1. Introduction

In “The restless mind”, Smallwood & Schooler (2006) describe mind wandering as follows: “the executive components of attention appear to shift away from the primary task, leading to failures in task performance and superficial representations of the external environment” (p. 946). Characteristically, mind wandering is seen as distractedness; a shift of attention toward internal information, such as memories, takes resources away from the task; this leads to less accurate awareness of external information and potentially a failure to achieve the goal of task – thus, mind-wandering is tantamount to disfunctionality.

Here we will make a case for a more positive view of mind wandering as a possible important element of brain function. But first, let us distance ourselves from introspective reports; as our mind wanders, we are often unaware of the contents of our current experiences (Schooler 2002). This means not only that mind-wandering is underreported, but also that it is likely to remain undetected until something goes wrong. The claim that mind-wandering is dysfunctional, therefore, may largely be a matter of sampling bias.

We propose to use psychophysical methods instead to study mind-wandering. Whereas introspective reports are often unreliable, extremely reliable reports on experience can be obtained in psychophysics. This will allow us to investigate what the antecedent conditions are for mind-wandering as a cognitive phenomenon, what possible positive effects it may have, and how individuals may differ in their mind-wandering brains.

The psychophysical approach may be applied to cases somewhat like the following. Study Figure 1 for a while and you will repeatedly experience spontaneous changes in the grouping of its components, to which we sometimes, but not always, attribute meanings: a star, a staircase, an open cardboard box, a toy house, etc. This phenomenon is known as perceptual multi-stability. Some
instances of perceptual multi-stability may be more compelling than this one. The present demonstration, however, has an important feature that we may also expect from the real world: it is suggestive of a rich variety of different structures, without supporting any of these unambiguously. In the real world, this is due, for instance, to figures occluding each other or, over time, to partial views of the same image (cf. Peterson & Hochberg 1983).

The perceptual mind-wandering exemplified by Figure 1 might perhaps seem dysfunctional – isn’t our visual system supposed to insure that our perceptions are robust and stable? True: evolution has assigned to the visual system the role of providing tolerance against variability in the visual world: to detect recurrent patterns in continuously shifting and changing stimulation. Recurrent patterns are detected at a range of levels in the perceptual process: early, mid, and high-level vision. Early vision provides tolerance against variation in, for instance, contrast and color under variable illumination (e.g. Healy & Slater 1994; Lucassen & Walraven 1993). Mid-level vision involves perceptual organization: the grouping of early features into tentative object structures (Gepshtein & Kubovy 2007; Kubovy, Holcombe & Wagemans

Figure 1. From van Leeuwen (2007). Perceptual multi-stability as mind-wandering. A wandering mind can discover several structures in this figure, such as the star (lower right part of the figure), a staircase on the main diagonal, a house (in the upper right), etc.
1998). The groupings are unaffected by a variety of transformations, involving repetition, rotation and reflection (Garner 1962), and scaling. High-level vision renders them as identifiable objects despite, for instance, occlusion and location or viewpoint changes (Thier, Haarmeier, Chakraborty et al. 2001).

Even though perceptual mind wandering threatens the stability of representations, it may for the exact same reason have an adaptive function. While detecting recurrent patterns is a major factor in perception, the visual system must also satisfy the evolutionary demands of flexibility: it must enable rapid revision if the situation requires so, in order to respond to unexpected objects, events, or to discover new aspects to familiar ones.

Multistability is a sign that flexibility is at work in our perceptual system. When the perceptual system groups together the components of the “star” pattern in Figure 1, the “staircase” pattern can no longer be formed, as some of its components are already assigned to the flower. Mind-wandering could break up the existing pattern structure, such that the components can be reassigned to a different pattern, like the staircase. Items in the background – or, if you like, outside of the focus of our attention – tend to receive weaker groupings than those in the foreground (Rock & Gutman 1981). Thus, when the mind wanders away from a certain grouping, it will dissolve and release its components for novel use. This means that perceptual mind wandering allows the perceiver to detect initially hidden surplus structure.

The detection of surplus structure plays an important role in evolution. It allows a perceiver to discover something in the current scenery that is not detectable at first sight, such as a camouflaged predator hiding in the bushes. It also characterizes some highly cultured aspects of perception. Discovering the hidden structure in a visual display plays a role in the creative process of designers (Verstijnen, van Leeuwen, Goldschmidt et al. 1998a,b; Verstijnen, van Leeuwen & Hamel 2000) and artists (van Leeuwen, Verstijnen & Hekkert 1999), who typically use externalizations of their creative process, such as sketches, to detect the surplus structure in their images and guide the further course of their design process. Towards the end of the design process, the various structures are then assembled to be integrated in the final design (Jaarsveld & van Leeuwen 2005).

