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Neural correlates of experimentally induced flow experiences☆

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ABSTRACT

Flow refers to a positive, activity-associated, subjective experience under conditions of a perceived fit between skills and task demands. Using functional magnetic resonance perfusion imaging, we investigated the neural correlates of flow in a sample of 27 human subjects. Experimentally, in the flow condition participants worked on mental arithmetic tasks at challenging task difficulty which was automatically and continuously adjusted to individuals' skill level. Experimental settings of "boredom" and "overload" served as comparison conditions. The experience of flow was associated with relative increases in neural activity in the left anterior inferior frontal gyrus (IFG) and the left putamen. Relative decreases in neural activity were observed in the medial prefrontal cortex (MPFC) and the amygdala (AMY). Subjective ratings of the flow experience were significantly associated with changes in neural activity in the IFG, AMY, and, with trend towards significance, in the MPFC. We conclude that neural activity changes in these brain regions reflect psychological processes that map on the characteristic features of flow: coding of increased outcome probability (putamen), deeper sense of cognitive control (IFG), decreased self-referential processing (MPFC), and decreased negative arousal (AMY).

Introduction

The concept of flow (Csikszentmihalyi, 1975) refers to an activity-associated, subjective experience under conditions of a perceived fit between abilities or skills and task demands in the context of clear goal settings. Characteristic determinants of this psychological state have been conceptualized as high though almost effortless attention, reduced self-referential processing, sense of control, and the feeling that the activity per se is rewarding (Csikszentmihalyi, 2000; Csikszentmihalyi and Nakamura, 2010). Flow experience has been investigated in a wide spectrum of activities from chess playing (e.g., Abuhamdeh and Csikszentmihalyi, 2009, 2012) to skiing or rock climbing (e.g., Delle Fave et al., 2003).

Flow experiences have been studied under modulating conditions including motivational task aspects (Csikszentmihalyi and Csikszentmihalyi, 1988; Keller and Bless, 2008; Nakamura and Csikszentmihalyi, 2002), cognitive aspects (Mosing et al., 2012), and personality traits mediating individual proneness to experience flow (Asakawa, 2004, 2010; Csikszentmihalyi and Csikszentmihalyi, 1988; Csikszentmihalyi and Schneider, 2000; Ishimura and Kodama, 2006; Keller and Bless, 2008; Keller and Blomann, 2008; Ullén et al., 2012). Also physiological correlates of flow experiences have been of interest (de Manzano et al., 2010; Keller et al., 2011). However, the neural correlates of flow experiences have been investigated in only two studies, so far (de Manzano et al., 2013; Klasen et al., 2012). Employing functional magnetic resonance imaging during a video game, brain activation patterns, encompassing reward-related structures as well as cognitive and sensorimotor networks, have been reported to associate with flow factors derived from a content analysis of that video game (Klasen et al., 2012). A recent [11C]raclopride positron-emission-tomography study (de Manzano et al., 2013) showed an association between inter-individually different flow proneness (Ullén et al., 2012) and availability of dopamine D2 receptors in the striatum. The correlation was particularly evident in the putamen and parts of the caudate nucleus extending into the ventral striatum.

To study flow experiences under experimentally controlled conditions at the behavioral level several paradigms have already been tested. A study by Rheinberg and Vollmeyer (2003) used a computer game requiring subjects to keep a spaceship undamaged by approaching rockets. Although three different levels of difficulty had already been implemented, the "optimal" level was adjusted to participants' skills

Abbreviations: AMY, Amygdala; ANOVA, Analysis of variance; B, Boredom (experimental condition); BA, Brodmann area; CASL, Continuous arterial spin labeling; CNR, Contrast-to-noise ratio; DMN, Default-mode network; EPI, Echo-planar imaging; F, Flow (experimental condition); FoV, Field of view; IFG, Inferior frontal gyrus; MNI, Montreal Neurological Institute; MPFC, Medial prefrontal cortex; MRI, Magnetic resonance imaging; O, Overload (experimental condition); R, Rest (experimental condition); rCBF, Regional cerebral blood flow; SPM, Statistical Parametric Mapping; TE, Echo time; TR, Repetition time.

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only once prior to the experiment but not, critically, continuously and automatically in the course of the experiment to account for possible alterations in participants' performance over time. Our own studies had then implemented a continuous and automatic fit between task demands and subjects' abilities in a modified tetris game (Keller and Bless, 2008), or in a computerized knowledge task (Keller et al., 2011, Experiment 1). However, in neither study a within-subjects design has been employed with repeated blocks of different task demands enabling more systematic comparisons between states of flow and non-flow.

Acknowledging the methodological problems so far, in the present study, we employed a new and innovative approach investigating subjective experiences of flow and associated neural correlates during engagement in mental arithmetic tasks. A mathematical framework has the strong advantage of full experimental control to adjust different levels of task difficulty necessary to realize an almost complete fit between individuals' skills and task demands. Employing a within-subjects study design, addition tasks were used to create three different experimental conditions of “boredom”, “flow”, and “overload” which were repeatedly presented throughout the entire experiment. In the putative flow condition task difficulty was automatically and continuously adjusted to individuals' skill level. Subjective experiences were assessed after each condition. Perfusion imaging implemented as continuous arterial spin labeling (CASL; e.g., Wang et al., 2005) was performed to measure regional cerebral blood flow (rCBF) as a surrogate marker of energetically demanding neural activity (Logothetis et al., 2001; Wang et al., 2005).

