Modulations of the experience of self and time

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Review

Modulations of the experience of self and time

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ABSTRACT

Empirical findings in the Cognitive Sciences on the relationship between feeling states and subjective time have led to the assumption that time perception entails emotional and interoceptive states. The perception of time would thereafter be embodied; the bodily self, the continuous input from the body is the functional anchor of phenomenal experience and the mental self. Subjective time emerges through the existence of the self across time as an enduring and embodied entity. This relation is prominently disclosed in studies on altered states of consciousness such as in meditative states, under the influence of hallucinogens as well as in many psychiatric and neurological conditions. An increased awareness of oneself coincides with an increased awareness of time. Conversely, a decreased awareness of the self is associated with diminished awareness of time. The body of empirical work within different conceptual frameworks on the intricate relationship between self and time is presented and discussed.

Contents

> “*Time and the self, time and consciousness, affect and time are pairs of subjective reality, phenomena that appear together in the course of man’s ontogenetic development and define human nature [. . .]. Even though conceptualized independently, they cannot be experienced separately, they cannot exist without each other.*”
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> [Hartocollis, 1983, p. 56]

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1. Modulations of subjective time

The common understanding is that the subjective passage of time is modulated by changing experiences within different situational context. That is, we are aware that subjective time is not isomorphic to physical time. Estimates of the same physical duration vary intra-individually: an hour may pass painfully slowly while waiting for the phone call from the loved one. The same duration, when we are entertained, may elapse hardly noticed. In waiting situations, but especially when we are bored, we feel trapped in time (Zakay, 2014). Empirical evidence indeed shows how boredom-prone individuals relatively overestimate duration in the seconds-to-minutes range (Danckert & Allman, 2005; Watt, 1991). Boredom-related subjective time dilation may arise either from an understimulation where nothing interesting happens or an overstimulation where one is overcharged with complexity (Flaherty, 1993). Impulsive individuals, who are more likely to feel tedium in uneventful situations, overestimate duration and report a slowing down of the passage of time (Wittmann & Paulus, 2008). On the other side of the spectrum of temporal experiences, "time seems to fly when we are having fun", i.e. when entertained by rewarding activities. Individuals who are in a situation where they are highly motivated are less aware of time, check the clock less often, and experience time to pass more rapidly (Conti, 2001). The tendency to lose track of time is most pronounced when fully immersed in challenging activities accompanied with the feeling of enjoyment – as experienced in the mental state of "flow" in sports, work, or play (Csikszentmihalyi & Csikszentmihalyi, 1988). Then, typically, one loses track of time and may be surprised about how much time has actually passed.

These common experiences can be explained by variations in the sense of self. In waiting situations without the possibility of distraction, when time is in the focus of awareness and duration expands, self-consciousness is most pronounced. In contrast, when we are absorbed in a pleasant activity, we are less aware of ourselves. Time is hardly noticed and therefore contracts. These everyday experiences are in line with a theoretical framework of self-regulation where effortful emotion regulation accompanied with an increased self-awareness elongates felt duration (Vohs & Schmeichel, 2003). Self-regulation is understood to happen when the self undergoes adaptations by resisting temptation and inhibiting behavior, i.e. by altering one's mood when staying attentive during a boring lecture; all this is done by executive aspects of the self (Baumeister & Vohs, 2003). Self-regulation also refers to positive emotions such as the feeling of awe, which evokes an update of one's mental schema and leads to the feeling of time expansion (Rudd, Vohs, & Aaker, 2012). In contrast, when mind wandering or day dreaming we lose touch with the present state of ourselves and of time; duration is then relatively underestimated (Terhune, Croucher, Marcusson-Clavertz, & Macdonald, 2014). In the controlled setting of a hypnosis session, as one example of an altered state of consciousness, where an individual vividly imagines scenes and is not focused on himself or herself, temporal intervals within a hypnosis session or the hypnosis session itself are typically underestimated (Naish, 2007; Noreika, Falter, Arstila, Wearden, & Kallio, 2012).

A more mechanistic account of these temporal phenomena is provided by cognitive models of prospective time perception, such as the attentional-gate model (Zakay & Block, 1996), according to which increased attention to time in waiting situations leads to an accumulation of more hypothesized time units or pulses, upon which duration judgments are based, and which, in turn, results in an expansion of subjective time (Wearden, 2004; Zakay & Block, 2004). In an uninspired waiting situation we focus more on time, leading to more accumulated pulses and a corresponding relative overestimation; whereas when we are distracted by activities we focus less on time, thus evoking relative time contraction through a smaller amount of represented time units. In juxtaposing the model of self-regulation and the attentional-gate model one is tempted to conclude that time consciousness and self-consciousness are strongly related and thus are jointly modulated in a situation when attention is actually directed to time: if the experience of the self is intensified, the subjective feeling of time changes accordingly, experienced as expansion or as slowing down of the passage of time.

2. Interoception, emotions, and the experience of time

The equalization of 'time' and 'self' has been discussed in recent conceptualizations in which intertwined affective and interoceptive states of the body would create our experience of duration (Craig, 2009a; Craig, 2015; Droit-Volet, Fayolle, Lamotte, & Gil, 2013; Wittmann, 2009, 2013). The sense of time thereafter would be related to the temporal integration of signals from the interoceptive system – the bodily self. Subjective feelings depend upon bodily signals, as visceral and somatosensory feedback from the peripheral nervous system are integrated with perceptual, motivational, social and cognitive information leading to the awareness of complex feeling states (Damasio, 1999; Singer, Critchley, & Preuschoff, 2009). This idea is in line with a philosophical tradition proposing that the experience of time is a creation of the self, i.e. subjective time is related to the conscious self as an enduring entity over time (Edmund Husserl) and subjective time being in essence embodied (Maurice Merleau-Ponty) (Förster-Beuthan, 2012; Zahavi, 2005). Accordingly, and merging the above mentioned attentional gate model with the physiological account of subjective time, bodily signals could function as 'pulses' accumulating steadily when attention is directed to time and thus modulating subjective duration. Importantly, however, the attentional gate model is one among several other functional models of timing behavior (French, Addyman, Mareschal, & Thomas, 2014; Sysoeva, Wittmann, & Wackermann, 2011). It is employed here because of its strong heuristic value in explaining subjective time.

The notion that interoception and time perception are closely linked is supported by studies showing an association between duration estimates and psychophysiological parameters such as the heart-beat. In one study, time estimation accuracy was related to the slope of cardiac slowing during the perception of temporal intervals with durations between 8 and 20 s (Meissner & Wittmann, 2011). Conscious awareness of the own heart beat – as assessed with the heartbeat perception test (Pollatos, Kirsch, & Schandry, 2005) – was also related to time perception accuracy (Meissner & Wittmann, 2011). That is, individuals who were more sensitive to their heart beat, who more accurately counted the number of heart beats during a given time interval, were more accurate in a subsequent time estimation task. Moreover, in a recent study, synchrony between signals from the heart cycle and timing responses were detected in a duration reproduction task in the multiple seconds' range (Pollatos, Yeldesbay, Pikovsky, & Rosenblum, 2014).

