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# Neurocognitive mechanisms underlying the experience of flow

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## Abstract

Recent theoretical and empirical work in cognitive science and neuroscience is brought into contact with the concept of the flow experience. After a brief exposition of brain function, the explicit–implicit distinction is applied to the effortless information processing that is so characteristic of the flow state. The explicit system is associated with the higher cognitive functions of the frontal lobe and medial temporal lobe structures and has evolved to increase cognitive flexibility. In contrast, the implicit system is associated with the skill-based knowledge supported primarily by the basal ganglia and has the advantage of being more efficient. From the analysis of this flexibility/efficiency trade-off emerges a thesis that identifies the flow state as a period during which a highly practiced skill that is represented in the implicit system's knowledge base is implemented without interference from the explicit system. It is proposed that a necessary prerequisite to the experience of flow is a state of transient hypofrontality that enables the temporary suppression of the analytical and meta-conscious capacities of the explicit system. Examining sensory-motor integration skills that seem to typify flow such as athletic performance, writing, and free-jazz improvisation, the new framework clarifies how this concept relates to creativity and opens new avenues of research.

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## 1. Introduction

The paper sketches out the possible neurocognitive mechanisms underlying the flow experience. The subject of optimal human functioning has a long history in humanistic and health psychology. Maslow (1959), who called such moments of self-actualization “peak experiences,” described these memorable experiences as instances of happiness, fulfillment, and achievement that create a feeling of realizing one’s human potential. More recently, Csikszentmihalyi (1996) has described it as a state of flow because it is characterized by “an almost automatic, effortless, yet highly focused state of consciousness” (p. 110).

Flow is a commonly reported phenomena and the concept is intuitively appealing. A flow state ensues when one becomes so deeply focused on a task and pursues it with such passion that all else disappears, including a sense of time or the worry of failure. The person experiences an almost euphoric state of joy and pleasure, in which the task is performed, without strain or effort, to the best of the person’s ability. According to Csikszentmihalyi (1996), any activity, mental or physical, can produce flow as long as it is a challenging task that demands intense concentration and commitment, contains clear goals, provides immediate feedback, and is perfectly matched to the person’s skill level.

Despite the rich descriptions in the psychological literature, next to nothing is known about the brain mechanisms that give rise to such exceptional human functioning. Yet, like any other mental experience, a state of flow must be grounded in ordinary brain processes. From this point of view, the present paper attempts to apply the knowledge base of cognitive science and neuroscience to the concept of flow, building a new framework that is intended to increase the heuristic value of this psychological construct.

## 2. Brief exposition of brain function

Modern brain research conceptualizes cognitive function as hierarchically ordered. Evolutionary pressures forced the development of ever more integrative neural structures able to process increasingly complex information. This in turn led to increased behavioral flexibility and adaptability. The cerebral cortex, and in particular the prefrontal cortex, is at the top of that hierarchy, representing the neural basis of higher cognitive functions (e.g., Frith & Dolan, 1996; Fuster, 2000a). Historically, consciousness was approached in a similar manner (Markowitsch, 1995). Consciousness was defined by selecting various attributes, such as self-reflective consciousness, attention, memory, perception and arousal, which were ordered in a functional hierarchy with the frontal lobe necessary for the top attributes (Dietrich, 2003).

The brain has developed two different types of neural systems, each designed to extract a different kind of information from the environment. On the one hand, the emotional brain is designed to attach a value tag to the incoming information that allows the organism to evaluate the biological significance of a given event (LeDoux, 1996). On the other hand, a separate and parallel line of information processing that is devoid of any salient information is designed to perform detailed feature analysis. This perceptual evaluation of the environment is used to construct sophisticated representations that function as the basis for cognitive processing. Each line of information processing contains a functional hierarchy in which increasingly higher-order struc-

tures perform progressively more sophisticated computations. These two functional systems can be dissociated not only anatomically, but also in the way they process information. Unlike the computational mode of cognitive system, the emotional system appears to compute information in a nonalgorithmic, skilled-based manner (Churchland, 2002). Each system keeps a record of its activity so that emotional memory is part of the emotional circuitry and perceptual and conceptual memory is part of the cognitive circuitry (LeDoux, 1996).

The two distinct tracks of information processing start to diverge at the level of the thalamus. Initial processing of emotional content occurs in various limbic system structures such as the amygdala (LeDoux, 1996). The computational product of these limbic structures is used by the next levels of affective processing represented by the cingulate cortex and the ventromedial prefrontal cortex (Damasio, 1994). The most common deficit associated with amygdala lesions is impairment of basic emotions such as fear and aggression, while lesions to the VMPFC are associated with impaired complex or social emotions. The latter deficit was epitomized by the famous case of Phineas Gage, who after a freak accident that damaged his frontal lobe, exhibited what is now recognized as the typical frontal syndrome: inappropriate social behaviors, lack of moral judgment, few social inhibitions, few abstract thought processes, an inability to plan for the future, and/or difficulty to maintain a plan of action. He showed a lack of concern for himself and others and behaved with little regard for social constraints. Damasio (1994) suggested that the VMPFC might assess the personal consequences of one's behavior and that the resulting emotions are essential prerequisites to making logical and rational decisions.