We predicted subjective experiences of flow to result in higher rating scores relative to control conditions. Particularly, items testing for relative enjoyment and for subjectively experienced task-skill balances should yield significantly higher positive ratings. Functionally, from previous evidence (de Manzano et al., 2013) we hypothesized stronger involvement of the striatum during the flow relative to control conditions. Since flow has been characterized by reduced self-awareness (Csikszentmihalyi, 2000; Csikszentmihalyi and Nakamura, 2010), we also expected regions in the medial prefrontal cortex mediating self-referential processing (Brewer et al., 2011; D'Argembeau et al., 2007; Goldberg et al., 2006; Gusnard et al., 2001; Jenkins and Mitchell, 2011; Johnson et al., 2009; van Buuren et al., 2010; Whitfield-Gabrieli et al., 2011; Zysset et al., 2003) to be down-regulated during flow.

Material and methods

Participants

Twenty-seven male, right-handed German native speakers (average age: 23.0, standard deviation: 2.3) were recruited from the local university and were paid 20 EUR for participation. Due to the novelty of the present experimental approach only men were included, in order to control for putative sex differences as possible source of variation (particularly, hormonal alterations during the menstrual cycle possibly affecting magnitude and local distribution of cerebral hemodynamics, e.g., Dietrich et al., 2001; Fernández et al., 2003; Hausmann et al., 2002). Structured interviews were conducted during recruitment of the volunteers. None of the participants reported to have any psychiatric/neurological diseases or contraindications regarding the magnetic resonance imaging (MRI) procedure. The study was in accordance with the Declaration of Helsinki and the local ethical committee at Ulm University. Written informed consent was obtained prior to the experiment.

Experimental design

Participants had to perform mental arithmetic tasks varying in difficulty. There were three conditions, a boredom condition (B) with low task demands, an adaptive or “flow” condition (F) where challenging task difficulty was dynamically adjusted to participants' individual level of skill, and an overload condition (O) with very high task difficulty.

In all conditions, the participants were asked to sum two or more numbers in their mind and to enter the result as accurately and as fast as possible using an on-screen keyboard in combination with a trackball (see Fig. 1). The result which always consisted of three digits had to be entered digit by digit and submitted by pressing an “Enter” button. Mistakes could be corrected using a “Delete” button. Input was immediately displayed in the result box which initially had the default value “000” until a result was entered. After submitting the result, there was a break of 4 s (indicated by the expression “xxx + x”) before the next calculation was presented. Each calculation remained on the screen for a maximum duration of 18 s or until subjects submitted the result. Different degrees of task difficulty associated with the B, F, and O conditions were achieved as follows.

In the boredom condition, only two numbers were to be summed, with the first summand randomly drawn from the interval 100 to 109, and the second summand from the interval 1 to 9. Also, the result of summation was confined to numbers between 101 and 110, so that the participants did not have to break up the second summand to obtain the result. As a consequence, task demands were constantly low.

In the flow condition, task demands adapted automatically and continuously to the participants' level of skill which had been estimated beforehand in a preparation phase (see below), and used as starting level. After an evaluation period consisting of two completed calculations, the results were analyzed with respect to accuracy. When two out of the last two results were correct task difficulty increased by one level which was achieved using two distinct mechanisms. In case the last summand had only one digit, the level increased by changing the last summand to a two-digit number in the upcoming calculations (e.g., Level 5: 23 + 45 + 59 + 3 changed to Level 6: 73 + 46 + 54 + 17). For a further up-level change, an additional one-digit number was added to the mathematical expression (e.g., Level 6: 89 + 38 + 65 + 15 changed to Level 7: 26 + 24 + 33 + 60 + 8). Both mechanisms were applied alternately. Analogously, when two results were incorrect in succession, task difficulty decreased by one level, and this was achieved by the two mechanisms outlined above but in reverse order. Otherwise, task demands remained unchanged.

In the overload condition, the starting level of task difficulty was set three levels higher than the starting level of the flow condition. A level-up adjustment occurred when at least three out of the last five results were correct. Task demands decreased when at least four out of five results were wrong. However, task difficulty did never fall below the starting level. This algorithm was applied to ensure that task demands were always higher than the participants' level of skill, thus “overloading” subjects but also minimizing the probability to permanently frustrate participants.

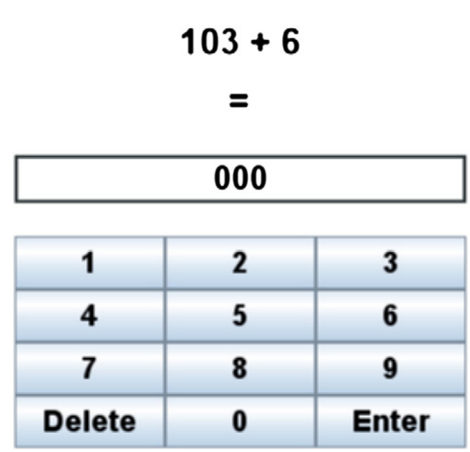

Fig. 1. Experimental design. Depicted is the relevant middle section of a screen shot taken from the boredom condition. Subjects had to sum the numbers and to enter the result using the on-screen keyboard operated by a trackball.