This last aspect is particularly intriguing, as the notion of creativity has been associated with the production of novel structure, but not any novel products are equally creative. Many of the artists we investigated stated that they were trying to achieve some form of “balance” in their design – a property they were unable to describe further. Designers and artists, it seems, tacitly know how to lure perceivers into looking longer their work, by offering them the pleasure of discovering over time the surplus structure of the work on display.

These mechanisms are interesting for the following reason: It is still a major puzzle how perceptual systems accommodate the seemingly opposing demands
imposed by evolution of robustness under variability versus flexibility. Most theoretical models, including recurrent neural networks, are geared towards \textit{stability}. Their behavior is robust, but not flexible. Hopfield (1982), for instance, defined a function describing the “energy” of a representational state, and proposed that approaching an attractor from initial conditions given by stimulation corresponds to minimizing the system’s energy expenditure. Models like this are inherently oriented towards stability. They do not change their representation, unless perturbed by, for instance, newly incoming information. Such systems would not be capable of discovering surplus structure.

1.1 Escaping robustness

We may consider, as Hopfield did, to use classical Gaussian noise for escaping an attractor. The concept of an internal Gaussian noise source attenuating the signal in sensory channels has gained wide acceptance in the study of perceptual processes due to signal detection theory (Green & Swets 1966). However, for driving change in a stability-oriented system it is highly inefficient; the very stability of attractors protects them against change. We might, alternatively, consider systems far from equilibrium (Maturana & Varela 1980), in which a small perturbation may have large consequences (the “butterfly effect”). But this would clash with the requirement that perceptual representations should be stable. Far-from-equilibrium systems are flexible but not robust.

Novel approaches are emerging from multidisciplinary collaborations in the physical, biological, computational, and social sciences, operating under the banner of complex systems science. Complex systems are, in principle, any network of multiple components that interact nonlinearly, giving rise to emergent behavior. Complex adaptive systems in addition have the capacity to adapt to their environments and so achieve optimality in their functioning. Examples include social insect and ant colonies, the biosphere and the ecosystem, the immune system, large-scale online systems and, of course, the brain.

In the current text, we purport to show, first, that the dynamics of perceptual mind wandering bears the hallmark of a complex adaptive system. Next, we will discuss what function it may have: mind-wandering, we propose, is for integrating perceptual information with its context. In regulating the integration, we will attribute a crucial role to alpha band activity observed in human scalp electro-encephalography (EEG; Linkenkaer-Hansen et al. 2004; Monto et al. 2010). We will discuss alpha EEG in a state prone to mind wandering, which is called the “resting state”, and observe that complexity is equally prominent there as in the perceptual dynamics. We will discuss the characteristics of the dynamics underlying the complexity; a dynamics in which stability and instability of neural
synchronization patterns are tightly interwoven. We will discuss what happens to this dynamics when mind-wandering is effectively put aside, and the observer concentrates on a task. At crucial points, we will discuss what the implications of these results are for our visual conscious experience.

2. Perceptual switching

To simplify from Figure 1, a special case of perceptual multi-stability can be found, suitable for psychophysical measurement: the class of widely-known bi-stable or ambiguous figures, such as the Necker cube (Necker 1832; see Figure 2). Prolonged exposure typically leads to switching between these interpretations. This behavior is involuntary to a large extent and occurs independently of external cues such as local disambiguation (Peterson & Gibson 1991) or internal ones such as eye-movements (Einhäuser, Martin & König 2004; Nakatani & van Leeuwen 2005, 2006; van Dam & van Ee 2006). We conclude that there are mechanisms within the visual system that go against the stability of its interpretations.

Along the lines set out by Hopfield, spontaneous switches in visual perception might simply be considered a matter of Gaussian noise. Empirical evidence suggesting that such a mechanism is responsible for perceptual switching is found in the dwell times (Borsellino, De Marco, Allazetta, Rinesi & Bartolini 1972; Levelt 1967). These are the durations with which a certain interpretation is maintained. They follow a Gamma distribution, consistent with the view that they are produced by a number of independent occurrences of a chance event. This observation has motivated discrete state models of which randomly alternate between states after a critical number of random events that favor the new state (Taylor & Aldridge 1974).

A Hopfield-type of model giving rise to a Gamma-like switching behavior would have two roughly equivalent minima (a “double well” model). Noise events can drive the system a step away from a minimum, and an accumulation of such events can drive it sufficiently far away to enable approach of the other minimum. Note that the spontaneous changes are still driven by Gaussian noise and thus dwell times would still be sequentially independent. In reality, however, these correlations are consistently above zero and decrease with lag (Bassingthwaighte, Liebovitch & West 1994; van Ee 2009); significant temporal correlations may survive over seconds or even tens of seconds. These sequential dependencies suggest that macroscopic fluctuations play a role in switching as well. Indeed: Kim, Grabowecky, and Suzuki (2006) induced stochastic resonance in switching by periodically alternating the stimulus, thereby demonstrating the presence of macroscopic noise in the system.
Consider, accordingly, a version of the double well model that cycles spontaneously between approach and avoidance of the equilibria; in other words between being governed by stability and flexibility. Suppose, for instance, that the well in which the system is residing becomes gradually shallower due to mechanisms such as adaptation or competition. This means that fewer noise events would suffice to drive the system out of its state. This assumption has been embedded into macroscopic models of the dynamics of switching behavior as a phase transition (Ditzinger & Haken 1989, 1990). In such models, the fast noise and a slow dynamic cycle work together to produce perceptual switching behavior.