The second tract is the cognitive system, which is represented by another set of limbic structures, primarily the hippocampal formation, and the temporal, occipital, and parietal cortices, which will be collectively referred to as TOP. TOP neurons are devoted primarily to perception and long-term memory. The primary sensory cortices of all sense modalities are located in TOP, and its association cortex further assembles and assimilates sensory information decoded initially in primary cortex. The required level of selective attention to process the information is also supplied by these structures (Taylor, 2001). It is generally agreed that TOP is the site of long-term memory storage (e.g., Gilbert, 2001).

Although there are multiple connections at various levels between the two information processing systems, full reintegration of emotional and cognitive information does not appear to happen until both types of computations converge back on the dorsolateral prefrontal cortex (e.g., Fuster, 2000b). The DLPFC does not receive direct sensory input, is not involved in emotional computations, and does not store long-term memory. It is involved in executive function, that is, it further integrates already highly processed information to enable still higher cognitive functions such as a self-construct, self-reflective consciousness, abstract thinking, cognitive flexibility, planning, willed action, and theory of mind (Dietrich, 2003). It formulates plans and strategies for appropriate behavior in a given situation and instructs the adjacent motor cortices to execute its computational product. At all levels of the functional hierarchy, neural structures have direct access to activating the motor system, but behavior that is based on prefrontal activation is most sophisticated.

Three other cognitive functions of the DLPFC, working memory (Baddeley, 1996; Fuster, 2000a; Goldman-Rakic, 1992), temporal integration (e.g., Fuster, 1995; Knight & Grabowecky, 1999), and sustained and directed attention (e.g., Posner, 1994; Sarter, Givens, & Bruno, 2001) provide the infrastructure to compute these complex cognitive functions by actively attending

to information, providing a buffer to hold that information in mind, and ordering it in space-time (Dehaene & Naccache, 2001; Duncan & Owen, 2000). The view emerging from the cognitive and neuroscientific literature is that working memory contains the content of consciousness (e.g., Baddeley, 1996; Courtney, Petit, Haxby, & Ungerleider, 1998). Put another way, our immediate conscious experience of the here and now is made possible by the sustained buffering of information in working memory. It is this ability to superimpose already highly complex mental constructs that dramatically increases cognitive flexibility.

These bottom-up processes are complemented by top-down processes, as the DLPFC appears to exert inhibitory control over inappropriate or maladaptive emotional and cognitive behaviors. François Lhermitte (1983, Lhermitte, Pillon, & Serdaru, 1986) documented this tendency by showing that frontal lobe patients are overly dependent on immediate cues. They tend to act on what they see without taking into account the bigger picture. Similarly, patients show a strong tendency to imitate inappropriate behaviors modeled by others. As Lhermitte put it: “the sight of the movement is perceived in the patient’s mind as an order to imitate; the sight of an object implies the order to use it” (p. 330). Without a fully functional frontal lobe, patients can utilize only immediate cues, and they fail to select behaviors based on more universal principles. Thus, the frontal lobe provides for cognitive flexibility and freedom, and it releases us from the slavery of direct environmental triggers or the memory stored in TOP.

How can individuals engaged in very complex tasks—playing chess, composing music, performing surgery—claim that they are acting without thinking, with effortless spontaneity? From a neuroscientific point of view, one would expect such tasks, which must undoubtedly count among the pinnacles of human achievement, to require the engagement of the most zenithal higher-order brain structure, the prefrontal cortex. However, the fact that people report automatic processing during flow and feel they operate without conscious thinking suggests that the prefrontal cortex is not required for the successful execution of these tasks. To solve this apparent puzzle and elucidate the brain processes that might enable a state of flow, we must first delineate explicit from implicit information processing.

### 3. Explicit and implicit systems

In addition to the type of knowledge (emotional or cognitive), the weight of the evidence suggests that the brain also operates two distinct information processing systems to acquire, memorize, and represent knowledge. The explicit system is rule-based, its content can be expressed by verbal communication, and it is tied to conscious awareness. In contrast, the implicit system is skill or experience-based, its content is not verbalizable and can only be conveyed through task performance, and it is inaccessible to conscious awareness (Ashby & Casale, 2002; Dienes & Perner, 1999; Schacter & Bruckner, 1998). Similar distinctions such as conscious-unconscious, declarative-non declarative, voluntary-automatic, or deliberate-spontaneous have been made in other domains.

