 described along Csikszentmihalyi's (1990) nine dimensions. Three of these dimensions are
4 described as setting the conditions for flow; a balance of challenges and skills, clear goals and
5 immediate feedback (Kawabata & Mallett, 2011; Nakamura & Csikszentmihalyi, 2009).
6 Csikszentmihalyi suggests that flow occurs when challenges and skills are in balance, in a
7 channel between the states of boredom and anxiety. The remaining six dimensions are
8 experiential components (Nakamura & Csikszentmihalyi, 2009); intense concentration,
9 merging of action and awareness, loss of self-consciousness, a sense of control, distortion of
10 time, and intrinsic rewards (autotelicity). This conceptualisation of flow has received robust
11 support across a range of domains; including art and science (Csikszentmihalyi, 1996), sport
12 (Jackson, 1996) and literary writing (Perry, 1999).

13 **Flow in Sport**

14 The sport setting is ideally suited for achieving flow, as sporting activity can provide
15 the three basic conditions Csikszentmihalyi suggests are necessary; clear goals, immediate
16 feedback and a balance between challenge and skill. The added effect of physical exertion
17 may further enhance the experience of total absorption (Dietrich, 2006). Finding flow is
18 highly desirable, as athletes report effortlessness and fluency of performance when in the
19 state (Swann et al., 2015). As there is reasonable agreement over what characterises a flow
20 experience (Swann et al., 2012) research in sport has mainly focused on its antecedents. For
21 example a systematic review by Swann et al. (2012) found the most common antecedents to
22 be focus, preparation, motivation, arousal and positive thoughts. Unfortunately research in
23 sport is yet to identify important mechanisms that underpin the experience and has made
24 limited use of experimental approaches to studying flow. As such, findings from other

domains applying neuroscientific approaches will be discussed as they provide both methods that can drive flow research forwards, and important implications for how attention during flow may enable superior performance.

Attention

Attention is the cognitive process of selecting discrete aspects of information for further processing; it allows an animal to behave adaptively in a world containing an overabundance of information (Knudsen, 2007). Attention therefore shapes our experience but is also key to selecting our responses to it (Allport, 1989) and is a viable candidate for facilitating beneficial effects of flow given that effective attentional control has been shown to have significant benefits for sporting performance (Abernethy et al., 2007). For example, optimising the target and timing of visual attention can enhance psychophysiological efficiency, visuomotor coordination and movement kinematics (Moore et al., 2012).

As four of Csikszentmihalyi's (1990) six experiential components of the flow experience (intense concentration, merging of action and awareness, loss of self-consciousness, and distortion of time) allude to changes in attentional processes, these mechanisms deserve further clarification. Within the sporting literature athletes report focus as being crucial for finding flow (Jackson, 1992). Swann et al. (2012) also found the most reported aspects of the experience to be concentration and action-awareness merging, again suggesting a fundamental role for attention. In order to build an initial picture of attention during flow, we focus on four topics that emerge from current literature: the degree of automaticity, the role of effective attentional control, the extent to which flow requires effortful attention, and the experience of reduced self-awareness.

Automaticity

A prominent theoretical approach is to describe flow as a state of enhanced automaticity, essentially an absence of controlled attention. Automated control is generally, though not always, thought to provide benefits for action in terms of efficiency, fluency and reduced resource allocation (see Toner et al., 2015). Automatic or implicit processes are fast and efficient, and circumvent conscious awareness of effort (Moors & DeHouwer, 2006), and as such may contribute to the frequent perception of ease during flow. As automaticity involves reduced executive activity, it is characterised by reduced frontal activation (esp. lateral and dorsolateral PFC), as regions of basal ganglia acquire motor sequence knowledge (Poldrack et al., 2005). A model of the flow experience centred on a reduction in prefrontal control is proposed by Arne Dietrich (2003).

Transient Hypofrontality Theory (THT). Dietrich (2003) suggests that the core components of the flow experience, and other altered states of consciousness, can be explained by reductions in processing by the prefrontal cortex (PFC). Higher processes like abstract thinking, self-reflective consciousness and working memory are lost (known as phenomenological subtraction), creating states of reduced function (common in running, meditation or hypnosis). These states are suggested to be linked to flow due to a common mechanism of hypofrontality (i.e. reduced frontal activity and executive functioning).

