Review

Do cortical midline variability and low frequency fluctuations mediate William James' "Stream of Consciousness"? "Neurophenomenal Balance Hypothesis" of "Inner Time Consciousness"

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ABSTRACT

William James famously characterized consciousness by 'stream of consciousness' which describes the temporal continuity and flow of the contents of consciousness in our 'inner time consciousness'. More specifically he distinguished between "substantive parts", the contents of consciousness, and "transitive parts", the linkages between different contents. While much research has recently focused on the substantive parts, the neural mechanisms underlying the transitive parts and their characterization by the balance between 'sensible continuity' and 'continuous change' remain unclear. The aim of this paper is to develop so-called neuro-phenomenal hypothesis about specifically the transitive parts and their two phenomenal hallmark features, sensible continuity and continuous change in 'inner time consciousness'. Based on recent findings, I hypothesize that the cortical midline structures and their high degree of variability and strong low frequency fluctuations play an essential role in mediating the phenomenal balance between sensible continuity and continuous change.

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Contents

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1. Introduction

1.1. Aims and parts

"Inner time consciousness" describes our subjective experience of time and how that structures and organizes the various contents in our consciousness, the "stream of consciousness" as James (1890a) said. James characterized the "stream of consciousness" by different phenomenal features like the contents in consciousness, the "substantive parts", and the linkages or transitional periods between them, the "transitive parts". The transitive parts themselves can be described by balance between "sensible continuity" and "continuous change". Most importantly, there seems to be a particular balance between sensible continuity and continuous change which makes possible the stream of consciousness in our inner time consciousness. This touches upon what can also be described as implicit time consciousness as distinguished from explicit time consciousness which shall be discussed below in further detail.

Recent neuroscience has developed several theories of the neural correlates of consciousness with the information integration theory (Tononi, 2004; Tononi & Koch, 2008) and the global workspace theory (Baars & Franklin, 2007; Dehaene & Changeux, 2011) being most popular (see Dehaene & Changeux, 2011; Northoff, 2014b recent overviews). These and other theories concern the neural mechanisms of the contents in consciousness, the substantive parts, in general while not addressing specific phenomenal features like the stream of consciousness in inner time consciousness. Recent proposals for the neural mechanisms of inner time consciousness have been suggested and focused on cognitive functions like working memory or iconic memory (Fuster, 1997; Kelly, 2005), affective functions (Craig, 2009b, 2009a, 2010a, 2010b, 2010c; Varela, 1999), or interoceptive functions (Seth, Barrett, & Barnett, 2011; Wittmann, 2013; Wittmann, Simmons, Aron, & Paulus, 2010; Wittmann et al., 2011; Wittmann, Virginie van Wassenhove, & Paulus, 2010). These approaches focus on stimulus-induced or task-evoked activity related to the various functions during perception and cognition of time which allows accounting well for the contents, the substantive parts, in inner time consciousness. One may thus speak of neuro-cognitive, neuro-affective, and neuro-vegetative hypothesis of 'inner time consciousness'.

In contrast, these approaches focusing mainly on contents in time leave open the neural mechanisms underlying the transitive parts, sensible continuity and continuous change. The transitive parts allow for the construction of the ongoing stream of consciousness as experienced in inner time consciousness within which the various contents are temporally integrated. As such the transitive parts may be central for constructing specifically the phenomenal features of the stream of consciousness as distinguished from its contentual features, the substantive parts, as we perceive and cognize them. We may thus need to shift our focus from the neural correlates of the perception and cognition of contents in inner time consciousness, the substantive parts, to those neural mechanisms that are related to the construction of the phenomenal features of inner time consciousness, the transitive parts.

The aim of this paper is to develop a hypothesis about the neuronal mechanisms underlying specifically the transitive parts of inner time consciousness and its phenomenal balance between sensible continuity and continuous change. Since I aim to directly link neuronal and phenomenal features without any intermediation by vegetative, affective, or cognitive functions, I speak here of neuro-phenomenal hypothesis (see also Northoff, 2014b). Such neuro-phenomenal hypothesis target the neural mechanisms related to the construction of specifically the phenomenal features like sensible continuity and continuous change including their balance. I propose that the neural balance between variability and non-variability as well as the one between low and high frequency fluctuations in resting state activity in specifically cortical midline structures may be central in constructing and mediating the phenomenal balance sensible continuity and continuous change in the transitive parts in the stream of consciousness. Therefore I speak of a neuro-phenomenal 'balance hypothesis' of inner time consciousness.

Before going ahead with the development of neurophenomenal hypotheses, I shall note that my approach specifically focuses on the "transitive parts" as described by William James. Though not explicitly discussed here (due to space reasons), this does not exclude other phenomenological approaches to "inner time consciousness" like the one by Husserl (1991) and more recently Dainton (2008, 2010). What James describes as "transitive parts" may well be compatible in conceptual, phenomenal, and neural regard with what Husserl refers to as "protention", "retention", and "primal presentation" as well as "duration bloc" and "width of present" that may specify the former (see Northoff, 2014b).

The paper contains three parts. The first part describes the resting activity and its neuronal features that are specific to the cortical midline structures as distinguished from other regions. This will lead to specific neuronal hypothesis. The second part builds on that and describes recent observations of the involvement of cortical midline structures in mental time travel. That is followed by the third part that suggests specific neuro-phenomenal hypothesis how the neural and mental features of the cortical midline structures are related to phenomenal features of the transitive parts, e.g., sensible continuity' and continuous changes, of inner time consciousness. Before though let us briefly shed a light how such neuro-phenomenal approach stands in relation to the distinction between implicit and explicit time consciousness.

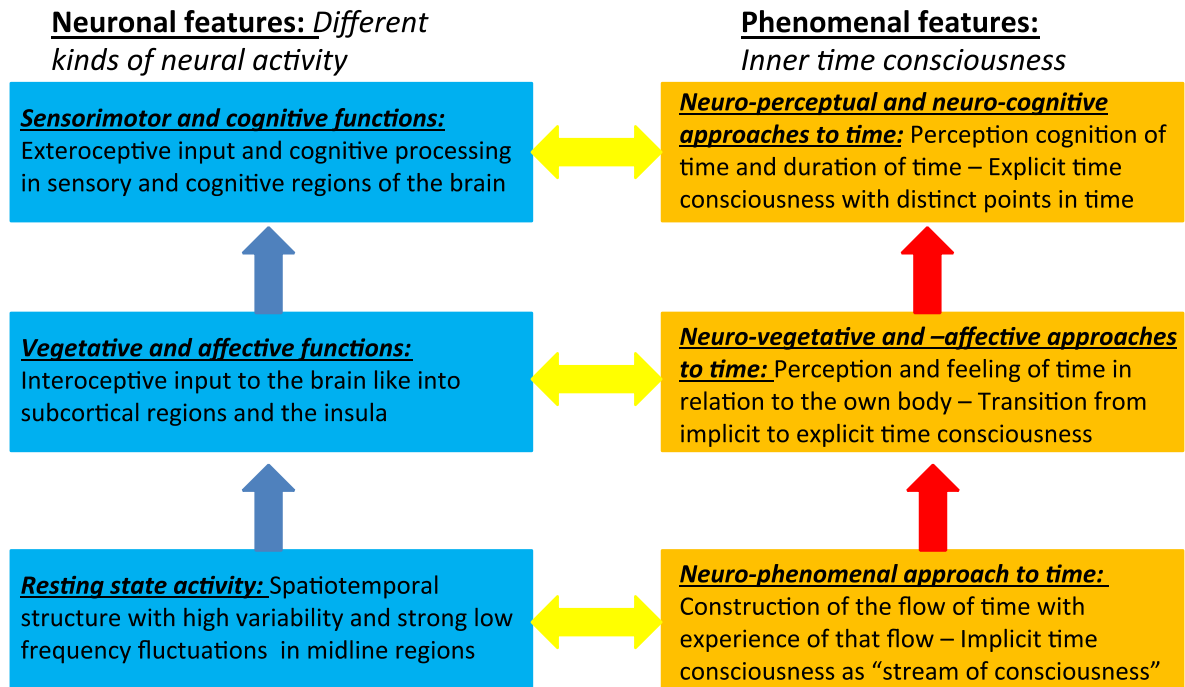## 1.2. Implicit versus explicit time consciousness

Let us rephrase and put the distinction between substantive and transitive parts into the contents of explicit and implicit time consciousness. Explicit time consciousness concerns the consciousness of time itself as it is for example investigated in time perception with "perception of duration" or "perception or temporal order" (see for instance Wittmann, 2013). In the case of explicit time consciousness, time itself becomes the content of consciousness and, to use William James' terminology, accounts for the "substantive part". In this case time is the object of perception like in the perception of time or, even more specific, the perception of duration.