Additionally, there are many studies showing how subjects overestimate time intervals filled with body arousing emotions in the range of up to a few seconds (Dirnberger et al., 2012; Droit-Volet & Gil, 2009; Gil, Niedenthal, & Droit-Volet, 2007; Lambrechts, Mella, Pouthas, & Noulhiane, 2011; Tipples, Brattan, & Johnston, 2013; Wackermann, Meissner, Tankersley, & Wittmann, 2014). An overestimation of duration is also detected when subjects anticipate emotional events such as pain stimuli (Ogden, Moore, Redfern, & McGlone, 2014). A similar overestimation of duration was seen in retrospective duration judgments of video clips lasting 45 s, where a fear-inducing video led to a subjective time dilation effect as compared to a documentary and a cartoon, an effect which was even increased when subjects had to additionally attend to their bodily reactions (Pollatos, Laubrock, & Wittmann, 2014). Similarly, timing of intervals around one second also lengthens perceived duration after watching a fear-inducing film clip (Droit-Volet, Fayolle, & Gil, 2011). In addition, anxious individuals are more likely to overestimate stimulus durations with various interval lengths of only a few seconds (Bar-Haim, Kerem, Lamy, & Zakay, 2010) or many minutes (Wittmann, Vollmer, Schweiger, & Hiddemann, 2006) and report a slowing down of the passage of time (Lamotte, Chakroun, Droit-Volet, & Izaute, 2014).

These findings are accompanied by neuroimaging studies showing that among many other regions the insular cortex is activated in time perception in the sub- as well as supra-second range (Bueti & Macaluso, 2011; Livesey, Wall, & Smith, 2007; Pollatos, Laubrock et al., 2014; Pollatos, Yeldesbay et al., 2014; for meta-analyses, see Lewis & Miall, 2003; Wiener, Turkeltaub, & Coslett, 2010). The insular cortex is discussed as the primary interoceptive cortex integrating body signals over time as received in the dorsal posterior insula (Craig, 2015). A representation of homeostatic feelings would be built in the anterior insula which generates an experience of the emotional self at a given moment (Craig, 2009b; Critchley, Wiens, Rotshtein, Öhman, & Dolan, 2004; Seth, 2013). The insular cortex as part of the saliency network is also discussed as being involved in cognitive control and attentional processes (Menon & Uddin, 2010). Thereafter, the same brain network would underlie attentional control, body awareness, and time perception. Accordingly, this adds to the idea that "attention to time" in essence means "attention to bodily signals" as implicated in the above integration of the attentional gate model within a neurophysiological framework.

In two studies, the posterior and anterior insula seemed specifically implicated in the experience of temporal intervals with several seconds' duration (Wittmann, 2013). In a functional magnetic resonance imaging (fMRI) study using temporal intervals of 3, 9 and 18 s, activation in the dorsal posterior insular cortex was linked to the temporal encoding of duration. Activation in this region increased with increasing interval length and peaked at the end of the interval (Wittmann, Simmons, Aron, & Paulus, 2010). When these intervals had to be reproduced as indicated by a button press, a similar linear increase of activation was seen in the anterior insula as well as regions of the frontal cortex which peaked shortly before the actual button press. A subsequent study replicated these findings with a different group of subjects (Wittmann et al., 2011). A single-case study with an epileptic patient with a focal lesion in the right anterior insula complements these neuroimaging findings (Monfort et al., 2014). The patient performed with severe distortions in the reproduction of multiple-second durations – an impairment that was not observed in the other tested epileptic patients without damage to the insular cortex. Moreover, neuroimaging studies in humans have repeatedly shown that the anterior insula, besides the striatum, is involved in explicit temporal prediction and expectations of future negative or positive events (Simmons et al., 2013; Tanaka et al., 2004; Tomasi, Wang, Studentsova, & Volkow, 2014; Wittmann, Lovero, Lane, & Paulus, 2010).

However, it is only fair to mention that regarding the question of localization and mechanisms – "where" and "how" in the brain time is represented – no agreement can be found in the literature; too many very different models exist (Grondin, 2010; Hancock & Block, 2012; Merchant, Harrington, & Meck, 2013; Wittmann & van Wassenhove, 2009). To some degree this variation of conceptualizations can be explained by relating them to different time scales (Buhusi & Meck, 2005; Wittmann, 2009, 2013) and to the nature of the timing processes being explicit or implicit (Coull & Nobre, 2008). Related to the sub-second time range, temporal processing may be distributed among different structures relying on modality-specific mechanisms rather than on a central timing region (Mauk & Buonomano, 2004). Moreover, since many different cognitive processes contribute to the perception of time such as attention, working memory, and decision making, this constant co-activation of all processes increases the difficulty in identifying the neural basis of time perception (Meck, 2005; Pouthas & Perbal, 2004; Wittmann, 2009).

A further difficulty regarding the measurement of subjective time has to be mentioned, which is important when considering the variations of temporal experiences. Statements about the passage of time and of duration in the complex world outside the laboratory – ultimately, we are interested in everyday time experience – can refer to an inter-individual variety of experiences for which the right measurements may still have to be developed (Wearden, O'Donoghue, Ogden, & Montgomery, 2014). Owing to these methodological shortcomings and to the comparably small amount of experimental studies on time perception in altered states of consciousness, the following paragraphs aim at providing a framework for empirical findings which has the status of a working hypothesis in progress.

3. Altered states of consciousness: modulations of time and the self

The aforementioned examples of boredom, mind wandering and distraction are common phenomena as experienced daily by everybody. However, time consciousness and self-consciousness are more prominently modulated in altered states of consciousness (ASC). Such ego and time modulations, in extreme cases a joint dissolution of the notions of self and time, can be induced in meditation, through sensory deprivation, in rhythm-induced trance (Block, 1979; Vaitl et al., 2005) and musical experience (Schäfer, Fachner, & Smukalla, 2013). Drugs affect the perception of time, as controlled laboratory experiments on alcohol (Ogden, Wearden, Gallagher, & Montgomery, 2011) and marijuana (Sewell et al., 2013) intake show, by provoking relative overestimation of duration in the time range of milliseconds to seconds. However, longer time ranges of hours may be affected differently, where alcohol leads to the feeling of a faster passage of time but marijuana expands experienced duration; these effects are potentially related to retrospective judgments depending on impaired attentional capacities in alcohol leading to fewer stored memories and more vivid if not bizarre memories after marijuana consumption (Ogden & Montgomery, 2012; Wittmann, 2015). Extreme distortions of time are also reported after accidents and frightening events, where people experience a slowing down of external events as if the world relative to the observer was moving in slow motion. These experiences are being interpreted as stemming from an increased bodily arousal level in a fight-and-flight situation which transiently speeds up internal processes to a maximum (Arstila, 2012).

3.1. States of meditation

States of meditation and long-term effects of meditation on cognition are perhaps the most systematically studied among the variety of means to induce ASC. In mindfulness meditation, as the most extensively studied meditation technique (e.g., Lutz et al., 2009; Moore & Malinowski, 2009; Sedlmeier et al., 2012; Zeidan, Johnson, Diamond, David, & Goolkasian, 2010), functional aspects of self-consciousness are affected by specific states of meditation, namely by increased attentional focus on body states and by emotion regulation (Hölzel et al., 2011). One aspect that is noticed by individuals during mindfulness meditation and in every-day life is that subjective time slows down considerably and the present moment expands (Kabat-Zinn, 2005; Wittmann et al., 2015). Conceptually, this effect can be understood as stemming from the ability of meditators to be more strongly aware of sensory experiences and to focus more on body states, which in turn leads to a slowing down of time and an expansion of the present moment (Sauer et al., 2012; Wittmann & Schmidt, 2014). But even mindfulness as a trait in the student population, i.e. not related to meditation skills, is associated with more accurate time perception of intervals with milliseconds-to-seconds duration (Wittmann et al., 2014). According to the body awareness theory of time perception, subjective duration – as awareness of time at the present moment – is expanded through an increased awareness of bodily states (Craig, 2009a,b; Wittmann, 2013). Moreover, stronger sensory awareness and then enhanced retrieval of contextual changes in memory leads also to a retrospective expansion of past duration (Zakay & Block, 1997).