Dietrich and Stoll (2010) argue that sports are particularly good at engendering flow states for two reasons. First, bodily motion is extremely complex in computational terms, and as such uses considerable mental resources (demonstrated by Stoll & Pithan, 2016). When prolonged, this is sufficient to divert processing away from non-critical cognitive processing (i.e. higher order function in the PFC). Second, Dietrich suggests that as an action becomes more automatic, and under control of the basal ganglia (Poldrack et al., 2005), it is easier for frontal function to decrease and for this altered state of consciousness to arise. Dietrich's suggestion that action in flow is more automatic also accounts for the effortless experience

often associated with flow, as automatic action is controlled through unconscious or implicit processes, and unavailable to conscious awareness (Moors & De Houwer, 2006). In attentional terms, they are not constrained by capacity limitations, excluding them from mental effort (Kahneman, 2011).

Imaging studies have provided some support for a reduction in frontal activity, but results suggest a very specific pattern, that does not constitute a general deactivation. Ulrich et al. (2016) and Ulrich et al. (2014) found reduced activity of the medial prefrontal cortex, an important structure in self-referential processing. Conversely, however, research by Yoshida et al. (2014) using functional near infrared spectroscopy (fNIRS) found increased ventrolateral PFC activation during a flow level of a gaming task. Additionally research by Harmat et al. (2015) again used fNIRS to test prefrontal activation during flow in a widely used paradigm utilising continual adjustment of difficulty in the game ‘Tetris’. There was found to be no reduction in frontal activity, suggesting that a general mechanism of hypofrontality may be overly simplistic. Support for hypofrontality comes mainly from studies finding reductions in cognitive function as a result of prolonged exercise (see Stoll & Pithan, 2016). Whether this state is representative of a general flow mechanism is questionable. Harmat et al. (2015) suggest that the demands on executive control, even during a relatively simple Tetris task, make a reduction in prefrontal activity unlikely.

Reduced verbal-analytic processing. Initial electroencephalogram (EEG) research does provide support for a move towards automaticity, and the avoidance of deliberative control of motor responses (e.g. Reinvestment theory, Masters & Maxwell, 2008). EEG assesses cortical activity through electrodes placed on the scalp, which give information regarding rhythmic neural oscillations, measured in Hertz (Hz), and may be useful for identifying brain areas that are particularly active or inactive during flow. Of particular

interest is the alpha band (8-12 Hz), which reflects relaxed wakefulness and may signpost areas that are inhibited during flow (Pfurtscheller et al., 1996).

Wolf et al. (2015) demonstrated that flow during table tennis imagery was related to a reduced influence of verbal-analytic processing on motor control, which was also related to expertise. EEG recordings showed relative deactivation (higher alpha power) of a left temporal site (T3), associated with verbal-analytic processing, compared to the corresponding right site (T4) which reflects visuospatial processing. Their results suggest that the flow experience may involve a shift away from verbal-analytic influence to a more automatic mode of operating; the same shift that has been found with a progression from novice to expert performance (Deeny et al., 2003), and from more explicit to more implicit forms of motor performance (Zhu et al., 2011). Further success of EEG in identifying markers of flow may provide opportunities for training flow experiences (see Cheron, 2016), due to previous success with EEG in neurofeedback training (Ring et al., 2015).

This conceptualisation of flow based on automation is appealing and indeed seems sufficiently entrenched to have permeated areas like philosophy; from the ancient Chinese concept of ‘wu-wei’ (Slingerland, 2014) to Dreyfus’ anti-representationalist account of choking and coping under pressure (see Dreyfus, 2007; Gottlieb, 2015). Automated processes provide benefits for action and are a hallmark of expertise (Fitts & Posner, 1967; Singer, 2002), so whilst the mechanism of hypofrontality may be questionable (based on neuroimaging and mental effort findings, see below), the benefits of automated action for avoiding conscious disruption of well-learned movement sequences are clear. As such, if flow enables an enhanced degree of implicitness in motor control we can expect to see benefits for sport. Whether this degree of automaticity extends to aspects of performance like decision-making, selective attention, creativity and problem solving seems unlikely (Harmat et al. 2015).