Although probably uncommon, information can be acquired exclusively by either system. Implicit learning “takes place largely independently of conscious attempts to learn and largely in the absence of explicit knowledge about what was acquired” (Reber, 1993, p. 5). A prototypical example is language acquisition in children, but implicit learning can readily be demonstrated

in adults (e.g., Schacter & Bruckner, 1998). For instance, the Tower of Hanoi is a game in which three rings that are stacked according to size on a pole have to be moved, one by one, over an intermediate pole to a third pole without ever putting a larger ring on top of a smaller one. The optimal solution involves seven steps and students learn it readily. Yet, it is virtually impossible for those students to give an accurate account of how they did it. If their verbal account is translated into a computer program the machine is unable to repeat it (Gazzaniga, Ivry, & Mangun, 1998). In contrast, explicit learning is not “learning-by-doing,” but proceeds through the conscious application of rules. In the process, the explicit system forms a mental representation that includes not only the actual information, but also knowledge about what and the fact that it was acquired. A prototypical example might be the acquisition of a second language in adulthood.

A more common scenario, however, is that learning engages both systems simultaneously. Studies on neurological patient populations and health subjects suggest that a typical learning situation results in the formation of two distinct mental representations, one explicit and one implicit (e.g., Milner, Corkin, & Teuber, 1968; Schacter, 1987). Because each system subserves different functions, it is unlikely that either representation alone is a complete characterization of the learned task. While some information may be represented in both systems, other information may reside in one system but not the other. For instance, cooking a multi-course dinner requires a variety of tasks that are exclusively explicit, such as mixing ingredients according to instruction, while a variety of other tasks, such as deciding when the vegetables are done, are largely implicit.

The degree to which either system has a complete representation depends on the amount of practice and the nature of the task. Consider, for instance, language. A person’s native language is entirely learned and largely represented in the implicit system, but with considerable study the explicit system can develop its own representation of the phonology, semantics, and grammar. This is not easy, as any English major will tell you, and a paramount requirement to be able teach a native language to others. On the other hand, a second language that is learned in adulthood is acquired painstakingly by the explicit system with no “feel” or intuitive understanding for it. Yet, with extensive practice, often nothing short of total immersion into the respective linguistic environment, the knowledge can also become represented in the implicit system. Building a representation in the implicit system is referred to as “internalizing” or becoming “second nature” in colloquial speech. Either case would result in two complete and independent representations, which is almost certainly a defining characteristic that qualifies a person as a true expert. Thus, knowledge can be explicit and/or implicit, but is mostly represented in varying, partially overlapping degrees of each.

The nature of the task appears to determine the initial degree of explicitness and implicitness. From an evolutionary perspective, the existence of two distinct systems for knowledge representation indicates that each must be specialized in some way. Thus, each system is likely to be predisposed to handle certain tasks or certain task features. For instance, tasks that are either one-dimensional, i.e., can be described by a single rule, or task that have relatively few conjunctive (sequential) rules are easily learned by the explicit system. An example is the Wisconsin Card Sorting Task (WCST), in which cards are sorted by one of three characteristics: color, number, or shape. The person is asked to discover the sorting rule empirically using only feedback from the examiner. When the sorting rule is changed, the person is to adapt to the new rule. Subjects have no problem accurately describing the rule(s) verbally. However, as the task complexity

increases and the optimal rule is either multi-dimensional, i.e., requires the integration of several rules, or is probabilistic in nature, the task is notoriously difficult to describe explicitly. This is nicely illustrated in a categorization experiment by Waldron and Ashby (2001). The experimenters created 16 stimulus cards that could vary in four dimensions: background color (blue or yellow), embedded symbol color (green or red), symbol number (1 or 2), and symbol shape (square or circle). The two levels of each dimension were coded in a binary fashion as either +1 or 0. In addition, one dimension was arbitrarily selected to be irrelevant. The subject was presented with a stimulus consisting of a combination of eight of these cards and was asked to decide empirically whether the stimulus belongs to category A or B. The implicit rule that determined category membership was: “The stimulus belongs to category A if the sum of the values on the relevant dimensions  $>1.5$ ; otherwise it belongs to category B.” The interesting result of the study was that virtually all subjects achieved perfect performance, however, no one was able to describe the rule. An analogous real-world illustration might be the difficulty of describing the offside rule in soccer in a single sentence. Thus, tasks that have less salient rules are more readily imprinted in the implicit system.

This raises the question, given that one-dimensional tasks, such as the WCST, are also coded implicitly, why the explicit system exists at all. This is, of course, part of the larger question of the evolutionary significance of consciousness. Anticipating a discussion in the next section, a simple solution has been offered by Crick and Koch (1998). A frog responds stereotypically, zombie-like if you will, to visual input, i.e., to small, preylike objects by snapping, and to large, looming objects by jumping. These responses are controlled by rigid and reflexive, but fast-responding systems. As the number of reflexive systems must grow to handle increased complexity, such an organization becomes inefficient. A more advantageous solution is to evolve a single system capable of temporarily buffering and sustaining multiple representations, so that the organism can examine them before making an output decision. This is particularly useful when two or more of the organism’s systems generate conflicting plans of action. Thus, implicit knowledge can be thought of as task-specific, that is, it is inaccessible to other parts of the system and thus less versatile (Karmiloff-Smith, 1992). Explicit knowledge on the other hand can dramatically increase behavioral flexibility, because it can be broadcast to a global workspace (Baars, 1989), which allows us to test conflicting hypotheses and to integrate seemingly counter-intuitive notions about the world. For instance, most scientific knowledge is not intuitive and the implicit system would have never learned that the earth is round, that it has a molten core, or that it is at the outer arm of some small galaxy, to say nothing of 11-dimensional string theory.

