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The Effect of Meditation Style on Binocular Rivalry

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Abstract

The present thesis aimed to investigate the effects of focussed attention (FA) and open monitoring (OM) meditation on visual perception in experienced meditators using a binocular rivalry paradigm. Binocular rivalry (BR) is the fascinating phenomenon occurring when each eye is presented with a different stimulus, resulting in frequent perceptual switches between the stimuli. Previous research reported that experienced meditators can substantially reduce these switches, using post-hoc self-reports (Carter et al., 2005). We included two meditation styles, because reduced switch-rate was expected for both, although through different mechanisms. Building on Carter and colleagues (2005), the present study tracked perceptual switches by utilizing two complementary approaches: button presses indicating which of the two stimuli was perceived, and a multivariate spatial filter called rhythmic entrainment source separation (RESS). RESS was used to extract steady-state visually evoked potentials (SSVEP) from EEG data, from which perceptual content can be objectively derived even in a no-report condition, so as to not disturb deep meditative states. Furthermore, questionnaires were administered to further inquire on perceptual content, meditative state and performance. Twelve experienced meditators were instructed to view BR stimuli while performing FA and OM meditation and applying the meditative state to the stimuli, as well as during a baseline condition. Self-reported switch-rate was found to be diminished in both meditation conditions compared to baseline. In contrast, no such reduction was found for RESS-derived switch-rate. Moreover, the two measures of switch-rate did not correlate, thus some suggestions to improve RESS are proposed. A few highly experienced meditators reported exceptionally low switch-rates and long percept durations, especially during the FA condition. Together, these findings highlight the profound effects that extensive meditation practice can have on subjective experience and the need for better measures to neurally track these experiences without disturbing the meditative state.

Abstract in German

Ziel der vorliegenden Masterabeit war es, die Auswirkungen der Meditation mit fokussierter Aufmerksamkeit (FA) und offenem Monitoring (OM) auf die visuelle Wahrnehmung erfahrener Meditierender anhand eines binokularen Rivalitätsparadigmas zu untersuchen. Binokulare Rivalität (BR) ist ein faszinierendes Phänomen, das auftritt, wenn jedem Auge ein anderer Reiz präsentiert wird, was zu häufigen Wahrnehmungswechseln zwischen den Reizen führt. Frühere Forschungen haben gezeigt, dass erfahrene Meditierende diese Umschaltvorgänge anhand von post-hoc-Selbstberichten erheblich reduzieren können (Carter et al., 2005). Wir haben zwei Meditationsstile einbezogen, da für beide eine geringere Kipprate erwartet wurde, wenn auch durch unterschiedliche Mechanismen. Aufbauend auf Carter und Kollegen (2005) wurden in der vorliegenden Studie die Wahrnehmungswechsel durch zwei komplementäre Ansätze verfolgt: Tastendrucke, die anzeigten, welcher der beiden Reize wahrgenommen wurde, und ein multivariater räumlicher Filter, die so genannte rhythmic entrainment source separation (RESS). RESS wurde verwendet, um aus den EEG-Daten stationäre visuell evozierte Potenziale (SSVEP) zu extrahieren, aus denen der Wahrnehmungsinhalt objektiv abgeleitet werden kann, selbst wenn kein Bericht vorliegt, um tiefe meditative Zustände nicht zu stören. Außerdem wurden Fragebögen verabreicht, um den Wahrnehmungsinhalt, den meditativen Zustand und die Leistung weiter zu erfragen. Zwölf erfahrene Meditierende wurden angewiesen, BR-Stimuli zu betrachten, während sie FA- und OM-Meditation durchführten und den meditativen Zustand auf die Stimuli anwandten, sowie während einer Baseline-Bedingung. Es wurde festgestellt, dass die selbstberichtete Kipprate in beiden Meditationszuständen im Vergleich zum Ausgangswert vermindert war. Im Gegensatz dazu wurde für die vom RESS abgeleitete Kipprate keine derartige Verringerung festgestellt. Außerdem korrelierten die beiden Messungen der Kipprate nicht miteinander, so dass einige Vorschläge zur Verbesserung des RESS gemacht werden. Einige sehr erfahrene

Meditierende berichteten über außergewöhnlich niedrige Kippraten und lange Wahrnehmungsdauern, insbesondere während der FA-Bedingung. Zusammengenommen unterstreichen diese Ergebnisse die tiefgreifenden Auswirkungen, die eine ausgedehnte Meditationspraxis auf das subjektive Erleben haben kann, und die Notwendigkeit besserer Messungen, um diese Erfahrungen neuronal zu erfassen, ohne den meditativen Zustand zu stören.