A mixed pattern of automatic and controlled processing has also been found in the study of musical improvisation, a flow-like activity where musicians display high levels of creativity, spontaneously producing complex musical structures (Nisenson, 1995). Limb and Braun (2008) found that during improvisation, in contrast to over-learned sequences, jazz pianists displayed a dissociated pattern of frontal activity with deactivation of lateral prefrontal areas associated with effortful problem solving and monitoring of goal-directed behaviours (Ashby, Isen & Turken, 1999). However, several other studies of improvisation *have* supported the involvement of monitoring and cognitive control processes (Bengtsson, Csikszentmihalyi & Ullén, 2007) suggesting a greater coupling between creative and controlled (executive) processes (see Beaty, 2015 for a review). Losing yourself in the performance may not be as simple as a complete absence of cognitive control, but a more balanced cooperation between spontaneous and deliberative processing.

Similarly, Csikszentmihalyi and Nakamura (2010) postulate that the importance of automaticity during flow lies in allowing automated sequences to take care of themselves, so that *more* attention can be paid to essential aspects of the activity. They suggest that effortless attention is rarely fully automatic, and a person is often more open, alert and flexible within the structure of the activity. Such a balance between attentional effort and automatic processing perhaps provides the benefits for sporting performance that accompany automated action sequences (Singer, 2002) and the flexibility and problem solving that come with more effortful, controlled processing (Miyake et al., 2000).

Attentional control

Attentional control involves the ability to direct attention to only those stimuli that are relevant to our current goals, minimizing the extent to which bottom-up influences capture our attention (Corbetta & Shulman, 2002). Sarter et al. (2006) describe top-down control as

the ‘biasing of attentional resources toward the detection and processing of target stimuli’ (p.148) which they link to attentional effort. While flow has not traditionally been associated with controlled processing (Dietrich, 2006), the characterization of flow as an extreme focus with immunity to distraction (Jackson & Csikszentmihalyi, 1999) suggests a strong influence of top-down attentional control. Effective attentional control might explain the performance advantages reported for flow, as limited attentional resources are optimised through becoming highly task focused.

Synchronisation theory. A theory of flow proposed by Weber et al. (2009) suggests that widespread synchronization between neural attention networks may provide the basis for the complete absorption apparent during a flow state. The theory is based on Posner, et al.’s (1987) tripartite theory of attention; involving executive, alerting and orienting networks. The alerting network is responsible for initiating and maintaining attentiveness, while the orienting network directs attention to a stimulus. The executive network modulates both and plays a crucial role in top-down control. Optimal attentional control depends upon directing attention to relevant stimuli, and if alerting and orienting networks were optimally synchronized with executive control we would expect attention to be highly goal-directed (Petersen & Posner, 2012).

Weber and colleagues propose that this organisation is achieved through synchronized firing rates of neurons within attentional networks. Neurons fire at varying rates at rest, but oscillatory activity in groups of neurons can arise from feedback connections between them, particularly in the alpha (8-12Hz) and theta (4-7Hz) bands. Synchronised neural activity is proposed as a solution to the binding problem of consciousness (Crick & Koch, 1990), as groups of neurons that have become synchronized may coordinate their processing. Weber et al. suggest that coordinated firing of alerting, orienting and executive attention networks, alongside reward networks (Schultz, 2006), gives rise to the experience of flow, as all

1 attention and reward systems are working harmoniously. This optimal organization (which
2 Csikszentmihalyi terms *negentropy*) is highly efficient, creating mental ease, which is often
3 reported during flow (Bruya, 2010). In effect, this theory suggests that flow enables an
4 optimal, highly efficient organisation of attention, with an important role for executive
5 function and top-down maintenance of goal directed attention.

6 *Top-down attention networks.* The importance of higher attentional processes during
7 the flow experience is supported by neuroimaging research. Ulrich et al. (2016) have
8 identified activation of brain areas associated with the Multiple Demand (MD) network
9 during flow in an arithmetic task. The MD system (Duncan, 2010) reflects activity of a
10 functionally general network of brain regions associated with a variety of cognitive
11 challenges. The MD network involves areas of the prefrontal and parietal cortex, including:
12 the inferior frontal sulcus, anterior insula, pre-supplementary motor area and in and around
13 the intraparietal sulcus. Duncan (2010; 2013) links the MD system to goal-directed
14 behaviour, fluid intelligence and selective visual attention. In particular it plays a function in
15 organizing multi-step behaviour. Interestingly, Ulrich et al. found brain areas related to the
16 MD network to be activated *more* during a flow level of difficulty than a harder level of
17 difficulty, with activation associated with performance.