In olfactory perception, Skarda and Freeman (1987) have described a system in which a similarly slow dynamic cycle is coordinated with the breathing rhythm; upon inhalation it is geared towards equilibrium states, and thereby ready to classify an incoming odor; upon exhalation the attractors are removed by changing the well depth. As a result, the system becomes optimally sensitive to new information. Freeman and van Dijk (1987) envisaged the same kind of mechanism for visual perception: the "perceptual sniff".

Köhler and Wallach (1944) proposed the slow dynamics to be neural fatigue or satiation. There is no evidence of neural fatigue at the level of active configurations. There is, of course, the well-established phenomenon of neural adaptation but this takes place at the local level of ion currents conductivity in the membrane of the neuron (Sanchez-Vives, Nowak & McCormick 2000), and is therefore not sufficiently selective at the level of global perceptual patterns (Barlow & Földiák 1989). Adaptation to patterns, according to these authors, occurs through a mechanism of anti-Hebbian decoupling between cells that are simultaneously active. Such a macroscopic mechanism could be useful to explain the steady, continuous increase in switching rate with prolonged presentation of a stimulus. Correlations between subsequent dwell times could be explained by fluctuations in adaptation rate (van Ee 2009).

But there is another possibility: rather than as noise added to a system at two different levels, we may regard the system's fluctuations as fractals. Consider a series of dwell times: they fluctuate irregularly from one time to the next. When these data have fractal characteristics, the means of different subsections fluctuate in a similarly irregular manner. Such similarities across all scales are estimated by the Hurst- or H-coefficient, of self-similarity (Beran 1992; Mandelbrot & Wallis 1969) or, for non-stationary series, the DFA exponent (Peng, Havlin, Stanley et al. 1995). With a H exponents of .5 the series consists of Gaussian noise. This means that adjacent time intervals are uncorrelated (or have correlations that quickly goes to zero with lag). If the exponent is < 0.5, the system tends to switch between high and low values and >0.5 < H < 1.0 means that the signals preserve trends over a long period – a long-term memory (Wagenmakers, Grünwald & Steyvers 2006).
Along with self-similarity as in fractals, such memory is the hallmark of complexity in time series. The phenomenon is sometimes referred to as \textit{1/f noise}; note, however, that a 1/f-type spectral density is necessary but not sufficient for fractal noise. It is possible, for instance, to scramble a fractal series, while preserving its spectral characteristics. Such series are used as surrogate data in bootstrapping estimation of statistics such as H.

Recently, Gao et al. (2006) presented H estimates for dwell times in the Necker cube, clearly demonstrating their fractal nature. Gao’s observations complement what is found in a large variety of behavioral tasks, such as mental rotation, lexical decision, speeded visual search, estimation of distance, estimation of rotation, estimation of force, estimation of time, simple reaction times, choice reaction times, and word naming (Gilden 1997, 2001; Gilden, Thornton & Mallon 1995; Kelly, Heathcote, Heath et al. 2001; Van Orden, Holden & Turvey 2003). It seems, therefore, that a complex systems characterization is appropriate for a much wider range of behaviors other than perceptual switching. This underlines the general relevance of perceptual instability for understanding perception, cognition, and the brain mechanisms underlying these processes.

3. An EEG-study of perceptual mind wandering

In a master thesis (Smit, Heslenfeld, Kenemans et al. unpublished manuscript), we investigated perceptual switching in a Necker cube paradigm adopted from Peterson & Hochberg (1983). These latter authors used Necker cubes that were locally disambiguated (Figure 2, left). When the disambiguated region of the picture is overtly or covertly (Peterson & Gibson 1991) attended to, observers perceive the orientation according to the local bias. Regional bias, however, fails to influence the perceived orientation when a different, unbiased region is attended to. This result shows that when the figure is presented in isolation and attention is focused on a part of it, the remaining parts are only loosely integrated with the rest of the figure, resulting in tolerance for global inconsistencies. According to the authors, this justified the much stronger claim that generally objects are perceived in a piecemeal fashion.

Smit et al. (1994) surrounded the Necker cube at a distance of 4.5° in all directions with eight wire-frame images, depicting cubes, all in one of two possible orientations. The central Necker cube was shown with two alternative local biases (indicated by the circles marked in the left hand side of Figure 2), in combination with one out of two alternative contexts as in the right hand side of Figure 2. Each unique stimulus was repeated 7 times. Participants reported on the perceived orientation of the central cube. The question was, whether adding surrounding
context to the Necker cube has any influence on its piecemeal perception and, in particular, whether perceptual mind-wandering (to the surroundings) strengthens figural integration.