The first studies testing time perception before vs. after mindfulness-oriented meditation practice are indicative of a prolongation of subjective duration, either after repeated sessions of mindfulness meditation over the course of weeks or directly after a meditation session (Berkovich-Ohana, Glicksohn, & Goldstein, 2011; Droit-Volet, Fanget, & Dambrun, 2015; Kramer, Weger, & Sharma, 2013; Sucala & David, 2013). These results can be discussed within the framework of an increased (more mindful) interoceptive awareness after extensive meditation experience or as transiently, i.e. state-induced, directly after a meditation session. It has been shown how self-reported regulatory aspects of interoception in daily life, i.e. the ability to regulate distress by attention to body sensations, are enhanced after extended contemplative practice regarding the "body scan" and "breath meditation" (Bornemann, Herbert, Mehling, & Singer, 2015). Also, the measurement of objective indices of body related judgment, i.e. tactile sensitivity and accuracy, reveal a better performance after body-centered meditation (Fox et al., 2012; Mirams, Poliakoff, Brown, & Lloyd, 2013). In general, individuals with long-term practice of mindfulness meditation are more sensitive to inner movements and impulses which are important for decision-making and action control (Jo, Hinterberger, Wittmann, & Schmidt, 2015; Jo, Wittmann, Borghardt, Hinterberger, & Schmidt, 2014). As elaborated above, an increased awareness of the (bodily) self would lead to a relative expansion of duration (Wittmann & Schmidt, 2014). In accordance with the aforementioned theoretical framework of self-regulation, which has shown to be accompanied with a prolongation of felt duration (Vohs & Schmeichel, 2003), mindfulness can be described as systematic mental training that fosters the development of meta-awareness of one self and the ability to effectively self-regulate behavior (Vago & Silbersweig, 2012).

Related to the interoceptive focus of mindfulness meditation, neuroimaging studies have shown how – among other regions – the insular cortex is functionally and anatomically modulated through mindfulness meditation practice. For example, as compared to meditation-naïve control subjects experienced meditators showed greater gray matter concentration (Hölzel et al., 2008) as well as greater cortical thickness (Lazar et al., 2005) in the right anterior insula. These findings were discussed as stemming from training bodily awareness during mindfulness meditation. Moreover, the instructions to either concentrate on 'being in the present – here and now' (Farb et al., 2007) and focusing on breathing sensations lead to a greater increase in neural activation in the insular cortex in trained meditators as compared to control subjects (Farb, Segal, & Anderson, 2012). These findings suggest that the interoceptive focus of mindfulness meditation practice leads to a more pronounced anatomical and functional representation in brain regions related to processing of one's bodily signals and to the perception of time. In addition to insular cortex activation, regions of the lateral pre-frontal cortex are activated which

Table 1
Aspects of experience, time perspective, the self, and duration estimates, concerning 'explicit' and 'implicit' time perception. For a detailed discussion, see the text.

	Experience	Time perspective	Aspect of self	Duration estimate
'explicit time'	Sensory experience in the 'here and now'	Present perspective	Bodily self	Relative overestimation
'implicit time'	Mind-wandering, Day dreaming	Past perspective Future perspective	Narrative self	Relative underestimation

can be interpreted as related to attention networks. When we focus attention on the bodily self at the present moment, attentional systems as well as areas related to bodily feelings are activated – next to additional functional networks (Hölzel et al., 2011).

Essentially, consciousness is altered during meditation practice through the sustained focus on the present moment, i.e. by keeping the focus of attention on a single object such as breathing-in and breathing-out. This ability encompasses the disregard of distractors such as thoughts and external sensations for an extended period of time. The constantly upcoming ideas, ruminations and sensations, William James' 'stream of consciousness' consists of self-related perceptual and narrative elements forming the contents of the continuity of consciousness, which are related to the 'default mode network' of cortical midline structures (Lloyd, 2012; Northoff, 2014). These structures are suggested to be associated with self-oriented processes of the narrative (autobiographical) kind such as mind-wandering, imagining personal past or future events (mental time travel), personal stimulus valuation and familiarity (Botzung, Denkova, & Manning, 2008; Northoff, Qin, & Feinberg, 2011; Qin & Northoff, 2011; Spreng, Mar, & Kim, 2009; Zaytseva et al., 2014) (see Table 1).

During meditation, attention is directed to the bodily self at the present moment and mind wandering and day dreaming are sought to be inhibited, an ability that has to be repeatedly practiced. In functional neuroanatomical terms, the insula – associated with self-related body focus in the here and now ('experiential focus') – is activated during meditation, and the default mode network of midline structures – associated with self-related mind wandering and projections into the past and future self ('narrative focus') – is at the same time inhibited (Farb et al., 2007). That is, the two negatively correlated neural systems can be distinguished as related to 'explicit time consciousness' (the insular cortex and related structures being linked to the explicit feeling of duration and the passage of time at the present moment) and to 'implicit time consciousness' or the 'stream of consciousness' associated with parts of the cortical midline structures and related areas (Northoff, 2014). Activation of the former system is associated with a relative slower passage of time and the feeling of presence; the latter system is associated with a relative faster passage of time and the flow of consciousness. An fMRI study adds to this rather schematic two-systems model, by showing how three separate neural systems are activated in different phases of meditation practice (Hasenkamp, Wilson-Mendenhall, Duncan, & Barsalou, 2012): the 'default mode network' during mind wandering, the 'saliency network' including the anterior insula during awareness that mind wandering has occurred, and the dorsolateral frontal cortex 'executive network' when shifting attention back to the focus of breathing and holding it there. Of course, it can be argued that also states of mind-wandering are related to explicit time perception in a very specific sense, namely having memories of past events and expectation of future happenings. The distinction made here is that subjective time in the seconds-to-minutes range is regarded as evolving within present sensory experience (Wittmann, 2011) and mind-wandering is associated with the propensity to transiently focus on the past as memories arise and the future as expectation of what might happen (Zimbardo & Boyd, 1999).

3.2. 'Selflessness' and 'timelessness'

Ultimately, the goal of very experienced meditators during meditation practice is the joint modulation of the perception of self, space and time culminating in the feeling of "selflessness", "spacelessness", and "timelessness" (Berkovich-Ohana, Dor-Ziderman, Glicksohn, & Goldstein, 2013; Wittmann, 2015). This peak experience attainable during meditation is describable (in retrospect) as joint modulation of the notion of self and time. That is, during this kind of ASC the feelings of the self and of time are intensely modulated, in the extreme leading to the feeling that time stands still – a reported universal experience in mystical states where time is not experienced at all and the self becomes one with the world (Achtner, 2009; Ott, 2013). The notions of self and time disappear.

There is a literary tradition reporting vividly the extreme distortions of time consciousness after ingestion of drugs, e.g. by Thomas De Quincy (on opium), Aldous Huxley (on mescaline), and Walter Benjamin (on hashish). Systematic research on time perception in drug-induced states with hallucinogens such as psilocybin shows how subjective time is distorted, this experience being correlated with impairments in psychophysical timing tasks (Wackermann, Wittmann, Hasler, & Vollenweider, 2008; Wittmann et al., 2007). In extreme cases, psychoactive substances such as ayahuasca, LSD, psilocybin or mescaline provoke a complete alteration of the sense of time, resulting in a feeling of 'timelessness' or, alternatively, the notion that time is felt, but that it has become irrelevant (Shanon, 2001). Such was Aldous Huxley's (1954) report after consumption of mescaline: "Along with indifference to space there went an even completer indifference to time. 'There seems to be plenty of it', was all I would answer when the investigator asked me to say what I felt about time. Plenty of it, but exactly how much was entirely irrelevant. I could, of course, have looked at my watch; but my watch, I knew, was still, of an indefinite duration or alternatively of a perpetual present made of one continually changing apocalypse."