18

Figure 2; The ventral network (blue), responsible for reorienting attention to salient stimuli, projects from the temporo-parietal junction (TPJ) towards inferior frontal gyrus (IFG) and middle frontal gyrus (MFG). The dorsal network (orange), responsible for top-down voluntary allocation of attention, projects from the superior parietal lobe (SPL) towards the frontal eye fields (FEF). The MD system includes overlapping fronto-parietal areas, from the SPL to the premotor cortex and inferior frontal sulcus (IFS) (Figure reproduced from Aboitiz et al., 2014).

Alternatively the areas identified by Ulrich et al. (2016) could also be interpreted as reflecting increased activity of the dorsal stream of attention (Corbetta & Shulman, 2002, see figure 2). The MD system depends on areas of parietal and frontal cortex which are identified by Corbetta and Shulman (2002) as part of the fronto-parietal dorsal stream. Indeed Duncan (2013) notes the overlap between MD and dorsal networks, and therefore the findings of Ulrich et al. may also be instructive of the important role played by the dorsal stream in promoting goal-directed control of attention during flow. Either way, these findings are indicative of top-down control of attention, as the MD system serves to coordinate a series of multi-step behaviours, guide selective focus to task-relevant information and provide cognitive control. These findings strongly challenge views of flow as a state of automaticity, with reduced frontal influence (Dietrich, 2004), and highlight that during flow supervisory attentional and cognitive control systems of the brain are highly active.

Dopamine pathways. Attentional processes during flow may also be affected by neurotransmitter activity, as findings highlight a role for dopamine. Dopamine pathways are

1 primarily associated with reward networks in the brain (Schultz, 2006), but also modulate
 2 attentional focusing (Nieoullon, 2002), error monitoring (Holroyd & Coles, 2002;
 3 Ridderinkhof et al., 2004) and response inhibition (Congdon et al., 2008; Chambers et al.,
 4 2009). De Manzano et al. (2013) have demonstrated that flow prone individuals have
 5 increased availability of dopamine D2 receptors in the striatum, which is functionally related
 6 to selective attention (Nieoullon, 2002). Gyurkovics et al. (2016) have identified flow
 7 proneness to be related to a D2 receptor coding gene, and suggest that the relationship
 8 between dopamine and flow may be through reduced impulsivity and more effective response
 9 inhibition.

10 Reduced dopamine action is associated with impulsive behaviour (Dalley & Roiser,
 11 2012) evidenced by its therapeutic effects on impulsivity in ADHD (Kollins & March, 2007),
 12 so individuals with enhanced D2 availability are predisposed to the behavioural control and
 13 monitoring benefits of dopamine. The findings related to dopamine fit with our wider
 14 discussion of attentional control, which requires response inhibition and impulse control
 15 (Miyake et al., 2000), that are modulated by dopamine action (Dalley & Roiser, 2012;
 16 Nieoullon, 2002). These findings also have important implications for individual differences
 17 in flow and the ‘autotelic personality’ (Csikszentmihalyi, 2000), which may therefore have a
 18 biological basis.

19 The findings discussed here point strongly to an important role for higher order
 20 attention control mechanisms during flow, although this is perhaps not the dominant
 21 approach within the flow literature (Dietrich, 2006; Jackson, 1996; Swann et al., 2016).
 22 Effective control of attention is established as crucial for optimal sporting performance. For
 23 example, optimal attention control, as indexed by the quiet eye (Vickers, 1996), provides
 24 significant inter- and intra-individual performance benefits (see meta-analysis by Lebeau et
 25 al., 2016). The quiet eye is a final fixation to a target prior to movement execution, which

provides task focus and allows organisation of neural networks for controlling movement (Vickers, 2009). The importance of optimal control of visual attention is highlighted by its negative corollary; as disrupted attentional control under pressure has been shown to impair motor performance (see Eysenck & Wilson, 2016 for a review). For example, there is ample evidence that conditions designed to increase anxiety and reduce flow can impair attention (indexed via quiet eye) and subsequent performance in a range of sport skills; including basketball free-throw shooting (Wilson et al., 2009), soccer penalties (Wood & Wilson, 2010) golf putting (Vine et al., 2013); and biathlon (Vickers & Williams, 2007). The use of technology, such as mobile eye trackers, to measure objective, task-relevant indices of attentional control (e.g., quiet eye) may therefore provide useful insights into the flow process while it unfolds.