The Effect of Meditation Style on Binocular Rivalry

1. Introduction

Many studies have demonstrated that long-term meditation practices can profoundly alter the mind. Even fundamental components of experience - such as the sense of self, or the experience of space and time - can dissolve during states of deep meditation (Ataria et al., 2015; Berkovich-Ohana et al., 2013; Dor-Ziderman et al., 2013; Dor-Ziderman et al., 2016; Fingelkurts et al., 2020; Travis & Pearson, 2000; Wahbeh et al., 2018). Studying cognitive processes during deep meditation states can help us better understand the capacities of the mind, and test the validity of existing theories of cognition in these extraordinary circumstances.

Cultivating stable attention forms a key part of many meditation practices, hence we may expect meditators to perform better on attention-related tasks. This was confirmed in a meta-analysis which demonstrated that expert meditators perform better on attentional tasks than meditation-naïve participants, irrespective of meditation style (Verhaeghen, 2021). For example, mindfulness meditation has been found to reduce the attentional blink (a visual target occurring shortly after a previous target is poorly detected, Fabio & Towey 2018; May et al. 2011; Slagter et al. 2007; van Leeuwen et al. 2009; van Vugt & Slagter 2014) and meditators are more likely to detect the gorilla (Hodgins & Adair, 2010) in the invisible gorilla experiment (developed by Simons & Chabris, 1999), showing reduced inattentional blindness. Besides, meditators are found to have higher accuracy on the Stroop task (Teper & Inzlicht, 2013). Furthermore, Verhaeghen (2021) also found that mindfulness interventions led to improved attention performance compared to active controls, showing that there is not merely a correlation, but a causal relation between meditation and attention performance. Trait mindfulness was also associated with better attention performance (Verhaeghen, 2021). It should be noted that the effect sizes found in Verhaeghen's meta-analysis were rather small, and that attention training (Peng & Miller, 2016) and working memory training (Melby-Lervåg & Hulme, 2013; Schwaighofer et al., 2015) both have considerably larger effects on attention performance.

A remarkable study by Carter et al. (2005) used this approach and demonstrated an effect of long-term meditation on visual attention in Tibetan monks using a binocular rivalry paradigm. Binocular rivalry (BR) is the fascinating perceptual phenomenon elicited by simultaneously presenting each eye with a different image. Rather than perceiving both images, one image on top of the other or a static mixture of the two images, as one might expect, one usually witnesses a dynamic spectacle in which the images flip back and forth every few seconds, oftentimes with a transition period in which a mixture of the two images is perceived. Strikingly, Carter and colleagues found that their participants could see a single stimulus for unusually long durations during one type of meditation. Some monks even reported seeing a single image for the entire five minutes that the experiment lasted. The monks were practicing one-point meditation, which is a form of focussed attention (FA) meditation. In FA meditation, attention is sustained on a single object, to the exclusion of anything else (Lutz et al., 2008). In contrast, no such prolonged image perception was observed in a group of monks who practiced a different style of meditation called compassion meditation, which enhances feelings of compassion and acceptance for oneself and others (Zeng et al., 2015), suggesting that the observed effect is likely specific to FA meditation.