Such explicit time consciousness must be distinguished from implicit time consciousness. Here time is experienced only implicit remaining in the background while specific contents that as foreground occur at a particular point in time are experienced explicitly. In contrast to the foreground and its particular point in time, the substantive part according to James, the transitive part cannot be localized at one particular point in time but rather accounts for the link and transition between the different particular points in time. This is experienced as flow and conceptualized as 'stream of consciousness' that underlies the various contents and their occurrence in time. Put in a nutshell, implicit time consciousness is about the 'experience of the flow of time' reflecting the transitive parts while explicit time consciousness concerns the 'experience of time as content within the flow of time' with time being here a substantive rather than transitive part.

Psychology and neuroscience of time have focused mainly on the first, the psychological and neural mechanisms related to the 'experience of contents within the flow of time'. Thereby they conceive time to be a content by itself and thus a substantive part that can explicitly be perceived and cognized. What are the neural mechanisms underlying such explicit perception of time? Recent accounts suggest neural mechanisms related to cognitive functions like working or iconic memory (Fuster, 1997; Kelly, 2005), affective functions (Craig, 2009b, 2009a, 2010a, 2010b, 2010c; Varela, 1999), or vegetative–interoceptive functions (Seth et al., 2011; Wittmann, 2013; Wittmann et al., 2010; Wittmann et al., 2011; Wittmann et al., 2010) to account for explicit time consciousness. As indicated above, one may therefore speak of neuro-cognitive, neuro-affective, and neuro-vegetative hypotheses of explicit time consciousness, i.e., 'experience of time as content within the flow of time'.

This is different in the present paper. I here focus on implicit time consciousness, 'the experience of the flow of time'. Rather than assuming stimulus-induced or task-evoked activity as related to affective, cognitive, or vegetative function to be central, I here focus on the brain's resting state or intrinsic activity. More specifically, I propose linkages between specific neuronal features of the resting state, i.e., its low and high frequency fluctuations in especially the cortical midline regions, and particular phenomenal, i.e., experiential features of the flow of time, i.e., implicit consciousness.

These so-called 'neuro-phenomenal hypotheses' (Northoff, 2014b for details) suggest that temporal features of the resting state activity like its low and high frequency fluctuations are directly related to the temporal features of our experience of the flow of time, i.e., implicit time consciousness. The neuro-phenomenal hypotheses highlight the commonality in temporal (and more generally spatiotemporal) features between neuronal and phenomenal levels with the former thereby constructing the latter, the 'flow of time' including our 'experience of the flow of time'. One may therefore conceive the neuro-phenomenal hypothesis also as neuro-temporal or neuro-spatiotemporal hypothesis that specifically target implicit time consciousness; this distinguishes them from neuro-cognitive, neuro-affective, and neuro-vegetative hypotheses about explicit time consciousness (see also Fig. 1).

Neuronal features: *Different kinds of neural activity*

Phenomenal features: *Inner time consciousness*

Sensorimotor and cognitive functions: Exteroceptive input and cognitive processing in sensory and cognitive regions of the brain

Neuro-perceptual and neuro-cognitive approaches to time: Perception cognition of time and duration of time – Explicit time consciousness with distinct points in time

Vegetative and affective functions: Interoceptive input to the brain like into subcortical regions and the insula

Neuro-vegetative and –affective approaches to time: Perception and feeling of time in relation to the own body – Transition from implicit to explicit time consciousness

Resting state activity: Spatiotemporal structure with high variability and strong low frequency fluctuations in midline regions

Neuro-phenomenal approach to time: Construction of the flow of time with experience of that flow – Implicit time consciousness as "stream of consciousness"

Fig. 1. The figure illustrates the relationship between different levels of neural activity (left) and inner time consciousness (right). The lowest level is the brain's resting state activity and its spatiotemporal structure that shows high level of variability and strong low frequency fluctuations in especially the midline regions. That corresponds on the phenomenal level to the construction of the flow of time as the "transitive part" of inner time consciousness that is experienced as flow of time reflecting implicit time consciousness which can be accounted for by a neurophenomenal approach. The middle level consists of vegetative and related affective functions of the brain and their processing of interoceptive input in the respective neural regions. Phenomenally, this is reflected in neuro-vegetative and neuro-affective approaches to time consciousness that mark the transition from implicit to explicit time consciousness. The highest level is related to the processing o exteroceptive input in sensory and cognitive regions which on the phenomenal side is related to explicit time consciousness with the focus on the contents of "substantive parts" like time (and other contents) as in perception and cognition of time and duration.

We have to be careful, however. The distinction between implicit and explicit time consciousness is only conceptually clear-cut while empirically and phenomenally it is rather blurry. As already said, time itself as constructed in terms of a flow on the level of implicit time consciousness can become a content by itself that as such is accessed and experienced in explicit time consciousness as in perception of time. Perceiving and cognizing time in an explicit way makes possible to abstract from the continuous flow of time, the transitive parts, on the implicit level; thereby the original flow of time is transformed into a series or sequence of discontinuous points in time at which the different contents, the substantive parts, are placed and located in our perception and cognition.

Accordingly, there seems to be a smooth transition from the construction of time, i.e., implicit time, to the perception and cognition of time, i.e., explicit time. This is especially apparent in the neuro-vegetative theory of explicit time consciousness (see Wittmann, 2013) where the perception of time is closely related to the continuous interoceptive input from the body that may also be involved in constructing the flow of time, i.e., implicit time consciousness. However, space constraints permit us to further discuss the exact neuronal mechanisms of this transition from implicit to explicit time consciousness (see Northoff, 2014b, Appendix 2). Instead, I here focus only on the construction of the flow of time itself and hence on implicit time consciousness while leaving open its transition to the perception and cognition of time, i.e., explicit time consciousness.

2. Resting state activity in cortical midline regions

2.1. Neuronal findings Ia: investigation of temporality in the brain's resting state activity

Lloyd (2002), and especially Lloyd (2012) sought to investigate correlates of temporality in neural activity recorded by functional magnetic resonance imaging (fMRI) in the resting state. A subject might lie aware in a static situation with no specific stimuli, not engaged in any specific task (any of which could involve active time-based cognition in some respect), and in particular not purposefully monitoring the passage of time—in short, in the resting state. Even under such circumstances, conscious experience will be in constant change in at least one sense: the subject will experience at a basic level the progressive flow of time. Lloyd focused on this experience as a reflection of temporality, not perfectly isolated from the confounds of higher cognition, to be sure, but at least with those confounds dimmed by virtue of being in the resting state.

For purposes of this investigation, Lloyd operationalized temporality as information in neural activity encoding time elapsed from the start of resting-state periods. Working with whole-brain time series of neural activity recorded in fMRI during multiple resting-state and stimulus- or task-related periods for each subject in the study, Lloyd used machine learning techniques to attempt to extract information from these time series about elapsed time from the beginning of any given resting-state period.

Specifically, he trained a machine learning algorithm with a set of time series corresponding to a sample of resting-state periods. He then tested those trained "machines" by setting them to predict elapsed time for frames taken from the remainder of their resting-state periods, of which they had no prior knowledge. The successful prediction of elapsed time in the test condition was an indication that information as to elapsed time was available, embedded, in the neural activity on which the machines had trained.

Lloyd was able to ask which patterns of voxels—that is, brain regions—contained the most information that the machines had used (see (Lloyd, 2012). In other words, he determined which brain regions were most responsible for encoding elapsed time in their BOLD activity insofar as removal of the activity variance in those regions from the machines' training most negatively impacted the accuracy of their predictions in testing.

He simply took all the images acquired during the course of scanning from both task-related and resting-state studies. Instead of comparing task- versus non-task periods and resting state as a whole, he compared the neuronal changes from one image/scan to the next subsequent image/scan across both task- and resting-state periods. Thereby, depending on what is called "repetition time in imaging," the images/scans were parsed 2–3 seconds apart from each other, and comparing them allowed him to account for their difference in activity levels (see Lloyd, 2012).

Why did he choose such an approach? Lloyd proposed that the activity differences between subsequent images/scans signify the spontaneous activity changes and thus the temporal structure generated by the brain's intrinsic activity itself, independent of resting-state or stimulus-induced activity. He was thus interested in revealing the spontaneous temporal flow of the brain's intrinsic activity as distinguished from the temporal pattern of the extrinsic stimuli or tasks and their imposition upon the brain's intrinsic activity and its own temporal structure.