After intake of hallucinogens people report profound changes in mood, perception, thought and the experience of the self. During peak states under psilocybin individuals can experience depersonalization and derealization, ecstatic mood states, and a feelings of unity of the self with the universe (though negatively felt ego dissolutions can also occur); the self becomes one with the world (Studerus, Kometer, Hasler, & Vollenweider, 2011). Psychometric scales which are filled out when the drug effects fade out reveal how the item of ''I experienced the past, present, and future as oneness'' loads within the factor ''feeling of unity''; moreover, the factor ''disembodiment'' correlates highly with the factor ''feeling of unity'' (Studerus, Gamma, & Vollenweider, 2010). Thus, the three experiences of positive self-dissolution, the feeling of a unity of the three time perspectives (or ''timelessness'') are closely related to the accompanying feeling of detachment of the body. That is, the felt loss of body connection is related to the loss of an individuated self and of time, the notions of body, self and time thereafter being strongly modulated through psychoactive substances.

What happens in the brain during psilocybin-induced changes of the conscious state in humans? Psilocybin as 5-HT2A/1A receptor agonist acts primarily on the serotonin transmitter system with PET studies indicating dominant hyper-activation in frontal brain structures after oral intake of psilocybin (Vollenweider & Kometer, 2010; Vollenweider et al., 1997). This hyper-activation could potentially be linked to sensory overload of internal and external experiencing, in which a self-representation would merge and become one with the sensed world. However, findings are controversial and most likely dependent on the modes of application and analyses of data from the employed neuroimaging technologies. For example, one study points to an overall decrease of fMRI-detected activation after intravenous psilocybin administration with maximal decreases in anterior and posterior cingulate cortex – part of the default mode network; these modulations were associated with many experiences clearly different from the normal waking state, among them unusual body states and alterations in the sense of space and time (Carhart-Harris et al., 2012). In a more recent study by the same research group analyzing statistical properties of functional networks under psilocybin reveal many transient and more persistent functional connections that are potentially related to the massive experiential changes induced by the drug (Petri et al., 2014).

There is further evidence of what happens in the brain during the transition from an ordinary sense of a bodily self, space and time to the feeling of being out of time or ''timelessness''. This direct empirical evidence comes from two sources of investigation, from the study of very experienced meditators and from neurology. In an MEG study with long-term practitioners of mindfulness meditation, meditation-induced states of 'timelessness' versus 'focus on the present moment' were compared (Berkovich-Ohana et al., 2013). Theta activity was recorded in a right-lateralized network that comprised motor areas and the interoceptive network. That is, modulations in the sense of time which varied between 'being focused on the present moment' and achieving a state of 'being out of time' were related to variations of activity in areas of the brain that are related to the perception of time (Buhusi & Meck, 2005; Merchant et al., 2013; Wittmann, 2009).

The investigation of certain neurologic states such as in auras preceding epileptic ''ecstatic'' seizures (in temporal lobe epilepsy) provides a further clue about how self-consciousness and time consciousness are jointly modulated. In his novels and letters Fyodor Dostoyevsky meticulously describes what he felt when he had epileptic seizures during which he experienced to be ''entirely in harmony with myself and the whole world, and this feeling is so strong and so delightful that for a few seconds of such bliss one would gladly give up ten years of one's life, if not one's whole life'' (Rayport, Rayport, & Schell, 2011). Recent neuroimaging studies reveal how these ecstatic auras are provoked by a hyperactivation of regions centering in the anterior insular cortex (Landtblom, Lindehammar, Karlsson, & Craig, 2011; Picard & Craig 2009). During these states individual patients report an extremely heightened self-awareness (''I feel more conscious of myself'', ''I feel very, very, very present at that time''), spiritual emotions (''a feeling of unbelievable harmony of my whole body and myself with life, with the world, with the 'All''', ''well-being of almost spiritual consonance''), feelings of euphoria and 'orgasmic ecstasy' (''the pleasure goes crescendo until it reaches a peak''). That is, during those moments of bliss during seizures affecting the anterior insula, activation increases and the accompanying ''feeling became stronger and stronger, until it became so strong that it was unbearable and led to a loss of consciousness'', and in the moments before unconsciousness one person felt that ''I am in a radiant sphere without any notion of time or space'' (Picard & Craig, 2009). In the few minutes after onset of the aura and before unconsciousness sets in, there is a feeling of intensified and blissful body- and self-awareness which then reaches the experience of being outside of time and space.

4. A view of neurological and psychiatric syndromes and final remarks

A variety of psychiatric and neurologic syndromes is associated with fundamental distortions in the notions of the self, the representation of the body, feeling states and time (Hartocollis, 1983). For example, individuals with depression and anxiety report a slowing down of time and overestimate duration (Bschor et al., 2004; Wittmann et al., 2006). A case study of a patient who was probably suffering from a depersonalization syndrome is perhaps the most striking example of a person who, due to her illness, had lost her sense of bodily urges. She also did not feel any emotions and at the same time had lost any sense of duration (D'Allonnes, 1905). The patient Alexandrine had no feeling of hunger, satiety, thirst, pressure to go to toilette, or fatigue. Tests conducted showed that she was insensitive to ice water and needle pricks. She showed physiological reactions of emotion and had a cognitive understanding of emotional situations, but she did not feel anything. Moreover, she had lost her subjective sense of duration in the seconds-to-hours range and tests conducted on her revealed that she had an impaired sense for different metronome speeds. This single case is remarkable in that it shows that in a pathological condition, the bodily self, feeling states, and the sense of time can all be massively impaired at the same time.

It has also been suggested that schizophrenia is in essence a disturbance of the embodied self (de Haan & Fuchs, 2010; Seth, 2013), which in turn would lead to disturbances in the processing of time consciousness, i.e. to subjective feelings of patients being stuck in time (Fuchs, 2013; Vogeley & Kupke, 2007). Neuroimaging work shows how many different brain regions are functionally and structurally affected in schizophrenia (Meyer-Lindenberg, 2010). Moreover, recent empirical work points to the decisive factor regarding this psychiatric illness in insular cortex dysfunction which is related to a reduced cortical connectivity between the insula, dorsolateral frontal cortex, and the default mode network (Manoliu et al., 2013, 2014; Palaniyappan & Liddle, 2012, 2014). Since these structures are involved in the processing of the bodily self, the autobiographic self as well of time, it is tempting to relate the found neuronal dysfunctions impairments related to the self and of time.

Regarding subjective time, a variety of statements of schizophrenic patients has been collected (Fuchs, 2007; Minkowski, 1933|2005; Schilder, 1936) giving the impression that for those patients time is not passing and that lived presence feels expanded: "What is the future? One cannot reach it. [...] Time stands still [...]. This is boring, stretched time without an end" (Fischer, 1929). Empirical findings show how the perception of temporal intervals in the several seconds' range is affected as they are most frequently overestimated (Melges & Fougerousse, 1966; Tysk, 1983; Wahl & Sieg, 1980). The subjective feelings of schizophrenic patients as cited here are however better mirrored in recent experimental approaches showing enlarged windows of the functional present (Martin, Giersch, Huron, & van Wassenhove, 2013) and impairments in implicit time continuity (Giersch et al., 2009; Lalanne, van Assche, Wang, & Giersch, 2012). These psychophysical findings can be interpreted in the way that patients are indeed functionally stuck in the present moment (Martin et al., 2014).