During presentation of the surrounded Necker cube task-irrelevant stimuli (probes) occurred. The probes consisted of 4° diameter black dots. They were presented for 50 ms at a variable rate of between 800 to 850 ms, left or right visual hemifield and near 1.4° or far 5.0° from the fixation point. Each Necker cube presentation allowed for the presentation of 80 probes, 20 on each location, in random order. Observers were told to ignore the probes as well as the context cubes.

From nine participants, two scores were calculated for each condition from the proportion of time the cube was reported as seen in either orientation. Preference scores ($I_{\text{pref}}$) were obtained as in Formula 1. They indicate in which of the two possible orientations the cube is most frequently seen. They range from $-1$ to $+1$. Positive $I_{\text{pref}}$ mean a preference for the view-from-below orientation of the cubes, negative ones for the view-from-above orientation; zero means equal preference. Next, responses were analyzed in terms of $I_{\text{CoCo}}$, the degree of conformity of their preferred orientation with the context, as in Formula 2. A value of $+1$ stands for total consistency with the context, $-1$ for total inconsistency.

$$I_{\text{pref}} = \frac{\text{time viewed from below} - \text{time viewed from above}}{\text{time viewed from below} + \text{time viewed from above}}$$  \hspace{1cm} (1)

$$I_{\text{CoCo}} = \frac{\text{time Consistent} - \text{time Inconsistent}}{\text{time Consistent} + \text{time Inconsistent}}$$  \hspace{1cm} (2)

Analysis of variance on $I_{\text{pref}}$ showed main effects of local bias ($F(1,8) = 14.57; MSe = .203; p = .005$) and global bias ($F(1,8) = 8.88; MSe = .011; p = .018$). No
interaction was found ($F < 1$). The preferred interpretation, therefore, is independent of the focus of attention, a result which contrasts with Peterson & Hochberg (1983) and Peterson & Gibson (1991), who found that in isolated cubes, local biases operate locally, i.e. within the focus of attention. Here, the local biases operated globally and equally across the whole figure. The mere presence of a surrounding context, even though instruction discouraged observers to attend to it, is sufficient to eliminate the piecemeal object perception effect. Observers on average prefer to be in accordance with the global context. In other words, they not only prefer consistency within the figure, but also between the figure and its surroundings. The presence of the surrounding figures has not distracted the observers, but rather it has led them to enhanced integration of the central figure and reduced tolerance for inconsistencies within it.

Table 3. Data from Smit et al. (1994). Context consistency per subject. $I_{CoCo}$ is the index for context consistency. Observers with negative $I_{CoCo}$ (1) and/or too uneven numbers of probes within conditions (2) were excluded from the probe ERP analyses.

<table>
<thead>
<tr>
<th>Observer</th>
<th>$I_{CoCo}$</th>
<th>Inclusion</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>.0447</td>
<td>+</td>
</tr>
<tr>
<td>2</td>
<td>-0.0115</td>
<td>- (1,2)</td>
</tr>
<tr>
<td>3</td>
<td>-0.0303</td>
<td>- (1)</td>
</tr>
<tr>
<td>4</td>
<td>.0663</td>
<td>- (2)</td>
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<td>5</td>
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<td>+</td>
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<td>+</td>
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<td>7</td>
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<tr>
<td>8</td>
<td>.1404</td>
<td>- (2)</td>
</tr>
<tr>
<td>9</td>
<td>.0416</td>
<td>+</td>
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</tbody>
</table>

Table 3 shows that even though the majority of individual observers tended towards percepts that were in accordance with the context, there was considerable variability in individual preference for context consistency. To study whether the context consistency was related to perceptual mind-wandering, we measured event-related potentials evoked by probe stimuli (Probe ERP) in the observer's EEG. For trials where center and surrounding were oppositely biased, episodes in which the perceived orientation of the Necker cube in the center went with the surrounding context were classified as wandering; those in which it went with the local bias in the Necker cube itself were classified as focused. The remaining trials were used as baseline. ERPs were averaged per event (probe left/right and probe far/near), per cube configuration shown during that time (context from above/from below and stimulus from above/from below), and per perceived orientation.
at the time of presentation of the probe (consistent with the surrounding context or with the local bias).

Based on the extant ERP literature and visual inspection of the grand-averaged ERP curves we selected four time windows that matched positive and negative peaks. Windows 1 and 2 represented P1 and N1, 100 ms to 150 ms and 160 ms to 230 ms post-stimulus. Windows 3 and 4 were selected to cover the late positivity. Window 3 represents 200 ms to 270 ms, and Window 4 270 ms to 350 ms. For each of these the mean amplitude was calculated. The positivity that appeared from ca. 180 ms across the midline leads showed in Time Window 4 over the frontal region the effect of Figure 3.