#### **4. The flexibility/efficiency trade-off**

Recent advances in cognitive neuroscience have begun to identify the brain circuits underlying the explicit system. Evidence that the working memory buffer of the DLPFC holds the current content of consciousness, coupled with evidence that the executive attentional network of the DLPFC is the mechanism to select the content, suggests that the explicit system is critically dependent on prefrontal regions (Ashby & Casale, 2002; Dehaene & Naccache, 2001; Dietrich, 2003). Abundant evidence also suggests that medial temporal lobe structures are involved (see Poldrack & Packard, 2003). Because the prefrontal cortex develops most and last phylogenically and onto-

genically (Fuster, 2002), a case can be made that the explicit system is evolutionary more recent and best developed in animals with a highly developed prefrontal cortex. This hypothesis is consistent with the view that information processing is hierarchically structured and that such a functional hierarchy localizes the most sophisticated mental abilities, and thus explicit knowledge representation, in the highest-order structure, the prefrontal cortex (Dietrich, 2003). The neural substrates of the implicit system are less clear. The basal ganglia have been implicated most often, and these structures are critical for a type of implicit memory known as procedural memory (motor and cognitive skills), but contribute to other types as well such as priming, conditioning, and habituation (Mishkin, Malamut, & Bachevalier, 1984; Poldrack & Packard, 2003; Squire, 1992). Research on animals, brain-damaged patients, and neuroimaging studies of healthy subjects have shown that these systems can be dissociated from each other functionally and anatomically (Schacter & Bruckner, 1998; Squire, 1992).

This analysis of neural correlates helps to focus the discussion of the flexibility/efficiency trade-off between the explicit and implicit system on its significance to highly skilled human performance, a critical issue for understanding the effortlessness that characterizes the flow experience.

As reviewed above, multi-dimensional tasks are more likely embedded implicitly. This is likely due to the capacity limit of working memory (Cowan, 2001). Carefully controlled studies in which subjects are prevented from rehearsing or chunking support a capacity limit of  $4 \pm 1$  items that can be held in working memory at a time (Cowan, 2001). Alternatively, it has been suggested that “working memory limitations are best defined in terms of complexity of relations that can be processed in parallel” (Halford, Wilson, & Phillips, 1998, p. 723). Halford et al. (1998) have argued that the number of dimensions we can manipulate concurrently is one quaternary relation. Information of greater complexity overloads the capacity limit and invokes executive processes that collapse dimensions into fewer chunks and/or process chunks in a serial manner. This course of action, however, makes some information temporarily inaccessible. Thus, it is clear that explicit learning cannot occur if the rules governing the task reach a complexity that exceeds the capacity limit. The categorization task used by Waldron and Ashby (2001) demands more than a quaternary relation and cannot be understood explicitly without the activation of executive processes.

In contrast, the implicit system does not seem to be capacity limited. Take, for instance, a motor task such as a tennis serve. Anybody who has tried it can tell you that more is involved than tossing the ball straight in the air, swinging the racket in an arc, hitting the ball as it descends, and following the motion through. Consider, for instance, what it would take to write a computer program that specifies each muscle twitch in the correct order and intensity to make a world-class tennis serve. The computational difficulty of complex motion is enormous, a fact that is readily recognized by the artificial intelligence community. The amount of information that must be held concurrently in the focus of attention, and thus working memory, far surpasses the capacity limit. A complex motion such as a tennis serve is either learned by observation or, if learned through explicit instruction, by breaking it up into smaller components, each of which cannot contain more than 4 independent pieces of information. Once these are morphed into a single chunk, larger chunks can be combined to acquire intricate motion.