2.2. Neuronal findings Ib: spontaneous activity changes in cortical midline structures shape a "Dynamic Temporal Network"

What did his data show? Lloyd's analysis (Lloyd, 2012) showed that especially cortical midline regions like the ventromedial prefrontal cortex (VMPFC), the perigenual anterior cingulate cortex (PACC), the medial temporal cortex (MT), including the hippocampus, and, though weaker, also the posterior cortical midline regions (like the posterior cingulate cortex) and the subcortical midline regions (like the dorsomedial thalamus) showed the strongest signs of spontaneous activity changes; namely, temporality. In contrast, lateral cortical regions like the dorsolateral prefrontal cortex and others did not contribute to the same extent.

Lloyd characterized the implicated midline regions as the "dynamic temporality network" (DTN). What Lloyd calls the DTN obviously closely overlaps with the default-mode network (DMN) and cortical midline structures (CMS). One obvious objection that could be raised in response to these findings is that since the study analyzed resting-state data and the DMN is already well implicated in the resting state, perhaps the DMN-like pattern that emerged from Lloyd's analysis emerged simply "by default" on this basis.

Lloyd forestalled this concern by underscoring the fact that the activity time series comprised activity variance that was widespread across the whole brain. Recall that the DMN is established as more active than other regions during the resting state, but other regions are by no means inactive. Moreover, information that might yield to machine learning is not necessarily tied to amplitude—it could well have been less pronounced activity in disparate regions that embedded elapsed time information in its complex spatiotemporal patterns.

What exactly do these spontaneous activity changes mean? These spontaneous activity changes reflect, as Lloyd himself says, the "brain's intrinsic flow of time" or the "temporality of its own neuronal activity". By continuously changing its neuronal activity from one discrete point in time to the next subsequent one, the brain itself generates a flow of time or temporality. The terms "flow of time"/"temporal flow" or "temporality" describe the intrinsically generated changes in neuronal activity across different discrete points in physical time. Accordingly, the concept of "temporal flow" refers to the degree of change in the brain's neural activity (see below for a more detailed definition of "temporal flow").

The temporal flow or temporality of the brain's intrinsic neuronal activity seems to be the strongest in the midline regions, while the intrinsic temporal flow or temporality appears to be rather weak in lateral cortical regions. Lloyd therefore describes these midline regions as the "dynamic temporality network" (DTN) (Lloyd, 2012). Thus, that Lloyd's machine-learning approach isolated the strongest neural activity changes in a pattern of regions centering on CMS that closely resemble the default-mode network (DMN) does suggest that it is the midline structures in particular that are implicated in temporality, at least as operationalized in this study.

The special role of cortical midline structures is further evidenced by recent findings in brain imaging that investigated the variability of the spontaneous activity. Most of these studies operationalized resting state variability as the amplitude of low frequency fluctuations (ALFF) that describes the variability in the amplitude or power of the low frequency fluctuations as measured in fMRI (0.0001–0.1 Hz). Zang et al. (2007), Zou et al. (2008) and Han et al. (2011) observed in different samples increased ALFF in especially the cortical midline regions including PACC, PCC, and Precuneues/PCC. This suggests higher degrees of neuronal variability in resting state activity in the midline regions. That was extended in a recent study by

Xue, Li, Weng, Northoff, and Li (2014) to a particular slow frequency band (>0.78–0.1 Hz) within the infraslow frequency range, slow 5 (0.01–0.23 Hz), that is especially predominant and strong in the midline regions when compared to slow 4 (higher frequency; 0.23–0.78 Hz) in the midline and other regions.

Taken together, the midline regions seem to show particularly high degrees of variability in their neural activity which in addition can be characterized by particularly strong low frequency fluctuations. Taken together, high variability and strong low frequency fluctuations suggests a special role for cortical midline structures in mediating 'inner time consciousness' and more specifically its 'transitive parts' which would be in accordance with their characterization as 'dynamic temporal network'.

2.3. Neuronal hypothesis Ia: low-frequency fluctuations constitute temporal continuity of neural activity

What does the predominance of low-frequency fluctuations in the midline regions imply for the temporal flow of their neural activity? Lower frequency fluctuations imply longer time windows, meaning that the phase durations of their activity fluctuation are longer. Conversely, this means that their ongoing neural activity is less interrupted or perturbed by changes as induced either spontaneously or by intero- or exteroceptive stimuli.

Decreased degrees of interruption or perturbation imply that the level or degree of neural activity does not change and remains continuously the same. There is thus what can be referred to as a "temporal continuity" of neural activity. The concept of "temporal continuity" means that the degree and level of neural activity does not change implying low degree of variability and high degree of sameness of neural activity. This distinguishes temporal continuity from its sibling, "temporal flow," which refers to the degree of change in neural activity indicating high degree of variability rather than low ones with a high degree of sameness (see the next section for a more refined conceptual discussion of both terms).

Based on these considerations, I propose the following. I hypothesize that the degree of temporal continuity in neural activity depends on the range of frequency fluctuations: lower frequency ranges are proposed to go along with higher degrees of temporal continuity, while higher frequency ranges may reduce the degree of temporal continuity in neural activity. Strong power in low-frequency fluctuations as in midline regions may thus be indicative of a high degree of temporal continuity in neural activity, whereas strong power in high-frequency fluctuations may rather go along with a high degree of temporal flow (see Fig. 2a).

2.4. Neuronal hypothesis Ib: reciprocal balance between "Temporal Continuity" and "Temporal Flow" in the brain's intrinsic activity

We should note that the term "temporal continuity" is taken in a purely neuronal sense: the concept of temporal continuity means that the neuronal activity remains the same and does not change across those different discrete points in physical time, as they are, for instance, included within phase durations of the low- and high-frequency fluctuations in neural activity. In short, the term "temporal continuity" refers to the degree of sameness of neural activity.

The term "temporal continuity" describes the counterpart to "temporal flow," as used earlier. Like the concept of temporal continuity, the term "temporal flow" is used in a purely neuronal context, too: it describes the changes (rather than the non-change as in continuity) of neural activity across different discrete points in physical time, as discussed earlier. Accordingly, the term "temporal flow" describes the degree of change in neural activity rather than its degree of sameness.

Rather than the number of time points *during which* neural activity remains the same, as in temporal continuity, the concept of the temporal flow refers to the number of time points *after which* neural activity changes. Accordingly, the concepts of temporal flow and temporal continuity describe, metaphorically, the two sides of the same coin and can thus be compared to *yin* and *yang* in the Chinese tradition. This leads me to the following purely neuronal hypothesis about the relationship
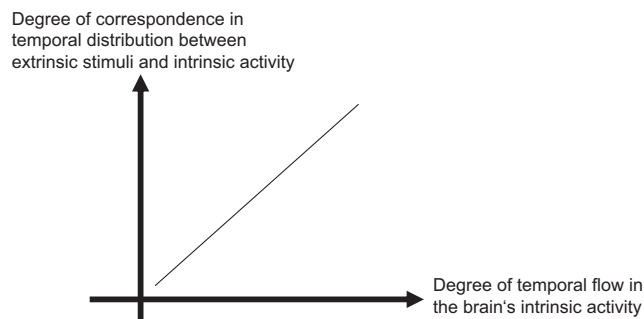
Fig. 2a. The figure depicts the relationship between perturbation by stimuli, temporal flow of intrinsic activity (a), and the range of frequency fluctuation, its relation to temporal continuity and discontinuity of the intrinsic activity (b), and the latters' relationship to the neuronal continuum of intrinsic activity changes (c). (a) The figure shows the relationship between the degree of temporal flow of the intrinsic activity and its correspondence to the temporal distribution of extrinsic stimuli (intero- and exteroceptive): The more extrinsic stimuli and intrinsic activity correspond in their temporal distribution, the higher the degree of temporal flow in the brain's intrinsic activity.
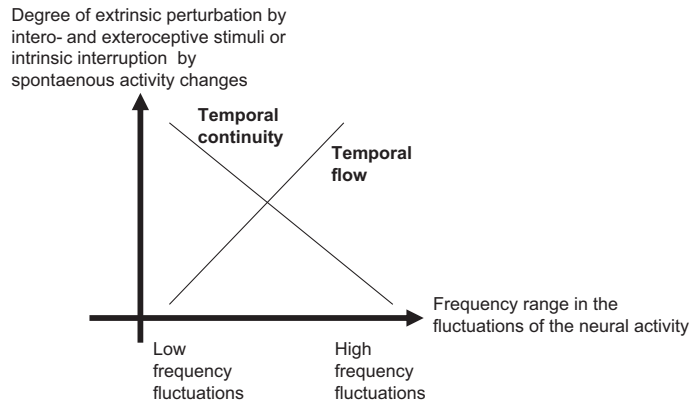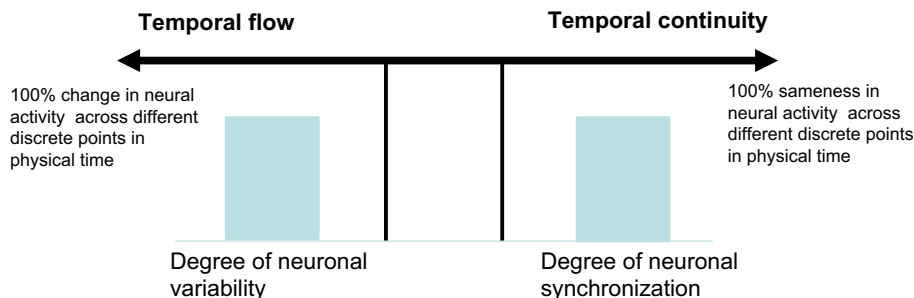
Fig. 2b. The figure depicts the relationship between perturbation by stimuli, temporal flow of intrinsic activity (a), and the range of frequency fluctuation, its relation to temporal continuity and discontinuity of the intrinsic activity (b), and the latters' relationship to the neuronal continuum of intrinsic activity changes (c). (b) The figure shows the relationship between the degree of perturbation by extrinsic stimuli (intero- and exteroceptive) and the frequency ranges of the fluctuations in neural activity (during both resting state and stimulus-induced activity): The more perturbation by extrinsic stimuli, the more the low frequency fluctuations become temporally partitioned and the higher the degree of the frequency range in the activity fluctuations. Temporal continuity is thus preserved by low degrees of extrinsic perturbation while temporal flow predominates in high extrinsic perturbation. Note the opposite curves between temporal continuity and discontinuity with both being ranging on a neuronal continuum.