Attentional effort

Traditional models of attention suggest that as a task becomes more difficult, requiring cognitive or executive control, more mental energy (or effort) is required to meet demands (McGuire & Botvinick, 2010). Mental effort, the motivated activation of attentional systems (Sarter et al., 2006), has a physical basis, leading to changes in both central (neural) and peripheral (e.g., cardiovascular) psychophysiological indicators (Berntson et al., 1997). However flow presents a challenge for attention researchers, as difficult tasks are met with a perceived *decrease* in felt effort (Bruya, 2010). This type of effortless attention has been referred to as ‘post-voluntary’: neither voluntary (effortful) nor involuntary (automatic), but captured by an absorbing activity (Dobrynin, 1966).

During flow, individuals report that task control becomes effortless as they become fully absorbed. Therefore either the task has become easier, and does not require mental effort, or the subjective experience has become dissociated from the objective level of mental

work. Several studies utilising objective markers of mental effort during flow, would suggest the latter. For example, Gaggioli et al. (2013) revealed that everyday flow experiences were indexed by increased sympathetic activity (increased heart rate), suggesting that the perception of ease is not reliably reflected in physiological activity.

Psychophysiological measures of attentional effort. Heart rate variability (HRV), the fluctuation in beat-to-beat interval, provides an objective measure of mental effort (Berntson et al., 1997) and attention (Bucks, 1997). Mental effort reduces HRV (particularly in the low frequency, 0.04-0.15 Hz band) due to increased sympathetic regulation and decreased influence of the baroreflex (Berntson et al., 1997). Keller et al (2011) found that a balance between challenge and skills (a precursor to flow) produced positive subjective reports, but decreased HRV, indicating increased mental effort. Likewise, Tozman et al. (2015) found that a flow-task reduced HRV in the low frequency component (i.e. required more mental effort) compared to an objectively easy task. Finally, Peifer et al. (2014) found an inverted-U relationship between flow and low frequency HRV; suggesting that once a moderate level of mental effort is reached, additional mental load is detrimental.

Conflict monitoring. The psychophysiological research provides a consistent picture that flow does demand attentional effort, and hence cannot be considered ‘automatic’. A possible explanation for the lack of felt effort can be found in the work of Botvinick and colleagues on the conflict-monitoring hypothesis (Botvinick et al. 2001), which indicates how a task may feel easier during flow. Within the conflict monitoring hypothesis, subjective mental effort arises from a change in cognitive control, when the demands of the situation are appraised as not being met. During flow, challenges and skills balance, performance is fluent and no change in cognitive control is required (McGuire & Botvinick, 2010). As highlighted by Dobrynin (1966), effortless attention occurs when the task is fully absorbing, and hence cognitive control is not required to maintain focus. The anterior cingulate cortex (ACC, see

figure 3) is proposed as a key structure within cognitive control and conflict monitoring (Botvinick et al., 2001; Botvinick et al., 2004; Van Veen & Carter, 2002), serving to monitor processing and determine when attention needs to be refocused or redirected. The importance of the ACC in the perception of effort is demonstrated by Naccache et al. (2005), who found a patient with ACC lesion did not experience effort in a Stroop task, in spite of normal executive control. In addition, Posner et al. (2010) suggest that early stages of meditation may depend on ACC to exert control, with activity receding as it becomes more effortless.

Figure3; Key prefrontal areas and some of their functions. The ACC may contribute to perceptions of effort during flow, while imaging has suggested reduced mPFC activity (Ulrich et al. 2016) but increased activity within IFG (Ulrich et al. 2014) and dlPFC (Yoshida et al. 2014). Reprinted by permission from Macmillan Publishers Ltd: Nature Reviews Neuroscience (Amodio, 2014), copyright (2014) www.nature.com.

Neuroimaging studies provide evidence that the same process may be occurring during flow. Klasen et al. (2011) found reductions in rostral ACC activity associated with increased focus, and reductions in dorsal ACC activity associated with clear goals in the task, in participants experiencing flow while playing a video game. Ulrich et al. (2016) also found

reduced neural activation in the right anterior cingulate during a flow level of an arithmetic task. These findings indicate how the nature of a flow task, providing clear goals and holding an individual's focus, may allow reductions in the need for cognitive control through reduced activity of the ACC, and subsequent reductions in felt effort.