To illustrate, consider how we learn to drive a car. Using the explicit instructions of the person in the passenger seat, our explicit system in the prefrontal cortex forms a mental representation of the task requirements and recruits the premotor cortex and primary motor cortex to execute it (Jenkins, Brooks, Nixon, Frackowiak, & Passingham, 1994). This effortful process takes time

because the capacity limit restricts the number of items that can be amalgamated at a time to smooth out motion. As a result of this working memory cap, the frontal attentional network is fully engaged, making it impossible to attend to anything else, such as listening to the radio or daydreaming. Neuroimaging studies have shown that skill acquisition activates the prefrontal cortex, the premotor cortex, the parietal cortex as well as the cerebellum (Jenkins et al., 1994). It is thought that during this acquisition process the basal ganglia acts as a passive observer (Gazzaniga et al., 1998). However, studies have also shown that shifts in neural control occur as a function of practice so that the details of a motor task become gradually controlled by the basal ganglia (Mishkin et al., 1984) in a circuit that also includes the supplementary motor cortex, the motor thalamus, and the hippocampus (Jenkins et al., 1994). Put another way, the implicit system builds its own mental representation, which is the equivalent of what is known conversationally by the unfortunate misnomer “muscle memory.” A thus internalized motor pattern is controlled entirely by this basal ganglia circuit and little prefrontal activity is required during its routine execution. This is the brain’s conquer and divide principle: as the basal ganglia and supplementary motor cortex drives the car, aided by perceptual input from the parietal cortex, working memory is no longer tied up, allowing executive attention to fill its premium computational space with other content such as listening to the radio or reloading a favorite daydream scenario. In other words, performance of implicit skills bypasses consciousness. This confirms on a neural level what has been known on a psychological level for some time: to do two things at a time, one has to be automatic or implicit (Broadbent, 1958).

The main advantage of the implicit systems is its efficiency. The mechanism(s) by which knowledge shifts from an unconscious state to a conscious state is one of the most fundamental questions of cognitive science and lies at the heart of consciousness research (e.g., Cleeremans & Jiménez, 2002; Dulany, 1996). From a theoretical point of view, this boundary is not sharp and several steps might occur before knowledge is fully accessible to consciousness (Karmiloff-Smith, 1992). Take the example provided by Dienes and Perner (2002): “I know that this is a cat.” This information has three elements, (1) the content (this is a cat), (2) the attitude (knowing, as opposed to a different attitude, for instance, wishing), and (3) the holder (I—rather than you). At the lowest level, the content (this is a cat) is part of the information processing system and can be put to use, i.e., run away if the system is a mouse brain. This is the level of procedural knowledge and it leaves the elements of attitude and holder implicit. At the next level, the system represents the attitude explicitly, that is, the system *predicates* the information to be knowledge (rather than a wish). The system now not only possesses and uses the information, but also represents what it is that it possesses and uses. In other words, it labels it as knowledge. This is a higher-order or meta-representation that makes the information useable for other parts of the system. This, however, leaves implicit whether or not the information is a fact. Information can be false, and the ability to engage in hypothesis testing necessitates that we can distinguish between true and false, which requires the validity of the information be made explicit in a higher-order representation. Thus, at the next level, the system represents content, predication, and factivity, but leaves implicit the holder. Only if the holder also becomes a higher-order representation can we speak of information as fully explicit or fully conscious (Kihlstrom, 1996). Also, it is only then that we can verbally communicate the knowledge.

This makes clear why procedural knowledge is so limited in its usability. Because it is impossible for the implicit system to determine whether or not something is a fact (implicit knowledge

treats all events as true), it cannot represent the knowledge as a hypothetical possibility, making it inflexible, and idiosyncratic (Dienes & Perner, 2002). This also explains why procedural knowledge, such as a complex motor skill, is more efficient. Higher-order representations exponentially increase computational complexity. Given the mind-boggling complexity of even the simplest of motor skills, the explication of this knowledge would become a serious resource issue. Indeed, it would be impossible given the capacity limit of our highest-order computational space, working memory in the DLPFC. In contrast, procedural knowledge is contained in the application of the procedure and need not be extracted from general rules that are represented at a higher-order level and then applied to a specific example in real time. Motor skills are more efficient because they leave implicit predication, factivity, and the reference to self.

## 5. Interaction between explicit and implicit motor control

If information is part of the explicit *and* implicit knowledge base, as is the case with driving a car, the neural control of its execution can be transferred from one system to the other. However, a skilled behavior that is largely acquired implicitly, such as a tennis serve learned in early childhood, would have to be explicated first. This must proceed through the induction of inference processes (e.g., Dienes & Perner, 2002; Frensch et al., 2002). Naturally, a skill is performed by a conscious person and is thus *accompanied* by conscious experience. This allows the explicit system to buffer the event and engage in hypothesis testing that would eventually lead to the extraction of the skill's critical elements. It should be clear that this is an educated guessing game that is imperfect. Note that fully (predication and factivity) implicit knowledge cannot *cause* explicit knowledge through a bottom-up process. The implicit system cannot label the information itself as knowledge and thus cannot broadcast it to the system, preventing its use by other parts within that system. Only through the circuitous route involving actual behavior can the explicit system come to embody an implicitly learned skill. This is exemplified when trying to retrieve a phone number that is temporarily inaccessible. We typically solve that problem by dealing the number on an imaginary phone dial, using the execution of implicit knowledge to trigger explicit representation. As we have seen with the Tower of Hanoi task, the fact that the implicit system cannot tell the explicit system directly what it does and why it does it, leads to the exceedingly curious situation that we often cannot explain why we do what we do, leaving us little choice but to exclaim that the behavior was guided by intuition. This is a particularly common experience when trying to explain a motor skill to others.