However, the study by Carter and colleagues suffers from some other limitations. Most importantly, they relied on verbal after-the-fact self-reports, because online reporting of their visual perception disrupted the meditative state of the monks. These self-reports can be biased and are therefore unreliable, as the participants might have had a poor judgement of time. Therefore, the present study aims to replicate their findings in a well-controlled lab-environment and makes use of an EEG frequency tagging method to objectively track switches between percepts. By doing so, we aimed to find more compelling evidence of the assumed extraordinary effects of long-term meditation on the mind. Furthermore, like many studies with (expert) meditators (Thompson, 2020), Carter and colleagues (2005) did not properly control for potential contributions by nonspecific factors, such as demand characteristics or placebo effects, given that one cannot blind meditators towards the fact that they are participating in the study because of their meditation expertise. The present study addresses this issue by using expert meditators as their own controls, e.g., by having them do the same task twice but under different meditative states, or to contrast two groups of meditators with differential expertise.

In addition, the present thesis aims to situate the findings of Carter and colleagues, as well as our own, within the theoretical framework of predictive processing (Friston, 2010; Hohwy, et al., 2008), and to find supporting evidence for a recently put forward predictive processing theory of meditation, dubbed the 'Many to (n)one theory' (Laukkonen & Slagter, 2021). The Many to (n)one theory describes how different deconstructive meditation styles gradually break down the predictive hierarchy in the brain. In order to seek support for this theory, we compare the differences between the effects of two meditation styles on BR.

The upcoming background section is structured as follows. First, these two main meditation styles will be discussed, as well as how they can be distinguished. Next, we will delve into predictive processing and the Many to (n)one theory. Subsequently, binocular rivalry will be discussed, including its phenomenology, how it is influenced by attention and how predictive processing can account for what happens during BR. Lastly, the rationale, research questions and hypotheses of this thesis will be outlined.

1.1. Focussed Attention and Open Monitoring Meditation

In the scientific literature, two broad categories of meditation styles can be distinguished, namely focussed attention meditation (mentioned in the previous section), and open monitoring meditation (OM). A common object of focus in FA meditation is the breath whereby one sustains one's attention on the sensations caused by the breath, typically at a specific location, such as the nostrils. Whenever the mind wanders, one makes a note of the wandering, whereafter attention is redirected to the sensations of the breath. In OM meditation, the content of experience is monitored in a nonreactive and nonjudgemental fashion (Lutz et al., 2008). One does this by attending to anything arising in one's experience without focussing on a particular object and without reacting to any experiences. Rather, one should simply observe one's experience nonjudgmentally, letting the content of experience arise and pass without prioritizing or holding on to any content, nor turning away from it. Important differences between FA and OM meditation include that in FA meditation, one's attention is restricted to a single object in the field of awareness, whereas in OM meditation, there is no single object of attention and one's attention is wide and encompasses all that one is experiencing. Meditation practices such as mindfulness and insight meditation are typically categorized as OM meditation, and practices like concentration meditation and mantra meditation fall under FA meditation. Notably, many meditation practices have properties of both FA and OM meditation and can therefore not be classified as either one or the other. Besides, there are many other practices – such as compassion meditation and nondual meditation – that cannot be categorized as either FA or OM (Dahl et al., 2015).

Lutz and colleagues (2015) proposed a phenomenological matrix of mindfulness practices, which helps to elucidate the differences between FA and OM meditation at the phenomenological level (see Figure 1). It comprises seven dimensions that characterize different meditation styles at various levels of expertise. In the description below, we focus on these seven dimensions in expert meditators, since the present study does not investigate novice meditators. However, it should be noted that there are considerable differences in the phenomenological features of the meditation experiences of experts and novices.

Furthermore, FA and OM are rather broad categories of meditation, and there may be quite some differences in the phenomenology within these two styles, depending on the tradition and specific meditation instructions. In the description below, we discuss how FA and OM are ideally experienced, according to the proposed matrix.