between temporal continuity and temporal flow: lower frequency fluctuations and their longer phase durations (including a higher number of discrete time points) should go along with a higher degree of temporal continuity and a lower degree of temporal flow.

In contrast, higher frequency fluctuations (and their short phase durations with their lower number of discrete time points) should be characterized by the converse pattern, with a high degree of temporal flow and a low degree of temporal continuity. In short, I propose that both temporal flow and temporal continuity depend on higher and lower frequency fluctuations, though in a converse way, as we can well see in the next figure (Fig. 2b).

As pointed out earlier, high-frequency fluctuations may be generated by partitioning the low-frequency fluctuations. The high-frequency fluctuations and their shorter phase durations are thus generated on the expense of the lower frequency fluctuations and their longer phase durations. This implies that temporal flow and temporal continuity are intimately linked and, more specifically, reciprocally dependent on each other: an increase in one entails a decrease in the other, and vice versa.

Temporal continuity and temporal flow reciprocally balance each other: they must be regarded as the opposite ends of a neuronal continuum, signifying the reciprocal relationship between the degrees of sameness and change in neural activity across different discrete points in physical time. Depending on the degree of extrinsic stimulus input, this reciprocal balance between temporal continuity and temporal flow in the brain's neural activity is continuously changing. The degrees of both temporal continuity and temporal flow are thus dynamic and transitory, rather than static and fixed (see Fig. 2c here).

Fig. 2c. The figure depicts the relationship between perturbation by stimuli, temporal flow of intrinsic activity (a), and the range of frequency fluctuation, its relation to temporal continuity and discontinuity of the intrinsic activity (b), and the latters' relationship to the neuronal continuum of intrinsic activity changes (c). (c) The figure shows the neuronal continuum of neural activity changes (including both resting state and stimulus-induced activity) ranging from 0% to 100%. 100% indicates continuous activity change from time point to time point of neural activity. While 0% describes the lack of any change in intrinsic activity from time point to time point. The upper arrows describe the opposite directions of temporal continuity and temporal flow towards 0% and 100% of changes in changes in intrinsic activity. That indicates reciprocal balance between temporal continuity and flow with for instance increases in the one going along with decreases in the respective other (and vise versa). That reciprocal balance is maintained by balance between neuroanl variability and neuronal synchronziation (e.g., functional connectivity) in midline regions' neural activity as indicated by the blue bars in the bottom. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

2.5. Neuronal hypothesis Ic: from "Temporal Continuity and Flow" of the brain's neural activity to "Temporal Extension" in consciousness

How can we relate the purely neuronally defined concepts of temporal flow and temporal continuity to the experience of time in consciousness and thus the phenomenal level? Lloyd's empirical data of continuous change, especially in the midline structures, the "dynamic temporality network" as he calls it, provide direct empirical evidence for a particular neuronal mechanism. This concerned the degree of change and sameness of neural activity and thus the latter's temporal flow and continuity across different discrete points in physical time, as I described it.

However, Lloyd's data leave open how the neuronal mechanisms of increased variability in cortical midline structures is related to phenomenal features of inner time consciousness like sensible continuity and continuous as suggested by William James (see Section 1 and below). His results may thus be only neuronally but not phenomenally relevant. Lloyd himself (Lloyd, 2012) remarks that he infers the phenomenal relevance of the DTN for consciousness from its reported involvement in the consciousness of internal (like dreaming, mind-wandering).

How can we now bridge the gap from the neuronal level of the brain, including the temporal flow and continuity of its neural activity, to the phenomenal level of consciousness? A variety of imaging studies (Abraham, Schubotz, & von Cramon, 2008; Addis, Moscovitch, & McAndrews, 2007; Buckner & Carroll, 2007; D'Argembeau, Feyers, et al., 2008; D'Argembeau et al., 2010a; D'Argembeau et al., 2010b; D'Argembeau, Xue, Lu, Van der Linden, & Bechara, 2008; Schacter, Addis, & Buckner, 2007; Szpunar, Watson, & McDermott, 2007) investigated the relationship between self and time—that is, past and future. Let me focus on the studies by D'Argembeau, Feyers, et al. (2008), D'Argembeau et al. (2010a, 2010b), D'Argembeau, Xue, et al. (2008).

These studies (D'Argembeau, Feyers, et al., 2008, D'Argembeau et al., 2010a, 2010b, D'Argembeau, Xue, et al., 2008) tested the subjects' ability to imagine themselves in either the future (i.e., prospection) or past (i.e., retrospection) and thus to "extend time" in either direction. The ability to anticipate the future or imagine the past is called "mental time travel" in the current neuroscientific literature (see below for further references). Subjects have to extend themselves mentally from their present point in time to either the future or the past; they thus have to mentally stretch (or extend) their current discrete point in physical time to the future or the past. This presupposes what I later describe as 'temporal extension'. We have to be careful, however. While we are aware that these studies may not directly target the neuronal mechanisms of specifically the flow of time, i.e., implicit time consciousness, but may be rather the perception and cognition of time, explicit time consciousness (see below for further discussion), they may nevertheless provide some insight (albeit indirectly) (see below for more discussion).

3. Neural activity and mental time travel in cortical midline regions

3.1. Neuronal findings IIa: neural activity in cortical midline regions mediate "Mental Time Travel"

In a study on the interaction between prospection into the future and self (see D'Argembeau et al., 2010a), d'Argembeau included three conditions: imagination of future events that are relevant to one's personal goals, imagination of future events unrelated to one's own person, and imagination of routine activities. All three types of mental operations were cued and selected on the basis of a prescan interview.

What did d'Argembeau observe in his results? When comparing the two conditions related to the anticipation of the future (personally and non-personally relevant) with those of daily routine activities, he observed strong activity changes in anterior and posterior cortical midline structures (VMPFC, PACC, PCC). The same was the case when comparing both "future conditions" (personally and non-personally relevant) separately from that of routine activities. Accordingly, the anticipation of the future requiring extension or prospection of time was related to strong activity changes in the midline regions.

In addition to the temporal effects related to the future, the midline regions' neural activity was also modulated by the degree of personal relevance. Personally relevant items led to stronger activity changes in the midline regions than non-personally relevant ones.

These effects were not as strong, however, as the ones related to the anticipation of events in the future. This means that the anticipation of events in the future was the "driving factor" of neural activity changes in the midline regions, whereas their degree of personal relevance was more a "modulatory factor".

Does the degree of temporal extension into the near and far future make a neural difference? Interestingly, events pertaining to the far future induced more neural activity in the VMPFC when compared to those in the near future (see also Wittmann et al., 2010) who, conducting a study on subjective time dilation, also observed the involvement of cortical midline regions in subjective time extension or dilation). In contrast, a subcortical region, the caudate, was more active during events in the near future when compared to those in the far future. This suggests that cortical regions may be able to extend time (on a phenomenal level) to a wider degree than subcortical regions.