To sum up, the joint modulation of the experience of self and of time provides researchers the opportunity to investigate the unsolved riddle of consciousness through the investigation of time consciousness. Researchers have begun to study altered states of consciousness with different induction methods and in psychiatric and neurological illnesses to understand the underlying dynamics of neural system states which provide the basis for our experience of time and the conscious self. Beginning on the phenomenal level, future research will assess the psychological and neural mechanisms leading to altered time consciousness and will thereby also understand more about consciousness.

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References

Achtner, W. (2009). Time, eternity, and trinity. *Neue Zeitschrift für Systematische Theologie und Religionsphilosophie, 51*, 267–288.
Arstila, V. (2012). Time slows down during accidents. *Frontiers in Psychology, 3*(196).
Bar-Haim, Y., Kerem, A., Lamy, D., & Zakay, D. (2010). When time slows down: The influence of threat on time perception in anxiety. *Cognition and Emotion, 24*, 255–263.
Baumeister, R. F., & Vohs, K. D. (2003). Self-regulation and the executive function of the self. In M. R. Leary & J. P. Tangney (Eds.), *Handbook of self and identity* (pp. 197–217). New York: The Guilford Press.
Berkovich-Ohana, A., Dor-Ziderman, Y., Glicksohn, J., & Goldstein, A. (2013). Alterations in the sense of time, space, and body in the mindfulness-trained brain: A neurophenomenologically-guided MEG study. *Frontiers in Psychology, 4*(912).
Berkovich-Ohana, A., Glicksohn, J., & Goldstein, A. (2011). Temporal cognition changes following mindfulness, but not transcendental meditation practice. *Proceedings of Fechner Day, 27*, 245–250.
Block, R. A. (1979). Time and consciousness. In G. Underwood & R. Stevens (Eds.). *Aspects of consciousness* (Vol. 1, pp. 179–217). London: Academic Press.
Bornemann, B., Herbert, B. M., Mehling, W. E., & Singer, T. (2015). Differential changes in self-reported aspects of interoceptive awareness through three months of contemplative training. *Frontiers in Psychology, 5*, 1504.
Botzung, A., Denkova, E., & Manning, L. (2008). Experiencing past and future personal events: Functional neuroimaging evidence on the neural bases of mental time travel. *Brain and Cognition, 66*, 202–212.
Bschor, T., Ising, M., Bauer, M., Lewitzka, U., Skerstupeit, M., Müller-Oerlinghausen, B., et al (2004). Time experience and time judgment in major depression, mania and healthy subjects. A controlled study of 93 subjects. *Acta Psychiatrica Scandinavica, 109*, 222–229.
Bueti, D., & Macaluso, E. (2011). Physiological correlates of subjective time: Evidence for the temporal accumulator hypothesis. *NeuroImage, 57*, 1251–1263.
Buhusi, C. V., & Meck, W. H. (2005). What makes us tick? Functional and neural mechanisms of interval timing. *Nature Reviews Neuroscience, 6*, 755–765.
Carhart-Harris, R. L., Erritzoe, D., Williams, T., Stone, J. M., Reed, L. J., Colasanti, A., et al (2012). Neural correlates of the psychedelic state as determined by fMRI studies with psilocybin. *PNAS, 109*, 2138–2143.
Conti, R. (2001). Time flies: Investigating the connection between intrinsic motivation and the experience of time. *Journal of Personality, 69*, 1–26.
Coull, J. T., & Nobre, A. C. (2008). Dissociating explicit timing from temporal expectation with fMRI. *Current Opinion in Neurobiology, 18*, 137–144.
Craig, A. D. (2009a). Emotional moments across time: A possible neural basis for time perception in the anterior insula. *Philosophical Transactions of the Royal Society B, 364*, 1933–1942.
Craig, A. D. (2009b). How do you feel – now? The anterior insula and human awareness. *Nature Reviews Neuroscience, 10*, 59–70.
Craig, A. D. (2015). *How do you feel? An interoceptive moment with your neurobiological self.* Princeton: Princeton University Press.

Critchley, H. D., Wiens, S., Rotshtein, P., Öhman, A., & Dolan, R. J. (2004). Neural systems supporting interoceptive awareness. *Nature Neuroscience, 7*, 189–195.

Csikszentmihalyi, M., & Csikszentmihalyi, I. S. (1988). *Optimal experience: psychological studies of flow in consciousness*. Cambridge: Cambridge University Press.

D'Allonnes, G.-R. (1905). Role des sensations internes dans les émotions et dans la perception de la durée. *Revue Philosophique de la France et de l'Étranger, 60*, 592–623.

Damasio, A. (1999). *The feeling of what happens: Body and emotion in the making of consciousness*. San Diego: Harcourt Inc.

Danckert, J. A., & Allman, A. A. A. (2005). Time flies when you're having fun: Temporal estimation and the experience of boredom. *Brain and Cognition, 59*, 236–245.

de Haan, S., & Fuchs, T. (2010). The ghost in the machine: Disembodiment in schizophrenia – Two case studies. *Psychopathology, 43*, 327–333.

Dirnberger, G., Hesselmann, G., Roiser, J. P., Preminger, S., Jahanshahi, M., & Paz, R. (2012). Give it time: Neural evidence for distorted time perception and enhanced memory encoding in emotional situations. *Neuroimage, 63*, 591–599.

Droit-Volet, S., Fanget, M., & Dambrun, M. (2015). Mindfulness meditation and relaxation training increases time sensitivity. *Consciousness and Cognition, 31*, 86–97.

Droit-Volet, S., Fayolle, S. L., & Gil, S. (2011). Emotion and time perception: Effects of film-induced mood. *Frontiers in Integrative Neuroscience, 5*(33).

Droit-Volet, S., Fayolle, S., Lamotte, M., & Gil, S. (2013). Time, emotion and the embodiment of timing. *Timing & Time Perception, 1*, 99–126.

Droit-Volet, S., & Gil, S. (2009). The time-emotion paradox. *Philosophical Transactions of the Royal Society B, 364*, 1943–1954.

Farb, N. A., Segal, Z. V., & Anderson, A. K. (2012). Mindfulness meditation training alters cortical representations of interoceptive attention. *Social Cognitive and Affective Neuroscience, 8*, 15–26.

Farb, N. A., Segal, Z. V., Mayberg, H., Bean, J., McKeon, D., Fatima, Z., et al (2007). Attending to the present: Mindfulness meditation reveals distinct neural modes of self- reference. *Social Cognitive and Affective Neuroscience, 2*, 313–322.

Fischer, F. (1929). Zeitstruktur und Schizophrenie. *Zeitschrift für die gesamte Neurologie und Psychiatrie, 121*, 544–574.

Flaherty, M. G. (1993). Conceptualizing variation in the experience of time. *Sociological Inquiry, 63*, 394–405.

Förster-Beuthan, Y. (2012). *Zeiterfahrung und Ontologie. Perspektiven moderner Zeitphilosophie*. München: Wilhelm Fink.

Fox, K. C., Zakarauskas, P., Dixon, M., Ellamil, M., Thompson, E., & Christoff, K. (2012). Meditation experience predicts introspective accuracy. *PloS one, 7*, e45370.