The predictions of the CMH identify how felt effort may dissociate from the physiological markers of attentional effort discussed previously. This dissociation has been demonstrated experimentally by Harris et al. (2017), who directly tested opposing predictions for felt and physiological effort in a simulated driving task. While greatest physiological effort was found during a matched-to-skills (flow) condition, subjects reported effort to be highest in a difficult drive and only moderate in the matched level. Harris et al. (2017) propose a model of effort during flow whereby (low) felt effort relates to the conflict monitoring mechanism, but invested physiological effort is greatest under optimal challenge (based on the predictions of motivational intensity theory, Wright, 1996). These findings indicate that despite greater investment of resources, flow felt comparatively easy, as conflict was minimised. This effect may help to explain the *effort paradox* during flow.

The research discussed demonstrates that attentional effort is required during flow in order to meet the demands of a challenging task, which fits with our preceding consideration of top-down attention. It has been illustrated that while these processes can be highly effortful, during flow this is not necessarily the case, as when goals direct attention there is little psychological cost (Schmeichel & Baumeister, 2010) and goal-directed control may be maintained with little effort (Land, 2006). Optimal attentional control during flow is perhaps more dependent upon the absence of stimulus-driven disruption and monitoring processes, than of effortful top-down control. Subsequent reductions in cognitive control may be beneficial for sporting performance through avoidance of deliberative control of implicit processes which can lead to reinvestment and disrupted performance (Masters, 1992; Masters

& Maxwell, 2008). Feelings of ease may further contribute to performance through promoting confidence and positive emotions. While potential explanations have been outlined here, this paradoxical aspect of attentional effort during flow requires further consideration and should be considered a significant challenge for attention researchers (Bruya, 2010).

Self-awareness

Whilst there appears to be an increased deployment of attentional resources during flow, they appear to be largely directed away from the self (Csikszentmihalyi, 1975; 1990). When fully absorbed in a flow inducing activity, attention is directed towards the goal and the self recedes; bodily actions are reported to feel as though they are moving on their own, without conscious willing and where self-awareness does exist, it seems to be pre-reflective (see Toner et al., 2016 for discussion). Phenomenologist Jean-Paul Sartre (1957) recognized the reduction in awareness of the self that comes from complete absorption in an activity. He noted that ‘When I run after a streetcar, when I look at the time, when I am absorbed in contemplating a portrait, there is no I’ (p.48). The role of self-awareness links strongly to the preceding discussion of automaticity, as a switch from internal to external attentional focus provides performance benefits through enhanced automaticity (Zachry et al., 2005). This reduction in self-consciousness during flow is also strongly supported by recent neuroimaging findings.

For instance, Ulrich et al. (2014) utilised magnetic resonance perfusion imaging to investigate flow during differing levels of arithmetic challenge. Reduced relative cerebral blood flow (rCBF) was found in the medial prefrontal cortex (see figure 4), an area strongly linked to self-referential processing (Jenkins & Mitchell, 2011; Northoff et al., 2006) and an important part of the brains Default Mode Network (DMN, Buckner et al., 2008; Raichle et

al., 2001). The DMN is an interacting system of brain regions including the posterior cingulate cortex, medial prefrontal cortex and angular gyrus, which are active during passive states. Activity in the DMN is associated with mind-wandering and thinking about the self, past and future, and is known to be reduced during goal-directed behaviours (Raichle et al., 2001). As well as medial PFC, Ulrich et al. found reduced activity in other regions associated with the DMN (e.g. angular gyrus, supramarginal gyrus, parahippocampal cortex). While decreased activity in this network is not unique to flow, it highlights the importance of reductions in self-awareness and internal focus during the state.

Figure 4; Medial areas of the default mode network. Medial prefrontal cortex (mPFC), posterior cingulate cortex (PCC) and precuneus (PC) are active when the individual is engaged in mind wandering and thoughts about the self. The DMN also includes lateral parietal and medial temporal areas (Figure reproduced from Aboitiz et al., 2014).

Further research by Ulrich et al. (2016) using fMRI again found reductions in medial prefrontal areas and brain regions associated with the DMN. Goldberg et al. (2006) found reduced activity in self-related structures during sensory processing, likening it to ‘losing yourself in the act’, which is strongly suggestive of Csikszentmihalyi’s (1990) dimension of action awareness merging. Ulrich et al. (2016) suggest that this reduced self-awareness may also contribute to another facet of flow; the positive nature of the experience. As self-referential processing is associated with negative affectivity (Lemogne et al., 2011), reductions in activity of the medial PFC and DMN may contribute to a positive flow

experience. Further, an fMRI study by Garrison et al. (2013) applying real time neurofeedback in experienced meditators found reductions in areas of the DMN to link to effortless doing and contentment.