How about the extension of time into the past? Another study by d'Argembeau tested the comparison between present and past events being either personally related or not (D'Argembeau, Feyers, et al., 2008, D'Argembeau et al., 2010b). Subjects had to view adjectives and judge whether these described their present or past self, or past or present traits of an inti-

mate other. All four conditions recruited neuronal activity in the anterior and posterior midline structures. However, the degree of midline neural activity differed between the four conditions. The present self induced the strongest activity changes in the VMPFC, the DMPFC, and the PCC when compared to past self, and present and past other.

These findings are further confirmed by fMRI studies from other authors. (Addis et al., 2007; see also Abraham et al., 2008; Buckner & Carroll, 2007; Schacter et al., 2007; Szpunar et al., 2007) investigated the ability of subjects to project or anticipate events into the future and to recall events from the past. Interestingly, they observed a strong overlap between prospection and retrospection, especially in the anterior and posterior cortical midline structures (i.e., PACC, VMPFC, DMPFC, SACC, PCC, precuneus).

Taken together, these results demonstrate the central involvement of cortical midline structures in the subjective extension of time into either future (i.e., prospection) or past (i.e., retrospection). Neural activity in the cortical midline structures seems to be essential in extending the time point of our present moment into both temporal directions, the past and the future. In short, neural activity in the midline regions seems to account for temporal extension (see below for an exact definition of the latter term).

Metaphorically put, the midline structures' neural activity seems to continuously stretch and extend the single discrete points in physical time in very much the same way that we like to stretch and extend our chewing gum into one long band. The only difference consists of the difference between mouth and brain: we use the tongue in our mouth to extend the chewing gum, while we require our brain in the case of temporal extension in consciousness.

3.2. Neuronal findings IIb: resting-state activity mediates "Temporal Extension"

The findings by d'Argembeau and others show predominant involvement of cortical midline regions during the subjective extension of time into either the past or the future. Interestingly, these studies testing for the extrinsic stimulus – triggered prospection or retrospection of time showed exactly the same regions as the studies by Lloyd (see earlier), who focused more on the intrinsic neural activity changes across time.

Both sets of studies may thus be complementary in two aspects. First, they address distinct states. D'Argembeau focuses on the neuronal states underlying particular mental states, or mental time travel, implicated in temporal extension, while Lloyd targets only neuronal states independent of mental states. Second, Lloyd focuses on intrinsic neuronal activity changes in the resting-state of the brain, whereas d'Argembeau investigates extrinsically triggered mental states and their underlying stimulus-induced (or task-related) activity.

One may therefore be inclined to propose the following: the intrinsic neuronal activity changes in the midline regions, as described by Lloyd, may be related to the degree of "temporal extension" on the phenomenal level of consciousness. In short, I postulate that temporal extension to already occur in the resting-state and thus during the intrinsic activity in the midline regions especially.

This is indeed supported by a study by Østby et al. (2012). They demonstrated neural overlap between resting-state activity in the default-mode network and the neural activity changes during prospection (of the future) and retrospection (of the past) especially in the midline regions: the degree of resting-state functional connectivity in the midline regions predicted the degree of neural activity changes in the same regions during both remembering the past and imagining the future.

This strongly suggests that the extension of time and thus what is called "mental time travel" (in the psychological context) is indeed closely related to the resting-state activity in the midline regions as suggested above. The neural activity in the resting-state may already by itself constitute (or at least predispose) what on the phenomenal level is described as "temporal extension" and psychologically as "mental time travel." Accordingly, I hypothesize that temporal extension and mental time travel are already present in the resting-state activity of the brain itself.

4. Neuro-phenomenal hypotheses: 'Balance Hypothesis' of the "stream of consciousness" in "inner time consciousness"

I now intend to link the neuronal and mental findings and hypotheses about the midline structures to the phenomenal features of inner time consciousness. More specifically, I will argue that the increased variability and the relationship between low and high frequency fluctuations in midline structures provide the mechanisms by means of which the 'transitive parts' and their phenomenal features, sensible continuity and continuous change, in inner time consciousness are constructed. While the cortical midline structures can be considered the neural correlate, their specific neuronal features are here assumed to provide the possible neuronal mechanisms for the construction of the 'transitive parts' and ultimately the stream of consciousness in inner time consciousness. It shall also be noted again that I am not targeting the neuronal mechanisms related to the perception and cognition of time but rather the ones underlying the construction of the 'stream of consciousness' and its phenomenal features (see Section 1 as well as Northoff, 2014b, Appendix 2 for details).

Before going ahead, we though must hint upon possible discrepancy between Lloyd's data and d'Argembeau's data. Dan Lloyd clearly targets how the flow of time is constructed by the brain's neural activity or which he, based on his results, conceives the midline regions central. He thus reveals the neural mechanisms related to the construction of the flow of time that can also be described as implicit time consciousness (see above). While he focuses on the construction of the flow of time, he leaves open though the experience of such flow of time and thus implicit time consciousness. For that I recruited the studies on mental time travel (MTT) by d'Argembeau.

Does though MTT really tap into the experience of the flow of time, implicit time consciousness, rather than the experience of time as content (within the flow of time), explicit time consciousness, and hence, following James, into the transitive rather than substantive parts? The instruction in MTT compels participants to consciously and thus explicitly jump from different points in time like from a point in the present to one in the past or the future in relation to the own self. This seems to presuppose cognitive functions like autobiographical memory that are more related to the perception and cognition of time in terms of different discrete points in time therefore reflecting explicit rather than implicit time consciousness.

How then do the results by d'Argembeau as based on MTT stand in relation to the ones by Lloyd and, put more succinctly, how does the construction of time, implicit time consciousness, as conceived by the latter, relates to the perception and cognition of time, explicit time consciousness in MTT in the former? I suppose that any kind of "jumping between different discrete points in time" as required by the MTT is possible only on the basis of an underlying continuum that allows for the construction of the flow of time. Only if our brain constructs a continuous flow of time as for instance on the basis of its midline regions, we are able to abstract different discrete points in time in our perception and cognition of time. Accordingly, I suppose that the MTT though tapping more into explicit rather than implicit time consciousness are possible only on the basis of an underlying construction of a continuous flow of time, implicit time consciousness.

Taken together, we are confronted with the empirical situation that we have data by Lloyd on the purely neuronal level that tap into the construction of the flow of time; they leave out the experiential component, however so that they tap into the construction of time without though entailing the experience of that very same flow, i.e., implicit time consciousness. On the other hand, we have data from d'Argembeau and others about mental time travel that recruits perception and cognition of time, i.e., explicit time consciousness; those are presumed to be possible only on the construction of the flow of time, i.e., implicit time consciousness, which is indirectly supported by the neural overlap with resting state activity levels as shown in the study by Ostby (see above) and could be further supported by not yet conducted meta-analyses showing neural overlap between MTT tasks and undirected and uninstructed tasks (with a strong internally-guided thought and cognition). However, there nevertheless remains an empirical gap in the current data that leave out the experience or consciousness of specifically the construction of the flow of time, i.e., implicit time consciousness, as distinguished from the experience of time itself, i.e., explicit time consciousness. The following neuro-phennomenal hypotheses aim to close that gap and to provide starting points for future experimental testing of the experience of specifically the flow of consciousness, i.e., implicit time consciousness, as distinguished from the experience of time itself, i.e., explicit time consciousness.

4.1. 'Neurophenomenal Balance Hypothesis' Ia: from mental time travel and midline regions to temporal extension

What exactly is meant by the concept of "temporal extension"? And how does the temporal extension in consciousness relates to the "temporal flow and continuity" of the brain's neural activity? Let us start with temporal extension.

The concept of "temporal extension" describes the ability to "stretch" the current actual single discrete point in physical time into either the future or the past and thus to connect and link yourself (or others) with other single discrete points in physical time. As such, the concept of temporal extension must be considered a phenomenal concept that describes our ability to link different discrete points in physical time in our consciousness and thus to stretch and extend ourselves and our actual point in time into both past and future. Such stretching or extension is, however, possible only if present and past or future discrete points in physical time can be linked and integrated.

Let us compare the situation to a bridge spanning across a river. If I want to extend my reach to the other side of the river, I need to build a bridge and then cross it. The two sides of the river now correspond to the different single discrete points in physical time in the present and the future or past. In contrast, the river itself corresponds to the temporal gap between the single discrete points in the present and the future or past. If we now want to extend our actual discrete point in physical time and thus travel mentally to another one in the future, we need to link and integrate both discrete points in order to bridge their temporal gap.