French, R. M., Addyman, C., Mareschal, D., & Thomas, E. (2014). Unifying prospective and retrospective interval-time estimation: A fading-Gaussian activation-based model of interval-timing. *Procedia-Social and Behavioral Sciences, 126*, 141–150.

Fuchs, T. (2007). The temporal structure of intentionality and its disturbance in schizophrenia. *Psychopathology, 40*, 229–235.

Fuchs, T. (2013). Temporality and psychopathology. *Phenomenology and the Cognitive Sciences, 12*, 75–104.

Giersch, A., Lalanne, L., Corves, C., Seubert, J., Shi, Z., Foucher, J., et al (2009). Extended visual simultaneity thresholds in patients with schizophrenia. *Schizophrenia Bulletin, 35*, 816–825.

Gil, S., Niedenthal, P., & Droit-Volet, S. (2007). Anger and temporal perception in children. *Emotion, 7*, 219–225.

Grondin, S. (2010). Timing and time perception: A review of recent behavioral and neuroscience findings and theoretical directions. *Attention Perception & Psychophysics, 72*, 561–582.

Hancock, P. A., & Block, R. A. (2012). The psychology of time: A view backward and forward. *American Journal of Psychology, 125*, 267–274.

Hartocollis, P. (1983). *Time and Timelessness, or, the Varieties of Temporal Experience (A Psychoanalytic Inquiry)*. New York: International Universities Press.

Hasenkamp, W., Wilson-Mendenhall, C. D., Duncan, E., & Barsalou, L. W. (2012). Mind wandering and attention during focused meditation: A fine-grained temporal analysis of fluctuating cognitive states. *Neuroimage, 59*, 750–760.

Hölzel, B. K., Lazar, S. W., Gard, T., Schuman-Olivier, Z., Vago, D. R., & Ott, U. (2011). How does mindfulness work? Proposing mechanisms of action from a conceptual and neural perspective. *Perspectives on Psychological Science, 6*, 537–559.

Hölzel, B. K., Ott, U., Hempel, H., Hackl, A., Wolf, K., Stark, R., et al (2008). Investigation of mindfulness meditation practicioners with voxel-based morphometry. *Social Cognitive and Affective Neuroscience, 3*, 55–61.

Huxley, A. (1954). *The doors of perception*. London: Chatto and Windus.

Jo, H.-G., Hinterberger, T., Wittmann, M., & Schmidt, S. (2015). Do meditators have higher awareness of their intentions to act? *Cortex, 65*, 149–158.

Jo, H.-G., Wittmann, M., Borghardt, T. L., Hinterberger, T., & Schmidt, S. (2014). First-person approaches in neuroscience of consciousness: Brain dynamics correlate with the intention to act. *Consciousness and Cognition, 26*, 105–116.

Kabat-Zinn, J. (2005). *Coming to our senses*. New York: Hyperion.

Kramer, R. S., Weger, U. W., & Sharma, D. (2013). The effect of mindfulness meditation on time perception. *Consciousness and Cognition, 22*, 846–852.

Lalanne, L., van Assche, M., Wang, W., & Giersch, A. (2012). Looking forward: An impaired ability in patients with schizophrenia? *Neuropsychologia, 50*, 2736–2744.

Lambrechts, A., Mella, N., Pouthas, V., & Noulhiane, M. (2011). Subjectivity of time perception: A visual emotional orchestration. *Frontiers in Integrative Neuroscience, 5*(73).

Lamotte, M., Chakroun, N., Droit-Volet, S., & Izaute, M. (2014). Metacognitive questionnaire on time: Feeling of the passage of time. *Timing & Time Perception, 2*, 339–359.

Landtblom, A. M., Lindehammar, H., Karlsson, H., & Craig, A. D. (2011). Insular cortex activation in a patient with" sensed presence"/ecstatic seizures. *Epilepsy & Behavior, 20*, 714–718.

Lazar, S. W., Kerr, C. E., Wasserman, R. H., Gray, J. R., Greve, D. N., Treadway, M. T., et al (2005). Meditation experience is associated with increased cortical thickness. *NeuroReport, 16*, 1893–1897.

Lewis, P. A., & Miall, R. C. (2003). Distinct systems for automatic and cognitively controlled time measurement: Evidence from neuroimaging. *Current Opinion in Neurobiology, 13*, 250–255.

Livesey, A. C., Wall, M. B., & Smith, A. T. (2007). Time perception: Manipulation of task difficulty dissociates clock functions from other cognitive demands. *Neuropsychologia, 45*, 321–331.

Lloyd, D. (2012). Neural correlates of temporality: Default mode variability and temporal awareness. *Consciousness and Cognition, 21*, 695–703.

Lutz, A., Slagter, H. A., Rawlings, N. B., Francis, A. D., Greischar, L. L., & Davidson, J. R. (2009). Mental training enhances attentional stability: Neural and behavioral evidence. *The Journal of Neuroscience, 29*, 13418–13427.

Manoliu, A., Riedl, V., Doll, A., Bäuml, J. G., Mühlau, M., Schwerthöffer, D., et al (2013). Insular dysfunction reflects altered between-network connectivity and severity of negative symptoms in schizophrenia during psychotic remission. *Frontiers in Human Neuroscience, 7*(216).

Manoliu, A., Riedl, V., Zherdin, A., Mühlau, M., Schwerthöffer, D., Scherr, M., et al (2014). Aberrant dependence of default mode/central executive network interactions on anterior insular salience network activity in schizophrenia. *Schizophrenia Bulletin, 40*, 428–437.

Martin, B., Giersch, A., Huron, C., & van Wassenhove, V. (2013). Temporal event structure and timing in schizophrenia: Preserved binding in a longer "now". *Neuropsychologia, 51*, 358–371.

Martin, B., Wittmann, M., Franck, N., Cermolacce, M., Berna, F., & Giersch, A. (2014). Temporal structure of consciousness and minimal self in schizophrenia. *Frontiers in Psychology, 5*(1175).

Mauk, M. D., & Buonomano, D. V. (2004). The neural basis of temporal processing. *Annual Review of Neuroscience, 27*, 307–340.

Meck, W. (2005). Neuropsychology of timing and time perception. *Brain and Cognition, 58*, 1–8.

Meissner, K., & Wittmann, M. (2011). Body signals, cardiac awareness, and the perception of time. *Biological Psychology, 86*, 289–297.

Melges, F. T., & Fougerousse, C. E. (1966). Time sense, emotions, and acute mental illness. *Journal of Psychiatry Research, 4*, 127–140.

Menon, V., & Uddin, L. Q. (2010). Saliency, switching, attention and control: A network model of insula function. *Brain Structure and Function, 214*, 655–667.