Reduced awareness of the self may contribute, not just to the experience of flow, but to its benefits for performance. In sport, awareness of, and focus on, the self is associated with impaired skill learning and performance (Baumeister, 1984; Beilock & Carr, 2001; Masters, 1992). Wulf and Lewthwaite (2010) outline the self-invoking trigger hypothesis to describe how activation of the self-schema by environmental triggers (e.g. instructions, presence of others) can account for a variety of findings on motor learning and performance. Wulf and Lewthwaite (2010) link this self-schema system to the functional network of cortical mid-line structures found to be inactive during flow. As such, during flow the athlete may be resistant to the self-related triggers and their negative consequences. The reduced activity of the DMN also points to a reduction in internal focus, in favour of focusing externally, on the goal (Nideffer, 1976). Wulf (2013) reports how external focus has been shown to enhance effective and efficient movement, something that is often described in flow, but is yet to be measured empirically. Training target-related, external focus is therefore a potential route for enhancing flow (e.g. Moore et al., 2012). As such, a reduction in activity of self-referential neural structures and the DMN may be highly beneficial for sporting performance, as well as underlying key features of the flow experience.

Attention summary

We have considered four issues related to attention; attention control, mental effort, automaticity and self-awareness that have implications for understanding the experience and maintenance of flow. While there are certainly tensions, for example between automaticity and mental effort, all these features seem important in providing a full picture of the flow

state. A combination of efficient attention and automated action control would seem to account for many of the features identified by Csikszentmihalyi (1990) as well as providing benefits for sporting performance. Based on flow reports we might expect attention during flow to be more external, less self-conscious, less prone to distraction and more task directed, thus leading to improved performance (see Figure 1). Further empirical testing is needed in order to understand the extent of these attentional benefits.

Discussion

This chapter set out to use recent neuroimaging findings to illustrate how attentional processes may provide the best way to understand the mechanisms behind the flow experience. The studies discussed support our contention that attentional processes can explain the key features of flow (e.g. Gyurkovics et al., 2016; Klasen et al., 2012; Ulrich et al., 2016). Findings suggest a reduction in self-awareness, through reductions in medial prefrontal areas and the default mode network (Ulrich et al., 2014); improvements in impulse control related to dopamine activity (de Manzano et al., 2013); and considerable activity in networks related to higher order attentional processing in the Multiple Demand system or dorsal stream of attention (Ulrich et al., 2016). Together these findings account for many of the key features of the flow experience (Csikszentmihalyi, 2000). In addition, these features have implications for sporting performance. For example the activation of higher attentional processes like the MD network support selective and goal-directed attention, which have beneficial performance effects in many sports (Abernethy et al., 2007; Vine & Wilson, 2011; Williams & Davids, 1998). Additionally, reduced verbal-analytic influence (Wolf et al., 2015) and automated performance (Dietrich, 2003) have been linked to sporting expertise (Beilock et al., 2002). Overall, these findings suggest a mental state where improved performance is almost inevitable.

These results also have implications for theories of flow. Dietrich's (2003) hypofrontality theory has received mixed support, suggestive of a more nuanced pattern of activity across the PFC. While unnecessary or even detrimental activity such as self-awareness may be limited, areas of dorsolateral and ventrolateral PFC involved in response selection and inhibition are highly active. As such, current findings suggest that Weber et al.'s (2009) synchronisation theory may more accurately reflect neural activity during flow, as areas related to higher order attentional networks appear to be crucial. The overall pattern of activity during flow suggests a highly efficient 'switching on' of networks for goal-directed activity and a 'switching off' of areas related to the self and conscious control of movement. Additionally models of effort derived from the conflict monitoring hypothesis (Botvinick et al., 2001) such as that of Harris et al. (2017) have received initial support in describing the effort paradox during flow by addressing mechanisms for subjective and objective effort separately.