Figure 3 shows the average amplitude induced by near and far probes. Whereas the amplitudes showed a steep decline with “focused” conditions, those in the “wandering” condition were essentially the same across probe distance. Attention – measured with the probes – seemed evenly distributed in the mind-wandering condition, and indeed focused when observers were influenced by the local cue. The frontal activity may arise from the frontal eye fields, which are involved in directing attention (Crowne 1983). Even though electrode location does not reliably reflect the underlying EEG activity and the number of observers in this study was rather small, the results were at least suggestive of the view that context congruency depends on a wide attentional focus, and temporary increase of a mind-wandering state.

Figure 3. Data from Smit and van Leeuwen (1994; unpublished data). Probe ERPs in µV means and standard errors. The probe distance × interpretation interaction was found (F(1,4) = 9.3; p < .05) in the time window of 270–350 ms, recording site Fz. Similar trends were observed in neighboring electrodes.
The degree to which individual observers differ in context consistency varied greatly. This led us to remove subjects for which the interpretation times were so skewed that reliable ERPs were impossible, thus limiting the generalizability of the ERP results presented above. However, these individual differences also provided a window to the brain mechanisms underlying mind-wandering. To understand what causes an individual’s ability to focus, we additionally obtained from lead O2 a simple 3 minute eyes-closed resting EEG recording, from which we calculated the dominant alpha frequency. This frequency generally was easily determined, but when two clear peaks in power spectrum were visible, the mean of both peak frequencies was calculated. This measure ranged from 9.38 Hz to 11.72 Hz across subjects. The correlation between individual peak frequency and $I_{\text{CoCo}}$ was found to be negative, very strong and significant ($r = –.717; N = 9; p < .05$). Slower oscillations correspond to increased context dependency.

To interpret this correlation, observe that “alpha activity is a far from unitary phenomenon, and discussions of alpha must take into account the anatomical and behavioral context.” (Foxe & Snyder 2011, p. 10). Alpha frequency was found to increase during execution of difficult tasks compared with more simple ones (complex addition and mental rotation vs. simple addition and visual imagery). The increase is largest in the hemisphere that is dominant for a specific task, i.e. arithmetical tasks for the left, and visuo-spatial tasks for the right hemisphere (Osaka 1984). Alpha frequency also correlates positively with specific verbal and non-verbal abilities (Anokhin & Vogel 1996; Jausovec & Jausovec 2000; Shaw 2004), but a relationship with general intelligence is contentious, some have reported a correlation (Angelakis, Lubar, Stathopoulou et al. 2004; Doppelmayr, Klimesch, Stadler et al. 2002) others find inconsistent (Gaser, Von Lucadou-Muller, I., Verleger et al. 1983) or no effects (Posthuma, Neale, Boomsma et al. 2001; See Smit, Wright, Hansell et al. 2006 for a review).

Cortico-cortical interactions involved in alpha activity have a function in biasing attentional processes. Whereas enhancement of neural processing at the focus of attention is modulated by gamma frequency (Gruber, Müller, Keil et al. 1999; Sokolov, Lutzenberger, Pavlova et al. 1999), alpha activity is involved in suppressing the attention of neurons responsible for processing stimuli outside of the focus of attention (Lopes da Silva 1991). Alpha oscillations may thus represent a certain rhythm of “pulsed inhibition” (Mathewson, Lleras, Beck et al. 2011) on attentional processes. From this we hypothesize that alpha frequency reflects the pulsation: the higher the alpha frequency, the faster the process is updated. What are the implications of this hypothetical mechanism with regard to mind-wandering?
Recall that mind wandering does not inevitably lead to reduced cognitive functioning, as the association of mind wandering with a state of distract edness would suggest (Smallwood & Schooler 2006). Mind-wandering yields a positive contribution to perception. The more mind-wandering, the more likely that interpretation is taking context into account. Perceptual mind-wandering is beneficial to the perception of a figure, as it helps maintaining a consistent image of the whole – the figure is no longer piecemeal, i.e. broken into elements by an overly focused attention (Hochberg & Gibson 1991); the figure itself is seen in relation to its surrounding. In a way, this is a natural mode of perception. One of the functions of perception is to give a holistic, integral account of what we have in front of us. It is no less natural, however, than the analytic, context-independent view; both have their own preferred domains (Lachmann & van Leeuwen 2008; van Leeuwen & Lachmann 2004).

Individuals differ with respect to their preferred perceptual style. This difference has been addressed with the notion of field-(in)dependence (Witkin 1950). Here we observe holistic/analytic processing and field-(in)dependence to depend on a common mechanism: the pulsed inhibition of attention, the rate of which is controlled by the peak frequency in the alpha rhythm.