Two studies further illustrate the way the explicit and implicit systems interact in skill performance. In an experiment by Bridgeman and colleagues (1991, Bridgeman, Peery, & Anand, 1997) the motion of a rectangular frame across a computer screen created the apparent motion of a stationary dot placed inside the frame moving in the opposite direction. Subjects were briefly exposed to the visual illusion and then asked to either indicate verbally which of five marked spots best described the last location of the dot or to point to that location using their hands. The verbal condition would engage the explicit system while the implicit system would control the steering of the finger. The results showed that all verbal subjects were highly susceptible to the illusion, whereas half the subjects in the pointing condition could accurately specify the location of the dot. These results indicate that procedural knowledge is not only fast and efficient, but also more

accurate in real time sensory-motor integration. A famous Austrian downhill skier apparently hit the nail on the head when he said: “You can’t win a thing by thinking.” Interestingly, when the subjects in both conditions were asked to withhold their response for 8 seconds, all were susceptible to the Roelofs effect. This indicates that visually guided movement leaves time (along with predication and factivity) implicit; it is thus inflexible and only useful in the here and now.

A similar insight can be obtained from an experiment by Castiello, Paulignan, and Jeannerod (1991). Subjects were seated in front of three candle-sized rods and were asked to grasp one of the rods as soon as it was illuminated. On some trials a rod was illuminated but after the subject had already started a visually guided movement to that target, the target was changed by illuminating a different rod. Not surprisingly, this resulted in a smooth and very rapid correction of the hand’s trajectory. The subjects were also asked to give a vocal indication as soon as they were aware of the switch. The experiment produced numerous instances in which a subject had already grasped the new target before they were aware of it.

Compare this to the lightning-fast escape maneuvers of a squirrel. Lacking an overall strategy or plan, the squirrel gets to safety entirely by relying on moment to moment adjustments. Such smooth feedback-driven sensory-motor integration can produce extremely complex movement patterns that can serve an overall and/or higher goal (safety), yet requires no more than the reaction to immediately preceding input. Now consider how an outfielder catches a flyball. Starting with only a vague idea as to the ball’s ultimate location, the player progressively approximates that location by continuously adjusting his movements based on updates of the ball’s trajectory and speed as it approaches (McLeod, Reed, & Dienes, 2001). Because these are fluid situations occurring in real time, they require, first and foremost, efficiency. A system is most efficient if it represents knowledge in a fully implicit manner; that is, it codes the application of the knowledge within the procedure and refrains from buffering any other property (e.g., predication, factivity, or time) of the information in a higher-order representation. On the flip side, this setup is the reason why motor behavior must progress stepwise from immediately preceding input. The lack of meta-representation precludes the system from calculating hypothetical future scenarios that would enable it to anticipate several steps in advance.

Framed in computational terms, it becomes clear why such meta-representation is unattainable for movement. Even for squirrels, the number of possible next moves is so astronomically high that future projections would quickly bifurcate to infinity. Such a nonlinear system is unpredictable, rendering the calculation of hypothetical future scenarios useless. Accordingly, the complexity and speed requirement of purposeful motion makes explication not only prohibitively costly, but impossible. Such a nonlinear, dynamic system is unpredictable, but it is not random and might settle to a strange attractor (e.g., safety). Consequently, the explicit system is limited to representing tasks that can be solved outside real-time and that can be broken up into chunks of complexity less than a quaternary relation. Since this is not the case for movement, the only viable solution is to increase either the number of reflexive systems and/or the number of response patterns within a reflexive system. This does not change the system’s modularity; it is still a reflexive system, as output remains guided by the immediately preceding input, but it now has an increased number of specialized and independent response patterns.

A squirrel’s movement can be conceptualized as a number of basic moves (e.g., left turn, right turn, freeze, reverse, jump, etc.) and a number of independent variations within each basic move. Similarly, an acquired skill such as playing tennis would require a limited number of reflexive

systems, each responsible for a different basic stroke (e.g., forehand, backhand, serve, volley, etc.) in addition to a number of specific and independent response loops within each system. A tennis match is a dynamic system with two moving targets. Although it might settle to one or more strange attractors, such as one player's weak backhand, moment-to-moment events are completely unpredictable. Given the above analysis that such situations must be managed by the implicit system, it is proposed that initial practice of a skill leads to the establishment of broad reflexive systems (forehand, backhand, etc.), while extensive practice results in an increase in the number of specific and independent response pattern within each system. Moreover, it is proposed that with thousands of hours of highly dedicated practice these patterns become automated, that is, the application becomes part of the stimulus-response procedure.

## 6. Implication for the flow experience

It follows from this view that the skill level of tasks involving real time sensory-motor coordination such as sports, music, or language is directly related to the number of distinct response patterns *and* their level of automatization. Consequently, the implicit system's inherent information processing efficiency coupled with such experience-based increase in (reflexive) flexibility might underlie the rapid-fire effortless characteristic of the flow state.