How can we link and integrate and thus bridge the temporal gap between the different discrete points in the present and the future or past? In the case of the river this is easy. One takes a boat and cross the river from the one side to the other. In the case of consciousness, this is the question for the mechanisms that underlie the temporal extension of the present single discrete point in physical time to the ones in the future and past. As the results show, changes in the neural activity in the midline regions during both resting-state and stimulus-induced activity seem to play an essential role here. What, however, must happen in the neural activity changes of the midline ranges to allow for such temporal extension?

4.2. 'Neurophenomenal Balance Hypothesis' Ib: low and high-frequency fluctuations mediate different degrees of "Temporal Extension" in consciousness

This is the moment where the earlier-described concepts of temporal continuity and temporal flow come in. As we will recall, temporal continuity was determined by the number of discrete points across time *during which* no change in neural activity occurred. Temporal flow, in contrast, was characterized by the number of discrete points across time *after which* neural activity changes occurred. In short, temporal flow concerns the change in neural activity, while temporal continuity refers to its degree of sameness.

What does that imply for the temporal extension? Temporal continuity allows us to link different discrete points in time into one neural activity by remaining the same across different discrete points in physical time. We recall from earlier that
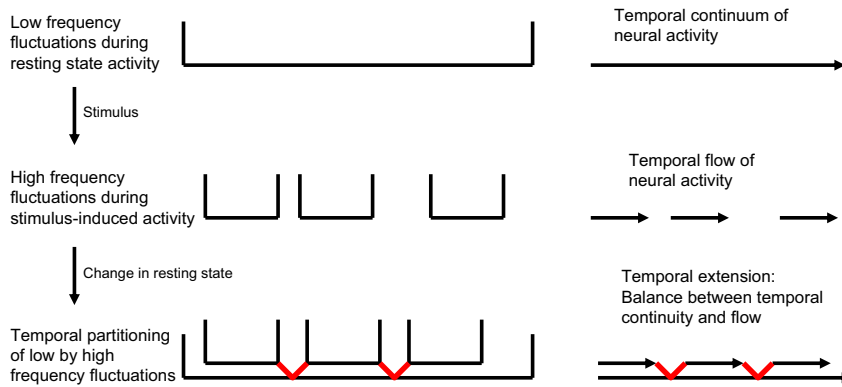
Fig. 3a. The figure depicts the relationship between changes in neural activity and temporal extension and how they are modulated by high and low frequency fluctuations (a) and the continuum of changes in neural activity (b). (a) The figure shows how the resting state's low frequency fluctuations (upper left) provide temporal continuity (upper right) on the basis of their long phase durations as symbolized by the length of the interval (left) and arrow (right). The low frequency fluctuations are then complemented by the stimulus-related high frequency fluctuations (middle left) that show much shorter phase durations and allow for temporal flow of neural activity (middle right). Taken both together implies the temporal partitioning of the resting state's long phase durations (lower left) which leads to temporal extension of the stimulus' present time point into the past and future (lower right) as indicated by the red lines. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)
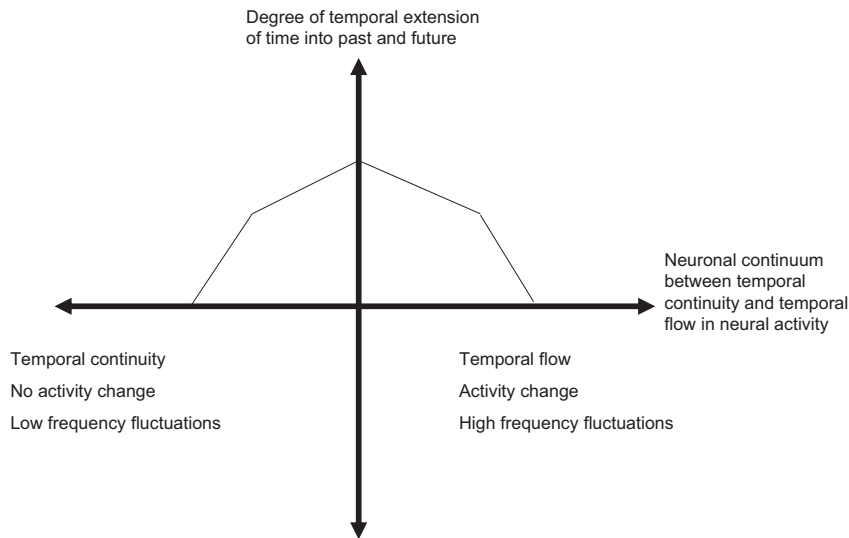
Fig. 3b. The figure depicts the relationship between changes in neural activity and temporal extension and how they are modulated by high and low frequency fluctuations (a) and the continuum of changes in neural activity (b). (b) The figure depicts the relationship between the degree of temporal extension into past and future (y-axis) and the neuronal balance or continuum between temporal flow and continuity of neural activity (x-axis). Temporal extension is based on a balance between temporal flow and continuity of neural activity as reflected in the inverted u-shape curve.

the long phase durations of the low-frequency fluctuations allow the neural activity to remain the same, entailing a high degree of temporal continuity. Since the neural activity remains the same during the low-frequency fluctuations' phase duration, the single discrete point in physical time can be extended to the discrete points in physical time that are still included in the period of the phase durations of the low-frequency fluctuations. Hence, sameness of neural activity can go along with temporal extension of the single discrete point in physical time to others.

How about high-frequency fluctuations? Here, the phase durations are much shorter. This means that the number or degree of other single discrete points included in the phase durations is much lower than in the case of the longer phase durations of the low-frequency fluctuations. Since the neural activity changes much quicker here, the degree of possible temporal extension of the single discrete point in physical time to others is much lower in high-frequency fluctuations when compared to the low ones.

This leads me to the following hypothesis. I suggest that the possible degree of temporal extension in consciousness is directly proportional to the degree of the phase duration in the fluctuations of the brain's neural activity. High-frequency fluctuations show shorter phase duration, which decreases the possible degree of temporal extension, whereas the longer phase durations of low-frequency fluctuations allow a larger degree of temporal extension in consciousness.

We should be careful, however. Temporal extension cannot be identified exclusively with either temporal flow or temporal continuity. Instead, it is the balance between them that accounts for temporal extension. Without temporal continuity and the sameness of neural activity, there would be no "stretching" of the neural activity to different discrete points in physical time in either past or future. This is neuronally well reflected in the long phase durations especially of low-frequency fluctuations.

Conversely, without temporal flow and the change in neural activity, there would be no dynamic in neural activity that is necessary to connect and bridge the temporal gaps between the different discrete points in physical time as provided by temporal continuity (see below for further explanation of this point). This is neuronally manifested especially in the partitioning of the low-frequency fluctuations' long phase durations by the short ones of the high-frequency fluctuations (see Figs. 3a and 3b).

4.3. 'Neurophenomenal Balance Hypothesis' IIa: "Temporal Continuity" of neural activity predisposes "Sensible Continuity" in consciousness

I proposed temporal continuity and temporal flow to be central in constituting temporal extension. The question now is how such temporal extension is manifested in our experience and thus in the phenomenal features of consciousness. For the answer, we briefly turn to the phenomenal features of consciousness, and more specifically to the experience of time. As already mentioned earlier, William James spoke of the "stream of consciousness." How can we characterize the stream of consciousness? James (1890a, 1890b) distinguished between the "substantive and transitive parts" in the stream of consciousness. "Substantive parts" concern the contents of consciousness, while the "transitive parts" provide the linkage and thus the transition between the different contents. Together, substantive and transitive parts form a homogenous stream, the "stream of consciousness." Let us focus on the transitive parts for now.

How can we describe the "transitive parts" in further phenomenal detail? James (1890a, pg 225) points out several features, of which two, "sensible continuity" and "continuous changes," are particularly relevant to our discussion. "Sensible continuity" means that no phenomenal state vanishes or perishes instantaneously. Instead, there are continuous transitions between different phenomenal states that glide or slide into each other: there is a transition from moment to moment with the transitive parts especially allowing such smooth transition.

I suggest that there is a close relationship between temporal continuity on the neuronal level and sensible continuity on the phenomenal level of consciousness, with the latter being dependent upon the former. I propose that what is described as "sensible continuity" on the phenomenal level of consciousness can be traced to the temporal continuity on the level of the brain's neural activity. More specifically, I hypothesize that the temporal continuity of neural activity is a necessary (rather than sufficient) condition and thus a neural predisposition of possible (rather than actual) sensible continuity in consciousness. Most importantly, my hypothesis of temporal continuity being a neural predisposition of sensible continuity implies direct linkage between neuronal and phenomenal levels as distinguished from mere correspondence (see below for more extensive discussion of this point) as for instance suggested in the neural correlates (see Northoff, 2013a, 2013b, 2014b) for the distinction between neural correlates and predispositions of consciousness).