The peak frequency operates as a pulsed inhibition of attention; a “reset” on the contextual information. The less frequent these resets, the more contextual information percolates into the mental representation. Down in the early visual areas, which preserve the retinotopic organization of the visual image, this would translate to a narrower spatial focus of attention. Analytic and holistic processing both involve attentional selection (Boenke et al. 2009). With analytic processing comes a style of spatially focused attention. With holistic processing, attention is “spilling over” to neighboring regions (Lavie & Cox 1997). The latter is also the preferred style of the field-dependent.

4. The dynamics of mind-wandering

So far, we have proposed that (perceptual) mind wandering is, at least sometimes, an active, cognitively relevant process, and that the instabilities it produces signify complexity. Can we observe these effects in brain activity? The results mentioned above found effects in the alpha range of EEG activity. It has been claimed that alpha (9–11 Hz) and beta (15–30 Hz) decrease during mind wandering whereas theta (4–7 Hz) and delta (2–3.5 Hz) EEG activity increases (Braboszcz & Delorme 2011). But this merely indicates that mind wandering was observed under conditions of low vigilance, and may therefore be subject to the sampling bias noted in the
beginning of this text. Since we wish to refrain from introspective reports, the best approach to study the dynamics of mind wandering is to look at the spontaneous EEG in the resting state – an awake neutral state that is not associated with any specific task and that is prone to mind wandering. We were interested in whether the EEG, and hence the wandering, could be understood as a classical random walk or rather, as perceptual switching research suggests, as a process of a complex system.

Pioneering work by Lehmann and coworkers showed that certain patterns in the spatial distribution of the potential across the scalp are systematically preferred (Lehmann, Ozaki & Pal 1987). The authors discovered typical concentric potential distributions around two extrema (maximum and minimum), which remained stationary for some time, and then suddenly jumped to new locations. They considered each such period as reflecting the type and content of information, which was momentarily processed in the brain. They called these periods ‘brain microstates’. More recently, the 1/f scaling behavior characteristic of complexity has been observed in amplitude fluctuations of 10 and 20 Hz oscillation (Linkenkaer-Hansen et al. 2001).

Important processes, such as phase synchronization between EEG signals or traveling waves in EEG potentials, however, are not necessarily accompanied by potential extrema. We therefore turned to dynamic phase synchrony as our analysis tool of choice. Phase synchronization of EEG has widely been used as a tool to study dynamic interactions among brain areas (Fell, Klaver, Lehnertz et al. 2001; Sarnthein et al. 1998; Silberstein, Danieli & Nunez 2003; Bhattacharya, Petsche, Feldmann et al. 2001; Schack, Weiss & Rappelsberger 2003) and is considered to reflect long-range neural integration (Varela, Lachaux, Rodriguez et al. 2001) and interaction in the brain (Breakspear, Williams & Stam 2004; Freeman & Rogers 2002; Nakatani, Ito, Nikolaev et al. 2005).

Ito, Nikolaev & van Leeuwen (2005) observed flexible, dynamic synchronization patterns in human scalp-recorded brain activity (EEG) in resting state EEG. The spatial structure of these patterns reveals a high coherence between frontal and occipital regions, and lower coherence between central and other regions (Thatcher, Krause & Hrybyk 1986; Ozaki and Suzuki 1987). As for the temporal structure: when phase synchronization over the entire scalp is strong, phase patterns took either of two forms; one is a gradual phase shift, observed between frontal and occipital regions; a traveling wave of electrocortical activity of which the direction of propagation is predominantly from anterior to posterior in three out of four participants, and opposite in the remaining one (Figure 4). The other pattern is a stepwise pattern with a sudden phase shift in the central region. This pattern may correspond to a standing wave composed of two traveling waves propagating in opposite directions.
Figure 4. From Ito et al. 2005. Snapshots of two typical phase patterns during phase synchronization. The phase difference is shown as the relative phase at each site in relation to the phase at the PO3 site. Top: Phase pattern with a gradual shift (pattern A). Bottom: Phase pattern with a sudden shift (pattern B)
Previous studies have resulted in conflicting reports on whether traveling waves predominantly occur from frontal to occipital (Shaw & McLachlan 1968; Inouye, Shinosaki, Toi et al. 1995) or from occipital to frontal (Nunez 1974; Petsche & Sterc 1968). Ito observed both to occur at different times, and sometimes simultaneously and superimposed. Most importantly, the patterns show an alternation highly akin to perceptual switching (Figure 5). The time periods during which a wave pattern remains apparently stable are referred to as laminar periods.

The laminar periods show 1/f scaling over two orders of magnitude in their durations. Gong, Nikolaev & van Leeuwen (2003) observed that the growth rates $(I_k/I_{k+1})$ of laminar periods $I_k$ have 1/f characteristics over 3 orders of magnitude. Fluctuations in intervals of spontaneous synchronization, therefore, have no characteristic preference for interval durations, once the common average is removed (Figure 6).