This is perhaps best illustrated with two behaviors that appear to epitomize flow, writing and free-jazz improvisation. Language is not an information-integration task but a rule-based task (Ashby & Gott, 1988), that is, it is produced by stringing together existing and automated units, but *components* of these units are not integrated along one or more dimensions (phonology, semantics, or grammar) before an output decision occurs. As mentioned above, the limited working memory capacity cannot handle the combinational explosion of multi-dimensional tasks. Language is produced from a small set of conjunctive rules that are applied sequentially as writing moves forward (e.g., subject-verb agreement), which eliminates a nearly infinite number of mistakes that are possible if all components were to be combined freely in all dimensions. Despite these restrictions, the remaining combinational potential of human language coupled with the real-time requirement of its production is sufficient to make it impossible for the explicit system to micro-manage language. The explicit system can steer an essay or poetry towards a strange attractor (the theme), but moment-to-moment execution must rely on reflexive loops. Music is also a conjunctive rule-based task. In free-jazz improvisation, the musician arranges units into a flowing string. Because the string progresses by each unit triggering the next, the application becomes part of the procedure. The overall product can be novel (indeed, if the string is long enough it must be novel due to the complexity of the musical system). The full string can even be multi-dimensional, but each individual step is not. It is the number of distinct reflexive loops as well as their level of automatization that determine the quality of the flow experience. It should be noted that such increased implicit expertise does not necessarily lead to the skill's representation in the explicit system.

Because a highly practiced skill is still performed by a conscious person, it is possible for the explicit system to partake in its execution. To stay with the example of tennis, this occurs when a player buffers any part of the game (e.g., reflecting on the strokes or what it would mean to lose) in a higher-order representation and allows such analysis to guide movements. It should be obvi-

ous now that any amount of transfer of the skill from implicit to explicit control gravely affects its quality. John McEnroe apparently knew this intuitively. The story is told that when he played an opponent who was “in the zone” and could do no wrong with his, say, forehand, McEnroe would call it to his attention by praising his rival on his excellent forehand during the switching of sides.

It is the central proposal of this paper that optimal performance involving a real-time sensory-motor integration task is associated with maximal implicitness of the task’s execution. Given that the explicit system is subserved by prefrontal regions, it follows from this proposal that a flow experience must occur during a state of transient hypofrontality that can bring about the inhibition of the explicit system.

The defining characteristics of flow are consistent with implicit execution and a state of transient frontal hypofunction. Csikszentmihalyi (1996, pp. 111–113), described nine main elements:

1. *There are clear goals every step of the way.* Describing this element in terms such as, “the musician knows what note to play next” and “the surgeon is aware of how the incision should proceed moment by moment” shows that, although the activity advances ultimately towards a higher goal, it is driven by the progressive realization of the next small goal.
2. *There is immediate feedback to one’s action.* This point is closely related to the first. Here the “musician hears right away whether the note played is the one,” demonstrating the characteristic feature of the implicit system that, due to the lack of higher-order representations, the event is not subjected to detailed analysis and feedback is binary and immediate. This also leads back to the first point that the “musician knows what note to play next,” building a sequence with each step contingent upon the last.
3. *There is a balance between challenges and skills.* According to the here presented view, this element is necessary for flow. Faced with a task that exceeds the skill level ingrained in the implicit system, we feel we must enlist the help of the explicit system to improve performance. However, this affects performance negatively and leads to frustration and anxiety. In contrast, tasks that do not test the implicit system’s full ability allow for the affordable interference of the explicit system. This leads to daydreaming or boredom but not feelings of self-actualization.
4. *Action and awareness are merged.* This element of flow describes concentration as being “focused on what we do.” At first glance, this feature of flow appears to contradict a state of hypofrontality, as it demands attention to be directed, and sustained, suggesting activity of the frontal attentional network. However, focused attention is also a prominent feature of other states of altered consciousness that are due to transient hypofrontality (see Dietrich, 2003). Unlike other functions of the prefrontal cortex that compute the content of consciousness, executive attention as a mechanism that selects the content (Posner, 1994). Phenomenologically, people in a state of flow report content that is consistent with decreased prefrontal function, such as the disappearance of self-consciousness, no worry of failure, a sense of timelessness, and no distractions (see below). Thus, flow is a state of hypofrontality with the notable exception of executive attention, which enables the one-pointedness of mind by selectively disengaging other higher cognitive abilities of the prefrontal cortex.
5. *Distractions are excluded from consciousness.* This feature of flow is a consequence of the above point. Humans appear to have a great deal of control over what they attend to (e.g., Cowan, 1995), and in flow, attentional resources are used to actively amplify the task at hand until it becomes the exclusive content in the working memory buffer. It is this attentional effort that

serves to accomplish the exclusion of other, intruding information, whether they are sensory, emotional, or cognitive. The phenomenological result is an awareness that is limited to the here and now with no indication of cognitive flexibility—a mental singularity if you like.