The important role of top-down focusing and higher attentional networks in flow that has been highlighted here has clear practical implications. To achieve an optimal task focus, the engaging and challenging nature of the task is clearly crucial (Csikszentmihalyi, 1990), but enhancing personal skills and capacities in attention control may also provide substantial benefits. Attention and self-regulation are trainable (Tang & Posner, 2009) and the efficacy of attentional training for sporting skills has recently been demonstrated (Ducrocq et al., 2016). While the transferability of the trained attention skills may require further validation (Shipstead et al., 2012), training sport specific attention skills through methods like quiet eye training may enable more frequent flow experience in the given task. As discussed, the quiet eye is an instance of optimal attention control in an aiming task (Vickers, 1996), but is also trainable, promoting external, goal-directed attention with subsequent performance benefits. Flow experiences are known to be fleeting, and are not a prerequisite for performing well, but

1 given the important role of attentional mechanisms, developing the ability to control attention
2 may be the best way to find flow more often.

3 Significant research questions lie ahead in understanding the role of attention in
4 creating and maintaining flow. For example, do those in flow experience enhanced perceptual
5 abilities? Do they always demonstrate an external focus of attention? And does flow prevent
6 skill disruption through reinvestment (Swann, Crust & Vella, 2017)? Future studies may wish
7 to examine attentional benefits, like immunity to distraction or improved focus on task
8 relevant stimuli. Initially inquiry may have to rely on creative laboratory research, where
9 internal control is high and objective measures can be reliably assessed, even if this is
10 unrepresentative of real sport environments. However, the need to disentangle cause and
11 effect makes such an approach a crucial step in furthering our understanding of this complex
12 phenomenon. Some of these questions can be answered by utilising eye tracking techniques
13 which provide an objective measure of how attention is being directed and controlled
14 (Corbetta, 1998).

15 For example, improvements in attentional control can be easily measured through
16 assessing the extent to which individuals direct attention to goal-relevant over irrelevant
17 stimuli in the environment. Attentional probes, attentional bias and unexpected events can
18 also be utilised to see how strongly visual attention is held by the goals of the current task.
19 Brain measurement should continue to be utilised, whilst psychophysiological methods may
20 prove a useful, more accessible first step in sport, due to the difficulties of direct brain
21 recordings during sporting performance. Intermediate steps like movement controlled gaming
22 (see Thin et al., 2011), simulators (Harris et al., 2017; Tozman et al., 2015) and virtual reality
23 may be important in applying imaging techniques to tasks representative of sport.

Conclusions

In this chapter we hoped to provide an overview of findings from direct measurement techniques regarding the nature of the flow experience and its underlying attentional mechanisms. Imaging findings have indicated that flow is a state where attention is focused, self-awareness is reduced, positive emotions are elicited and automatic actions are allowed to take control. A greater focus on the specific attentional processes and networks discussed will allow clearer theoretical predictions that will drive flow research forward, as well as making use of flow as an attentional anomaly that can inform wider theories of attention.

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Figure legends

Fig 1; Schematic representation of the focus of the article. While the experience of flow (box 3.) and it's antecedents (box 1.) have been well documented, the focus of our discussion is the attentional processes (box 2.) that happen alongside, and may be responsible for, the experiential components.

Figure 2; The ventral network (blue), responsible for reorienting attention to salient stimuli, projects from the temporo-parietal junction (TPJ) towards inferior frontal gyrus (IFG) and middle frontal gyrus (MFG). The dorsal network (orange), responsible for top-down voluntary allocation of attention, projects from the superior parietal lobe (SPL) towards the frontal eye fields (FEF). The MD system includes overlapping fronto-parietal areas, from the SPL to the premotor cortex and inferior frontal sulcus (IFS) (Figure reproduced from Aboitiz et al., 2014).

Figure3; Key prefrontal areas and some of their functions. The ACC may contribute to perceptions of effort during flow, while imaging has suggested reduced mPFC activity (Ulrich et al. 2016) but increased activity within IFG (Ulrich et al. 2014) and dlPFC (Yoshida et al. 2014). Reprinted by permission from Macmillan Publishers Ltd: Nature Reviews Neuroscience (Amodio, 2014), copyright (2014) www.nature.com.

Figure 4; Medial areas of the default mode network. Medial prefrontal cortex (mPFC), posterior cingulate cortex (PCC) and precuneus (PC) are active when the individual is engaged in mind wandering and thoughts about the self. The DMN also includes lateral parietal and medial temporal areas (Figure reproduced from Aboitiz et al., 2014).

Footnotes

1. Flow is often associated with creativity (Csikszentmihalyi, 1996), which has itself received neuroimaging interest. However findings from this area were not included as methods, definitions and results are sufficiently diverse as to create additional confusion. For a review, see Dietrich and Kanso, (2010).