Merchant, H., Harrington, D. L., & Meck, W. H. (2013). Neural basis of the perception and estimation of time. *Annual Review of Neuroscience, 36*, 313–336.
Meyer-Lindenberg, A. (2010). From maps to mechanisms through neuroimaging of schizophrenia. *Nature, 468*, 194–202.
Minkowski, E. (1933|2005). *Le temps vécu: Etudes phénoménologiques et psychopathologiques*, 2nd ed. Paris: Presses Universitaires de France.
Mirams, L., Poliakoff, E., Brown, R. J., & Lloyd, D. M. (2013). Brief body-scan meditation practice improves somatosensory perceptual decision making. *Consciousness and Cognition, 22*, 348–359.
Monfort, V., Pfeuty, M., Klein, M., Collé, S., Brissart, H., Jonas, J., et al (2014). Distortion of time interval reproduction in an epileptic patient with a focal lesion in the right anterior insular/inferior frontal cortices. *Neuropsychologia, 64*, 184–194.
Moore, A., & Malinowski, P. (2009). Meditation, mindfulness and cognitive flexibility. *Consciousness and Cognition, 18*, 176–186.
Naish, P. L. N. (2007). Time distortion and the nature of hypnosis and consciousness. In G. Jamieson (Ed.), *Hypnosis and conscious states: The cognitive-neuroscience perspective* (pp. 271–292). Oxford: Oxford University Press.
Noreika, V., Falter, C. M., Arstila, V., Wearden, J. H., & Kallio, S. (2012). Perception of short time scale intervals in a hypnotic virtuoso. *International Journal of Clinical and Experimental Hypnosis, 60*, 318–337.
Northoff, G. (2014). Do cortical midline variability and low frequency fluctuations mediate William James' "Stream of Consciousness"? "Neurophenomenal Balance Hypothesis" of "Inner Time Consciousness". *Consciousness and Cognition, 30*, 184–200.
Northoff, G., Qin, P., & Feinberg, T. E. (2011). Brain imaging of the self–conceptual, anatomical and methodological issues. *Consciousness and Cognition, 20*, 52–63.
Ogden, R., & Montgomery, C. (2012). High time. *The Psychologist, 25*, 590–592.
Ogden, R. S., Moore, D., Redfern, L., & McGlone, F. (2014). The effect of pain and the anticipation of pain on temporal perception: A role for attention and arousal. *Cognition and Emotion*. http://dx.doi.org/10.1080/02699931.2014.954529.
Ogden, R. S., Wearden, J. H., Gallagher, D. T., & Montgomery, C. (2011). The effect of alcohol administration on human timing: A comparison of prospective timing, retrospective timing and passage of time judgements. *Acta Psychologica, 138*, 254–262.
Ott, U. (2013). Time experience during mystical states. In A. Nikolaidis & W. Achtner (Eds.), *The evolution of time: studies of time in science, anthropology, theology* (pp. 104–116). Oak Park, IL: Bentham Science Publishers.
Palaniyappan, L., & Liddle, P. F. (2012). Does the salience network play a cardinal role in psychosis? An emerging hypothesis of insular dysfunction. *Journal of Psychiatry & Neuroscience, 37*, 17–27.
Palaniyappan, L., & Liddle, P. F. (2014). Diagnostic discontinuity in psychosis: A combined study of cortical gyrification and functional connectivity. *Schizophrenia Bulletin, 40*(3), 675–684.
Petri, G., Expert, P., Turkheimer, F., Carhart-Harris, R., Nutt, D., Hellyer, P. J., et al (2014). Homological scaffolds of brain functional networks. *Journal of the Royal Society Interface, 11*, 20140873.
Picard, F., & Craig, A. D. (2009). Ecstatic epileptic seizures: A potential window on the neural basis for human self-awareness. *Epilepsy & Behavior, 16*, 529–546.
Pollatos, O., Kirsch, W., & Schandry, R. (2005). On the relationship between interoceptive awareness, emotional experience, and brain processes. *Cognitive Brain Research, 25*, 948–962.
Pollatos, O., Laubrock, J., & Wittmann, M. (2014b). Interoceptive focus shapes the experience of time. *PloS One, 9*, e86934.
Pollatos, O., Yeldesbay, A., Pikovsky, A., & Rosenblum, M. (2014a). How much time has passed? Ask your heart. *Frontiers in Neurorobotics, 8*(15).
Pouthas, V., & Perbal, S. (2004). Time perception depends on accurate clock mechanisms as well as unimpaired attention and memory processes. *Acta Neurobiologiae Experimentalis, 64*, 367–385.
Qin, P., & Northoff, G. (2011). How is our self related to midline regions and the default-mode network? *Neuroimage, 57*, 1221–1233.
Rayport, S. M. F., Rayport, M., & Schell, C. A. (2011). Dostoevsky's epilepsy: A new approach to retrospective diagnosis. *Epilepsy & Behavior, 22*, 557–570.
Rudd, M., Vohs, K. D., & Aaker, J. (2012). Awe expands people's perception of time, alters decision making, and enhances well-being. *Psychological Science, 23*, 1130–1136.
Sauer, S., Lemke, J., Wittmann, M., Kohls, N., Mochty, U., & Walach, H. (2012). How long is now for mindfulness meditators? *Personality and Individual Differences, 52*, 750–754.
Schäfer, T., Fachner, J., & Smukalla, M. (2013). Changes in the representation of space and time while listening to music. *Frontiers in Psychology, 4*(508).
Schilder, P. (1936). Psychopathology of time. *Journal of Nervous and Mental Disease, 83*, 530–546.
Sedlmeier, P., Eberth, J., Schwarz, M., Zimmermann, D., Haarig, F., Jaeger, S., et al (2012). The psychological effects of meditation: A meta-analysis. *Psychological Bulletin, 138*, 1139–1171.
Seth, A. K. (2013). Interoceptive inference, emotion, and the embodied self. *Trends in Cognitive Sciences, 17*, 565–573.
Sewell, R. A., Schnakenberg, A., Elander, J., Radhakrishnan, R., Williams, A., Skosnik, P. D., et al (2013). Acute effects of THC on time perception in frequent and infrequent cannabis users. *Psychopharmacology, 226*, 401–413.
Shanon, B. (2001). Altered temporality. *Journal of Consciousness Studies, 8*, 35–58.
Simmons, A. N., Flagan, T. M., Wittmann, M., Strigo, I. A., Matthews, S. C., Donovan, H., et al (2013). The effects of temporal unpredictability in anticipation of negative events in combat veterans with PTSD. *Journal of Affective Disorders, 146*, 426–432.
Singer, T., Critchley, H. D., & Preuschoff, K. (2009). A common role of insula in feelings, empathy and uncertainty. *Trends in Cognitive Sciences, 13*, 334–340.
Spreng, R. N., Mar, R. A., & Kim, A. S. (2009). The common neural basis of autobiographical memory, prospection, navigation, theory of mind, and the default mode: A quantitative meta-analysis. *Journal of Cognitive Neuroscience, 21*, 489–510.
Studerus, E., Gamma, A., & Vollenweider, F. X. (2010). Psychometric evaluation of the altered states of consciousness rating scale (OAV). *PLoS One, 5*, e12412.
Studerus, E., Kometer, M., Hasler, F., & Vollenweider, F. X. (2011). Acute, subacute and long-term subjective effects of psilocybin in healthy humans: A pooled analysis of experimental studies. *Journal of Psychopharmacology, 25*, 1434–1452.
Sucala, M., & David, D. (2013). Mindful about time in a fast forward world. The effects of mindfulness exercise on time perception. *Transylvanian Journal of Psychology, 14*, 243–253.
Sysoeva, O. V., Wittmann, M., & Wackermann, J. (2011). Neural representation of temporal duration: Coherent findings obtained with the "lossy integration" model. *Frontiers in Integrative Neuroscience, 5*(37).
Tanaka, S. C., Doya, K., Okada, G., Ueda, K., Okamoto, Y., & Yamawaki, S. (2004). Prediction of immediate and future rewards differentially recruits cortico-basal ganglia loops. *Nature Neuroscience, 7*, 887–893.
Terhune, D. B., Croucher, M., Marcusson-Clavertz, D., & Macdonald, J. S. (2014). Time contracts when the mind wanders. *Procedia-Social and Behavioral Sciences, 126*, 125–126.
Tipples, J., Brattan, V., & Johnston, P. (2013). Facial emotion modulates the neural mechanisms responsible for short interval time perception. *Brain Topography*. http://dx.doi.org/10.1007/s10548-013-0350-6.
Tomasi, D., Wang, G. J., Studentsova, Y., & Volkow, N. D. (2014). Dissecting neural responses to temporal prediction, attention, and memory: Effects of reward learning and interoception on time perception. *Cerebral Cortex*. http://dx.doi.org/10.1093/cercor/bhu269.
Tysk, L. (1983). Estimation of time and the subclassification of schizophrenic disorders. *Perceptual and Motor Skills, 57*, 911–918.
Vago, D. R., & Silbersweig, D. A. (2012). Self-awareness, self-regulation, and self-transcendence (S-ART): A framework for understanding the neurobiological mechanisms of mindfulness. *Frontiers in Human Neuroscience, 6*(296).
Vaitl, D., Birbaumer, N., Gruzelier, J., Jamieson, G. A., Kotchoubey, B., Kübler, A., et al (2005). Psychobiology of altered states of consciousness. *Psychological Bulletin, 131*, 98–127.
Vogeley, K., & Kupke, C. (2007). Disturbances of time consciousness from a phenomenological and a neuroscientific perspective. *Schizophrenia Bulletin, 33*, 157–165.