6. *There is no worry of failure.* This element of flow is due to the one-pointedness of the mind. Without the ability to bring into focus additional information, worry of failure, along with other extraneous content, is prevented from entering consciousness. Given the evidence that the prefrontal cortex houses a person's cultural values and belief system (Damasio, 1994), flow is probably characterized by a number of such phenomenological subtractions.
7. *Self-consciousness disappears.* Self-consciousness is a meta-representation of the highest order and probably one of the first phenomenological subtractions to manifest itself in flow. There are simply not enough resources left to compute this highly sophisticated feature of consciousness.
8. *The sense of time becomes distorted.* As mentioned above, temporal integration is a prefrontal function and the subtle modification of the perception of time is predicted in hypofrontality. Indeed, a sense of timelessness is one of the hallmarks of any altered state of consciousness (Dietrich, 2003).
9. *The activity becomes autotelic.* This final element is a reinforcing property of the state of flow.

It appears from the above discussion that the inhibition of the explicit system needed to facilitate entrance into flow can be induced by one of two methods. First, volitional control over the executive attentional system can be used to narrow the focus of attention to exclusively buffer the task at hand, eliminating other phenomenological features computed by the explicit system to enter consciousness. Put another way, this is a behavioral method that maximizes the implicitness of the skill's execution by flexing the muscle of attention. It is a commonly reported experience by athletes, such as golf players, that intense focusing can lead to smoother and more accurate performance. In addition, it has been reported that this effort is associated with decreased brain activation in cortical regions (Ross, Tkach, Ruggieri, Lieber, & Lapresto, 2003). In contrast, simply letting attention drift induces daydreaming (Dietrich, 2003; Singer, 1978), not flow.

A second method, albeit restricted to tasks requiring substantial bodily motion, may also be possible. The brain has to make due with a finite amount of metabolic resources. As a consequence, we possess a limited information processing capacity, which is not only true at the bottleneck of consciousness (Broadbent, 1958; Cowan, 1995), but it must also apply to unconscious, parallel information processing. This notion builds on the fundamental principle that processing in the brain is competitive (Miller & Cohen, 2001). Because sensory-motor integration tasks require massive and sustained activation of sensory, motor, and autonomic systems (Ide & Secher, 2000; Vissing, Anderson, & Diemer, 1996), an individual may need to inhibit neural activity in regions performing functions that the individual can afford to disengage. These regions are, first and foremost, the higher cognitive centers of the prefrontal cortex, and thus the explicit system (see Dietrich, 2003; Dietrich & Sparling, 2004).

By identifying the possible neurocognitive mechanisms that might underlie the state of flow, it becomes feasible to delineate it from other manifestations of exceptional human experience, for instance, creativity. First, it is imperative to recognize that flow and creativity recruit different brain circuits. As proposed in this paper, flow necessitates a state of transient hypofrontality

that empowers the implicit system to execute a task at maximum skill level with maximum efficiency. Creativity on the other hand, is enabled by the cognitive capabilities provided primarily by the DLPFC (Dietrich, *in press*). I have proposed that creativity results from the factorial combination of four kinds of mechanisms. Neural computation that generates novelty can occur during two modes of thought (deliberate and spontaneous) and for two types of information (emotional and cognitive). Regardless of how novelty is generated initially, circuits in the prefrontal cortex perform the computation that transforms the novelty into creative behavior. To that end, prefrontal circuits are involved in making novelty fully conscious, evaluating its appropriateness, and ultimately implementing its creative expression (for details, see Dietrich, *in press*).

Given the definition that creativity is both novel and appropriate, the cognitive flexibility provided by the prefrontal cortex is critical to assessing whether a particular new behavior is creative as opposed to merely new. According to this view, the implicit system can only contribute to generating novelty, which may or may not be creative. In other words, creativity is essentially a Darwinian process, entailing a variation-selection process (Simonton, 2003). Because of the nonlinear nature of motion, a state of flow involving motor behavior generates ideational combinations all the time, but only a selection process based on explicit meta-representations can determine which combinations are truly creative.

In conclusion, from the proposed framework, a systematic reconceptualization of the experience of flow emerges that has a number of advantages. First, it provides a coherent, albeit basic, neurocognitive account of flow, and thus brings a concept that has been described thus far in purely psychological terms into contact with cognitive science and neuroscience. Second, it can help disentangle the concept of flow from other concepts of optimal human functioning, such as creativity, peak experience, and self-actualization. Third, and perhaps most importantly, the present novel synthesis makes the concept of flow eminently testable with the tools of modern cognitive neuroscience, opening new lines of research that can expand our knowledge of the state of flow. It is hoped that future research will be directed towards the difficult task of obtaining direct measures of hypofrontality during flow states.

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