Van de Ville et al. (2010) found long-range dependency, which is eliminated from the data when the durations of the intervals of synchrony are artificially equalized. This indicates that interval duration is a key characteristic of the dynamics. The observed 1/f signature and the long-term dependency are in accordance with the fractal characteristics of the time series. Patterns of the fast time scale recur in the slow time scale. This implies that patterns observed in rest-state EEG correlate with those of the BOLD signal in fMRI (Laufs et al. 2006; Mantini et al. 2007).

In an effort to characterize the underlying dynamics of spontaneous activity, Ito, Nikolaev & van Leeuwen (2007) studied the whole-head two-dimensional pattern of pair-wise phase synchronization patterns, using high density EEG. In Figure 7, a transition between two relatively stable traveling wave patterns can be observed. The stability of wave patterns was investigated and its fluctuations tested against randomness using surrogate series (Figure 8).
Figure 6. From Gong et al. 2003. (a) Duration of dynamical phase synchronization episodes versus their index number of the events; (b) scaling of growth fluctuation in the duration of dynamical synchronization.

Figure 7. From Ito et al. (2007). Typical phase map time series, containing snapshots of the phase pattern at every 12 ms (data from Participant #3). Time proceeds from left to right, from top to bottom. Each map shows a phase pattern of alpha activity on the scalp viewed from above (top is front, bottom is back), color-coded according to the color bar at the bottom. The letters a and b indicate the time points at which global phase-synchrony pattern shows changes. Phase values measured at 169 points on the scalp were linearly interpolated to obtain spatially continuous images.
Ito et al. (2007) observed a dynamic behavior characteristic of chaotic itinerancy (Kaneko & Tsuda 2001; Tsuda 2001). Chaotic itinerancy occurs when fragile attractors are corrupted by noise. Unlike stable attractors, fragile attractors are manifolds on which not all neighboring trajectories converge; in other words, there are always points near the attractor, from which it is possible to escape. As a result, infinitesimal noise can switch the system from an approaching to an escaping trajectory. Noise-corrupted attractors are still preferably visited, as overall the system is attracted to them. The system will dwell in one of its neighborhoods for some time, until noise enables it to escape. Once away from the attractor, the system will show some irregular behavior, and eventually become attracted again.

Gong, Nikolaev & van Leeuwen (2007) showed that this behavior could be attributed to a critical threshold phenomenon: dynamic synchronization with 1/f characteristics in the durations of synchrony occurs in a system of coupled oscillators (Kuramoto 1975), when the coupling strength between the oscillators is at the critical threshold of mutual entrainment.

As previously mentioned, the signature 1/f behavior also occurs in alpha amplitude (Linkenkaer-Hansen et al. 2001). How are both related? Alpha amplitude modulation may be a gating mechanism. Inhibition operates in a

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**Figure 8.** From Ito (2007). (a) Time series of the instantaneous instability index I of a relative-phase pattern. An arbitrary threshold used to determine laminar intervals is shown with a dotted horizontal line. The wave patterns before a and after b reflect laminar periods. (b) Time series of I for the real and typical surrogate data shown in red and green lines, respectively
topologically more restricted region when the peaks have a higher frequency (i.e. shorter peak to peak intervals). As argued, this has its influence on the degree of context-sensitivity with which information is being processed within cortical regions. The intervals of synchronized activity may reflect the time it takes to communicate the information between regions, as synchronization facilitates communication between neural assemblies (Livanov 1977; von der Malsburg 1985). It helps to keep the temporal “windows of communication” concurrently open for input and output (Fries 2005).

The wave patterns that appear during the laminar periods might be considered the basis for the unity of experience. The phenomenal counterpart to the duration of a laminar period would be the psychological present (Stroud 1967). This simple equivalence statement has a particularly strong consequence: people faze out of consciousness during the brief periods of instability between laminar processes. This prediction should be taken with a few grains of salt. First, there is no critical threshold for laminar intervals in Figure 7, and therefore, by consequence neither is a critical threshold for consciousness implied here. One could, accordingly, be more or less conscious. Or you could simultaneously be aware in some modality and unaware in another – think of you suddenly realizing the awful smell while engaged in studying the color specter of Limburg cheese. Nevertheless, there may be some residual truth in the prediction: Consider that perceptual switching is experienced as instantaneous whereas the actual processes last 0.5–1.0 s (Ito, Nikolaev, Luman et al. 2003). During the switching, the system is on a transient between two laminar intervals (Nakatani & van Leeuwen 2005, 2006), so there is no persistent synchrony and hence no experienced duration.

Perhaps, the critical threshold will be discovered in the neural dynamics underlying consciousness. Indeed, if the dynamics is governed by fragile attractors, a system on an approaching trajectory would be conscious and one escaping from the attractor would not.