Vohs, K. D., & Schmeichel, B. J. (2003). Self-regulation and the extended now: Controlling the self alters the subjective experience of time. *Journal of Personality and Social Psychology, 85*, 217–230.
Vollenweider, F. X., & Kometer, M. (2010). The neurobiology of psychedelic drugs: Implications for the treatment of mood disorders. *Nature Reviews Neuroscience, 11*, 642–651.
Vollenweider, F. X., Leenders, K. L., Scharfetter, C., Maguire, P., Stadelmann, O., & Angst, J. (1997). Positron emission tomography and fluorodeoxyglucose studies of metabolic hyperfrontality and psychopathology in the psilocybin model of psychosis. *Neuropsychopharmacology, 16*, 357–372.
Wackermann, J., Meissner, K., Tankersley, D., & Wittmann, M. (2014). Effects of emotional valence and arousal on acoustic duration reproduction assessed via the 'dual klepsydra model'. *Frontiers in Neurorobotics, 8*(11).
Wackermann, J., Wittmann, M., Hasler, F., & Vollenweider, F. X. (2008). Effects of varied doses of psilocybin on time interval reproduction in human subjects. *Neuroscience Letters, 435*(1), 51–55.
Wahl, O. F., & Sieg, D. (1980). Time estimation among schizophrenics. *Perceptual and Motor Skills, 50*, 535–541.
Watt, J. D. (1991). Effect of boredom proneness on time perception. *Psychological Reports, 69*, 323–327.
Wearden, J. H. (2004). Decision processes in models of timing. *Acta Neurobiologiae Experimentalis, 64*, 303–317.
Wearden, J., O'Donoghue, A., Ogden, R., & Montgomery, C. (2014). Subjective duration in the laboratory and the world outside. In V. Arstila & D. Lloyd (Eds.), *Subjective time: The philosophy, psychology, and neuroscience of temporality* (pp. 287–306). Cambridge, MA: MIT Press.
Wiener, M., Turkeltaub, P., & Coslett, H. B. (2010). The image of time: A voxel-wise meta-analysis. *Neuroimage, 49*, 1728–1740.
Wittmann, M. (2009). The inner sense of time. *Philosophical Transactions of the Royal Society B, 364*, 1955–1967.
Wittmann, M. (2011). Moments in time. *Frontiers in Integrative Neuroscience, 5*(66).
Wittmann, M. (2013). The inner sense of time: How the brain creates a representation of duration. *Nature Reviews Neuroscience, 14*, 217–223.
Wittmann, M. (2015). *Wenn die Zeit stehen bleibt. Kleine Psychologie der Grenzerfahrungen*. München: C. H. Beck.
Wittmann, M., & Schmidt, S. (2014). Mindfulness meditation and the experience of time. In S. Schmidt, & H. Walach (Eds.), *Meditation – Neuroscientific approaches and philosophical implications*. Studies in neuroscience, consciousness and spirituality 2 (pp. 199–210). Cham: Springer-Verlag.
Wittmann, M., Carter, O., Hasler, F., Cahn, R., Grimberg, U., Spring, D., et al (2007). Effects of psilocybin on time perception and temporal control of behaviour in humans. *Journal of Psychopharmacology, 21*, 50–64.
Wittmann, M., Lovero, K. L., Lane, S. D., & Paulus, M. P. (2010b). Now or later? Striatum and insula activation to immediate versus delayed rewards. *Journal of Neuroscience, Psychology, and Economics, 3*, 15–26.
Wittmann, M., Otten, S., Schötz, E., Sarikaya, A., Lehnen, H., Jo, H.-G., et al (2015). Subjective expansion of extended time-spans in experienced meditators. *Frontiers in Psychology, 5*(1586).
Wittmann, M., & Paulus, M. P. (2008). Decision making, impulsivity and time perception. *Trends in Cognitive Science, 12*, 7–12.
Wittmann, M., Peter, J., Gutina, O., Otten, S., Kohls, N., & Meissner, K. (2014). Individual differences in self-attributed mindfulness levels are related to the experience of time and cognitive self-control. *Personality and Individual Differences, 64*, 41–45.
Wittmann, M., Simmons, A. N., Aron, J., & Paulus, M. P. (2010a). Accumulation of neural activity in the posterior insula encodes the passage of time. *Neuropsychologia, 48*, 3110–3120.
Wittmann, M., Simmons, A. N., Flagan, T., Lane, S. D., Wackermann, J., & Paulus, M. P. (2011). Neural substrates of time perception and impulsivity. *Brain Research, 1406*, 43–58.
Wittmann, M., & van Wassenhove, V. (2009). The experience of time: Neural mechanisms and the interplay of emotion, cognition and embodiment. *Philosophical Transactions of the Royal Society B, 364*, 1809–1813.
Wittmann, M., Vollmer, T., Schweiger, C., & Hiddemann, W. (2006). The relation between the experience of time and psychological distress in patients with hematological malignancies. *Palliative & Supportive Care, 4*, 357–364.
Zahavi, D. (2005). *Subjectivity and selfhood: Investigating the first-person perspective*. Cambridge, MA: MIT press.
Zakay, D. (2014). Psychological time as information: The case of boredom. *Frontiers in Psychology, 5*(917).
Zakay, D., & Block, R. A. (1997). Temporal cognition. *Current Directions in Psychological Science, 6*, 12–16.
Zakay, D., & Block, R. A. (2004). Prospective and retrospective duration judgments: An executive-control perspective. *Acta Neurobiologiae Experimentalis, 64*, 319–328.
Zakay, D., & Block, R. A. (1996). The role of attention in time estimation processes. In M. A. Pastor & J. Artieda (Eds.), *Time, internal clocks and movement* (pp. 143–164). Amsterdam: Elsevier.
Zaytseva, Y., Gutyrchik, E., Bao, Y., Pöppel, E., Han, S., Northoff, G., et al (2014). Self processing in the brain: A paradigmatic fMRI case study with a professional singer. *Brain and cognition, 87*, 104–108.
Zeidan, F., Johnson, S. K., Diamond, B. J., David, Z., & Goolkasian, P. (2010). Mindfulness training improves cognition: Evidence of brief mental training. *Consciousness and Cognition, 19*, 597–605.
Zimbardo, P. G., & Boyd, J. N. (1999). Putting time in perspective: A valid, reliable individual-difference metric. *Journal of Personality and Social Psychology, 77*, 1271–1288.