4.4. 'Neurophenomenal Balance Hypothesis' IIb: co-occurrence between "Physical Absence" and "Neuronal Presence" of stimuli predisposes "Sensible Continuity" in consciousness

How can we explain the relationship between temporal continuity and sensible continuity in further detail? During the phase duration of the activity fluctuations, the neural activity remains the same across different discrete points in physical time. As described earlier, the sameness of neural activity makes it possible to link and integrate the stimuli and their different discrete points in physical time within the respective phase durations of the frequency fluctuation. This makes it possible to constitute what I described as the temporal continuity of neural activity.

I propose that such linkage and integration of different stimuli on the neuronal level resurfaces on the phenomenal level of consciousness in "sensible continuity." The neural activity associated with the single stimulus is continued and thus extended beyond the stimulus's single discrete point in physical time.

Such an extension and continuation of the single stimulus' neural activity makes it impossible for the single stimulus and its associated content to disappear right away in the precise instant of its physical disappearance. Accordingly, even though the stimulus has already disappeared physically, it is still present neuronally in the temporal extension of its neural activity, the temporal continuity. Most important, the extension of the stimulus' neural activity may still be ongoing when the next stimulus arrives at a later single discrete point in physical time. The physically absent previous stimulus is thus still somehow present neuronally during the physical presence of the next stimulus, which again induces changes in neural activity. This means that the extended neural activity of the previous stimulus (that is already absent) is modulated by the neural activity of the present stimulus (that is present now).

Such modulation of the former stimulus' neural activity by that of the later stimulus allows the continuous transition from one stimulus to the next one. The neural activities of both stimuli are thus combined, which accounts for exactly what William James himself (James, 1890a, 248, 82) described as a "summation of stimuli in the same nerve tract." Accordingly, the temporal continuity of neural activity related to single stimulus predisposes or makes possible the "sensible continuity" (between different contents) on the phenomenal level of consciousness.

4.5. 'Neurophenomenal Balance Hypothesis' IIc: spontaneous changes in the brain's neural activity predispose continuous change in consciousness

How about the second feature James attributes to the transitive part, "continuous change"? There is constant change in consciousness and, more specifically, in the contents of our consciousness, as pointed out by James and his concept of "continuous changes" (see earlier). We never experience our consciousness in exactly the same way twice; instead, there is "continuous change." Hence, consciousness can be characterized by what philosopher ([Van Gulick, 2011](#)) calls "dynamic flow," where continuity, that is, "sensible continuity," goes along with "continuous change."

We already postulated that the "sensible continuity" is predisposed by the temporal continuity of the brain's neural activity. How can we relate what James described as "continuous change" on the phenomenal level to the neuronal mechanisms discussed earlier? We recall from earlier that Dan Lloyd's empirical data showed particularly strong spontaneous neural activity changes, especially in the midline structures, the "dynamic temporality network," as he called it. This provides direct empirical evidence for continuous change in neural activity, which I have described as the "temporal flow" of neural activity. Unlike the temporal continuity that describes the degree of sameness of neural activity, temporal flow refers to the degree of change of neural activity.

I now postulate that the temporal flow of neural activity predisposes and thus makes possible the occurrence of "continuous change" on the phenomenal level of consciousness. As in the case of temporal continuity (see earlier), my neurophenomenal hypothesis goes beyond mere correspondence between neuronal and phenomenal levels. Rather than mere neurophenomenal correspondence, I claim that the temporal flow of neural activity makes necessary and unavoidable, and thus predisposes by default, the occurrence of "continuous change" in consciousness.

4.6. 'Neurophenomenal Balance Hypothesis' IId: modulation of stimulus-induced activity by spontaneous changes in the brain's intrinsic activity predisposes "Continuous Change" in consciousness

How can we explicate the role of the spontaneous activity changes in further detail? We associated the temporal flow of neural activity with the relationship between low and high-frequency fluctuations in neural activity. The shorter phase durations of high-frequency fluctuations partition the longer phase durations of low-frequency fluctuations. This may occur either during spontaneous activity in the resting-state itself, or during the encounter of extrinsic stimuli, which can both introduce change and thus a temporal flow in neural activity.

The resting-state activity itself and especially the one in the midline regions is characterized by continuous changes in its neural activity, as demonstrated by Lloyd and his data. Since the changes in neural activity are spontaneous, they cannot be avoided. Any extrinsic stimulus and its associated neural activity, or stimulus-induced activity, is therefore also subject to this spontaneous change and cannot avoid being modulated by it. This means that the resulting stimulus-induced activity is determined not only by the stimulus itself and its physical presence, but also by the degree of spontaneous change in the ongoing intrinsic activity of the brain.

What does this imply for the stimulus-induced activity? The necessary and thus unavoidable modulation of stimulus-induced activity by the neural activity changes of the ongoing intrinsic activity predisposes change in the stimulus-induced activity: even if the extrinsic stimulus is still physically present, the changes in the brain's intrinsic activity will modulate its associated stimulus-induced activity and thus change how the stimulus is processed.

Even worse, the continuous activity changes may bias or predispose the intrinsic activity for the processing of a different stimulus that either already disappeared (as past stimuli) or is not yet physically present; for example, to predict or anticipate the next stimulus. This means that the stimulus-induced activity associated with the physically still-present stimulus cannot avoid interfering with the neural processing of both past and future stimuli: the resulting stimulus-induced activity though elicited by the currently present stimulus consequently provides the transition to other stimuli in either past or future that are physically absent in the present moment.

How is such continuous change in neural activity and its transition between different stimuli that are either physically present or absent manifested on the phenomenal level of consciousness? The continuous change on the neural level will be accompanied by continuous change on the phenomenal level in that the stimuli and their associated contents cannot avoid continuously changing (and thus "flowing") in consciousness. In other words, the occurrence of temporal flow of neural activity predisposes the "continuous change" on the phenomenal level of consciousness. As we will see later, the necessary or unavoidable association of the temporal flow of the neural activity holds, not only during stimulus-induced activity, but also during resting-state activity, as it is phenomenally manifested in (for instance) the experience of time in dreams (see [Northoff, 2014b](#)).

4.7. 'Neurophenomenal Balance Hypothesis' IIIa: reciprocal balance between temporal flow and continuity of neural activity predisposes reciprocal balance between "Sensible Continuity" and "Continuous Change" in consciousness

We recall from our earlier discussion that the degree of temporal extension of a single discrete point in physical time into others in the past and future depends on the reciprocal balance between temporal flow and continuity of neural activity. What does this imply for the relationship between "sensible continuity" and "continuous changes" on the phenomenal level of consciousness?
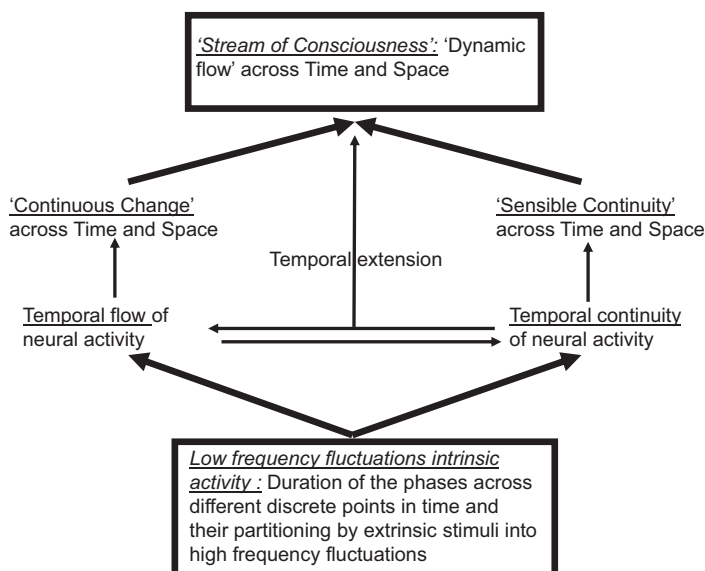
Fig. 4. The figure visualizes how the two main components of the 'stream of consciousness', sensible continuity' and 'continuous change' (upper part) depend supposedly on duration of the phases of the low frequency fluctuations in the brain's neural activity during both resting state and stimulus-induced activity (lower part). I assume that what is described as 'continuous change' on the phenomenal level of consciousness is related to the constitution of temporal flow of neural activity across different discrete points in time (middle left). While I suggest what is phenomenally described as 'sensible continuity' may correspond to the temporal continuity of neural activity (middle right). I thus propose that the temporal continuity and temporal flow of neural activity that are already present in the brain's intrinsic activity are central in constituting what phenomenally is described by 'sensible continuity' and 'continuous change' and hence ultimately as the 'stream of consciousness' by William James.