5. What happens to the laminar intervals when observers do engage in a task?

So far, we have been looking at the resting EEG. Once observers engage in a task, the large-scale patterns of alpha synchronization tend to disappear. Instead, we detect gamma or beta activity that accompanies the enhancement of a focus of mental activity in dedicated brain regions. Alpha activity plays a complementary role in other regions: it appears wherever objects or features need to be specifically
ignored or selected against (Foxe & Snyder 2011). Accordingly, in the Necker cube, switching was invariably preceded by transient patterns of synchrony in the gamma band (Nakatani & van Leeuwen 2006). These occur in parietal areas relevant to the emergence of a new perceptual organization (Nakatani, Orlandi & van Leeuwen 2011). Switching sometimes, but not always, was accompanied by transient alpha band activity in occipital areas. This activity may be related to the process of suppressing newly incoming sensory information to enable reading out information from the primary visual cortex (Shevelev, Kostelianetz, Kamenkovich 1991).

![Figure 9](adapted from Nikolaev et al. 2010). A. Grouping preference (columns vs. rows) as a function of Aspect Ratio (AR), based on the Gestalt principle of proximity. B. The mean (N = 8) duration of intervals of phase synchrony derived from evoked EEG in the parieto-occipital scalp areas as a function of AR. Dot lattice stimuli corresponding to AR = 1.0 and AR = 1.3 are shown under the graph.

As the characteristic whole-head alpha patterns disappear, preferred durations will emerge in the intervals of synchrony. It then becomes meaningful to consider, for instance, effects on duration averages. We adopted a psychophysical paradigm in which the perceived grouping of dot lattices is quantitatively determined as a function of a stimulus parameter: proximity (Kubovy et al. 1998). Proximity determines perceived grouping through a simple relationship called Aspect Ratio (AR) see Figure 9A. The larger AR the stronger is the preference for grouping according to the smallest distance (a); the more AR approaches 1, the more ambiguous is the perception of the lattice. Note that ambiguity equals uncertainty, or lack of information.
Figure 10. (adapted from Nikolaev et al. 2010). Following presentation of a dot-lattice (left panel) to an observer, evoked activity appears (rightmost panel). For this evoked activity we consider the pair-wise dynamic synchronization of an array of electrodes with a reference (Ref) depicted in the lowermost panel. Due to volume conductivity, the synchronization decreases, on average, with distance. Sometimes, however, the whole array takes on more uniform synchronization values, regardless of distance. This is expressed in their standard deviations (SD). We chose a threshold and define as a coherence interval the time the SD remains below the threshold.

We then determined which evoked component was sensitive to AR (Nikolaev et al. 2008b). At the scalp location of that component, we measured the durations of synchronized intervals in relation to the aspect ratio of the dot lattice (Figure 8A). We focused on the beta rhythm, which has been associated to visual attention and object related processing (Gross, Schmitz, Schnitzler et al. 2004; Tallon-Baudry, Bertrand, Fischer 2001; von Stein, Rappelsberger, Sarnthein et al. 1999, see also Wrobel 2000), and is of particular importance for our next example. We found a simple, linear relation of aspect ratio with coherence interval duration (Figures 9B; 10). Aspect ratio lawfully determines the ambiguity of the stimulus: the greater the aspect ratio, the less ambiguous the stimulus. Ambiguity is the
absence of information. Therefore, by definition, the less ambiguous a stimulus, the more information it contains. Thus, the more information in the stimulus, the longer the interval of synchrony the stimulus evokes. The steepness of the slope in individuals was found to be related to how sensitive they are to aspect ratio. Interestingly, the intervals of synchrony show extreme-value distributions, corresponding to the idea that the propagation of information takes place in parallel across multiple channels, and that the length of the interval is determined by the slowest of these processes (cf. Pöppel 1970). Intervals of synchronized activity, thus, reflect the time needed for intracortical communication of visual information. We concluded that the intervals of synchronized activity directly reflect the amount of stimulus information, as promulgated by the visual system to the rest of the brain.

Even though the episodes of synchrony occurring in “rest” alpha and those in the beta range are quite different, we might speculate that they both have similar information-processing functions, as well as being the vehicles of consciousness. Despite the differences in signal (alpha vs beta), the results from Smit and van Leeuwen’s (1994) Necker cube and Nikolaev et al.’s dot lattice studies point consistently to the same principle (van Leeuwen 1998): slower peak alpha and longer beta coherence intervals both indicate that more information is being integrated in the neurons, circuits, and brain regions involved in concurrent processing.

6. Conclusion

We have seen that mind wandering is not necessarily a process of distraction; minds engage in wandering to raise the quality of their percept. Greater consistency within a figure, and between the figure and its context, are the result. Artists, designers, and perceivers of art make use of mind-wandering to create, or detect, surplus structure. We found that wandering shows long-term regularities in its dynamics, which could be detected both in experience (the Necker cube) and in brain activity (rest alpha). It would therefore appear that “resting” is not the most appropriate term, when the mind is actively wandering.

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