We postulated that "sensible continuity" is predisposed by the temporal continuity of neural activity, while "continuous changes" were traceable to temporal flow. One could consequently suggest that the reciprocal balance between temporal flow and continuity of neural activity is manifested on the phenomenal level in a reciprocal balance between "sensible continuity" and "continuous change."

How can we detail that further? We recall that the impact of "temporal continuity" on "sensible continuity" is supposed to be predisposed by the low-frequency fluctuations' long phase durations, while the "temporal flow" makes possible "continuous change" via spontaneous activity changes (see Fig. 4).

Put together, this means that the spontaneous activity changes limit the low-frequency fluctuations' phase durations by partitioning them into the shorter ones of high-frequency fluctuations. The spontaneous activity changes consequently shorten not only the phase duration, but also the degree of sameness of neural activity as it is associated with the stimulus-induced activity and its relation to physically absent stimuli.

There is thus direct interaction between "sensible continuity" and "continuous change" with the latter determining the range of the former: the higher the degree of "continuous change", the shorter the temporal extension of the "sensible continuity". Accordingly, very much like temporal flow and continuity on the neural level, I propose "sensible continuity" and "continuous change" to be reciprocally dependent upon each other.

4.8. 'Neurophenomenal Balance Hypothesis' IIIb: reciprocal balance between "Sensible Continuity" and "Continuous Change" predisposes the "Stream of Consciousness"

How is this reciprocal balance between "sensible continuity" and "continuous change" manifested on the phenomenal level of consciousness? I propose that the reciprocal balance between them is manifested in the degree of temporal extension—the degree to which the actual discrete point in physical time can be extended and stretched into others in the past and future. And most importantly, I suggest the degree of temporal extension to be manifested in what phenomenally has been described as a "stream of consciousness" or "dynamic flow" (see earlier).

How can we specify these relationships? The more the reciprocal balance tilts toward temporal continuity at the expense of temporal flow in neural activity, the larger the possible degree of temporal extension, and the slower the "stream of consciousness" and its "dynamic flow" on the phenomenal level. Psychologically, this may be manifested in a reduced capacity to perform mental time travel, especially toward the future. As we have discussed earlier, the extreme case here may be depression, wherein the "stream of consciousness" comes to almost a "standstill," with no flow of time being experienced by these patients.

Conversely, the more the reciprocal balance tilts toward temporal flow at the expense of temporal continuity in neural activity, the lower the possible degree of temporal extension, and the faster the "stream of consciousness" and its "dynamic

flow." Psychologically, this may lead to an increased ability to perform mental time travel into both past and future which may be abnormally altered in for instance patients with mania (abnormal balance towards the future) or depression (abnormal balance tilting towards the past) and schizophrenia (disrupted balance with confusion and mixing between past and future or the absence of the continuous construction of the flow of time) (see Northoff, 2014a for details).

5. Conclusion

We here focused on the neural mechanisms underlying "inner time consciousness" and more specifically the construction of the flow of time, i.e., implicit time consciousness, as distinguished from the perception and cognition of time, i.e., explicit time consciousness. This let us develop several so-called neuro-phenomenal (or neuro-temporal) hypotheses about the relationship between neural activity and "inner time consciousness" in healthy subjects. Neurally, we focused on the midline regions while psychologically we associated them with "mental time travel", e.g., prospection and retrospection. This made possible to develop so-called 'neuro-phenomenal hypothesis' about the relationship between neural and phenomenal features in the 'stream of consciousness' of 'inner time consciousness'.

More specifically, we focused on two phenomenal features of the "stream of consciousness" in "inner time consciousness", "sensible continuity" and "continuous change" as suggested by William James. Specific neural features like the temporal continuity, temporal flow, and temporal extension of neural activity specifically cortical midline structures could be directly associated with these phenomenal features, e.g., "sensible continuity" and "continuous change", in the healthy subject.

We here focused on phenomenal features like "sensible continuity" and "continuous change" as described by William James to characterize the "stream of consciousness". "Inner time consciousness" has, however, also described in the phenomenological tradition of philosophy by Edmund Husserl by other phenomenal features as for instance protention, primal presentation, and retention (see Fuchs, 2013; Northoff, 2014a) for an overview in the context of schizophrenia). While these phenomenal features may be well compatible or, even stronger, imply or entail "sensible continuity" and "continuous change" that relationship needs to be demonstrated on both empirical, e.g., neural, and phenomenal, e.g., conceptual, levels. This, however, is beyond the scope of the present paper and must be left for the future (see Chapters 13–15 in Northoff, 2014b).

Phenomenological approaches like the one by Husserl closely linked the experience or sense of a self to the construction of the flow of time, i.e., implicit time consciousness or phenomenal time. This resulted in the concept of pre-reflective self-awareness (Zahavi, 2005; Northoff, 2014b) that describes an implicit experience or consciousness of a self as part of our ongoing experience of the flow of time, i.e., implicit time consciousness. Though not addressing directly, the link between construction of the flow of time and the sense of self is suggested also by our neurophenomenal hypotheses with for instance d'Argembeau investigating the relationship between self and time. If so, the self or better our sense or experience of self may be temporalized and thus be characterized by a flow of time. Though tentatively, such temporalization of self could lead to a novel approach to the rather complicated and sometimes confusing debate about self in both neuroscience and philosophy (see part VII in Northoff, 2014b).

Finally, I also did not discuss how the here suggested neuro-phenomenal account stands in relation to other more recent neuro-cognitive (Fuster, 1997, 2003), neuro-affective (Craig, 2009b, 2009a, 2010a, 2010b, 2010c; Varela, 1999), and neuro-vegetative (Wittmann, 2013; Wittmann et al., 2010) accounts of inner time consciousness. I indicated that they focus on the neuronal mechanisms related to perception and cognition of contents within time where as my neuro-phenomenal approach rather focuses on the construction of the time, the stream of consciousness, by itself (prior and independent of the contents and their integration within time).

More specifically, I hypothesize that the neural construction of the transitive parts and their phenomenal features, sensible continuity and continuous change (as described by William James) provide one cornerstone in constructing the stream of consciousness as experienced in inner time consciousness. Without being able to demonstrate it here, I would argue that the neuro-phenomenal approach is well compatible and complementary to the neuro-cognitive, neuro-affective, and neuro-vegetative suggestions in that it provides the construction of time upon which subsequent cognitive, affective, and vegetative functions are based including the integration of their respective contents within the prior, the stream of time.

One may also want to compare the here suggested neurophenomenal approach to inner time consciousness to other approaches to consciousness. This could include the information integration theory by Tononi as well as the global workspace theory by Baars and its neuronal application by Deheane (see Northoff, 2014b or details). One distinctive feature of the neurophenomenal approach is its focus on the brain's resting state activity and its spatiotemporal structure like the low frequency fluctuations and variability. This distinguishes it from both information integration theory and global workspace that focus mainly on task-evoked or stimulus-induced activity.

Another distinctive feature of the neurophenomenal approach is that it proposes direct linkage between the resting state's spatiotemporal feature and the different phenomenal features like the flow of time (or unity, intentionality, etc.) of consciousness with the latter being then conceived in (virtual) spatiotemporal terms. This link between neuronal activity pattern and phenomenal feature is left (more or less) open in both information integration theory and global workspace theory or which reason I call my approach explicitly 'neurophenomenal approach' that could also be termed as 'spatiotemporal approach to consciousness'. I here demonstrated how such neurophenomenal approach can account for one specific

phenomenal feature of consciousness, the flow of time or stream of consciousness; other phenomenal features may be equally accounted for by though distinct neuronal mechanisms (see Northoff, 2014b).

Let us conclude. What do we gain neuroscientifically from the here suggested neurophenomenal hypotheses? They put forward experimentally testable hypotheses about the relationship between specific neural features like cortical midline variability and particular phenomenal features like ":sensible continuity" and "continuous change". This will contribute to better understanding of the neurophenomenal relationships of the "stream of consciousness" in "inner time consciousness" in particular and consciousness in general. Moreover, our neuro-phenomenal balance hypothesis may open a door to better understanding many symptoms in psychiatric disorders like depression or schizophrenia that may ultimately be traced to temporal abnormalities in 'inner time consciousness' (see Fuchs, 2013; Northoff, 2014a, 2014b). That, in turn, may make possible the development of novel diagnostic and eventually also therapeutic markers in these disorders. Hence, despite tentative and tapping into some basic neuroscientific or better neurophenoemneal hypotheses, our approach may carry important implications for clinical use and application.

Acknowledgments

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