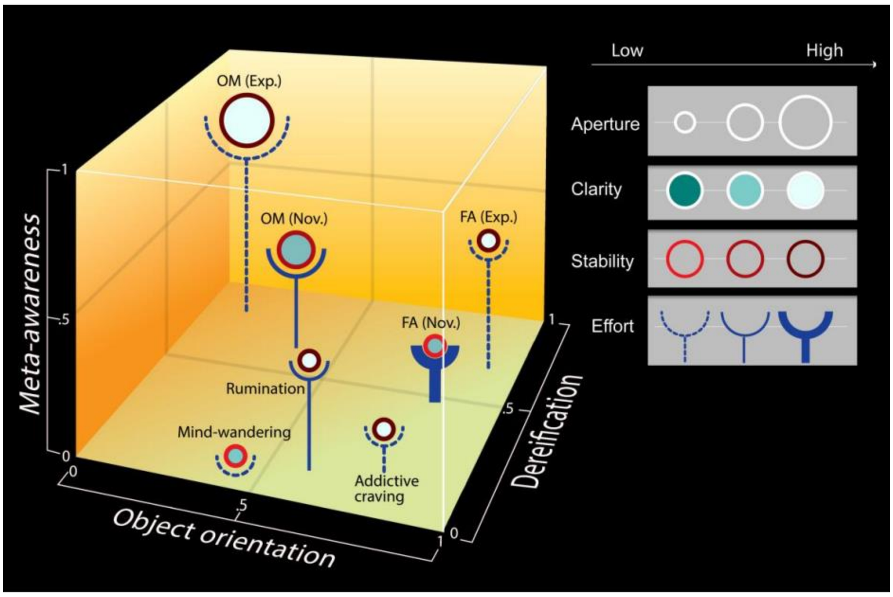
The phenomenological matrix of mindfulness practices has three functional dimensions and four qualitative dimensions. The functional dimensions comprise object orientation, dereification, and meta-awareness. Object orientation refers to whether an experience is oriented towards a particular object, whether in perception, memory or imagination. Object orientation is high when one has a high selective focus on a particular object – such as the breathing sensations in FA meditation – while it is low in OM meditation, as there is no focus on a specific object.

Dereification concerns the extent to which thoughts, feelings and perceptions are experienced as merely mental processes rather than as actual depictions of reality. For example, a thought about a delicious meal could cause one to actually salivate, which would be an instance of reification. When this thought would be dereified, the meal in mind is perceived as merely just another thought and one would not have a bodily response to it, or feel emotionally attached to it. During OM meditation, there is particularly high dereification, although dereification is also high in FA meditation.

Meta-awareness concerns the monitoring of experience. When one has high meta-awareness, one notes the current contents of experience, even the very subtle ones. Meta-awareness is high in OM meditation, as its primary aim is to maintain meta-awareness of all contents of experience. In FA, one uses meta-awareness to monitor if one's focus is still with the object of meditation and to notice the occurrence of mind-wandering. However, an excess of meta-awareness could reduce the primary focus on the object of meditation in FA meditation.

Figure 1.

Phenomenological matrix of mindfulness practices



Note. The relative scores on the different dimensions are displayed for FA and OM meditation in both experts and novices, as well as for some other non-meditative mental states, as a reference. The three functional dimensions are represented in Euclidean space and the four qualitative dimensions are represented by different colors and shapes. (Adapted from Lutz et al., 2015.)

The qualitative dimensions of the matrix consist of aperture, clarity, stability and effort. Aperture refers to the scope of attention, which can vary between wide (as in OM) and narrow (as in FA). Clarity is about the vividness of one's experience. Clarity should be high in FA, where the object of meditation is particularly clear, as well as in OM, where every aspect of experience is vivid. Stability indicates the extent to which experiences are unperturbed. In FA, one aims to maintain stable attention on the object of meditation, thereby maintaining stability in one's experience. In OM, experience constantly changes, but one proceeds to maintain a stable state of high meta-awareness and dereification. In that sense, experience also remains stable. Effort pertains to whether sustaining the current mental state is difficult and requires a lot of control, or if this is easy and requires little deliberate intention. Regardless of meditation style, the more advanced one's meditation practice becomes, the less effort is needed to maintain a meditative state.

Within Buddhism, meditation is seen as a way out of 'conditioned' existence, by reducing the extent to which one becomes wrapped up in patterns of thoughts, feelings and action, which are driven by past experiences. Freeing oneself from these patterns is thought to form the path to enlightenment. This conceptualization of the mind as shaped by past experiences has striking parallels with how the mind is thought of in the framework of predictive processing, namely, as grounded in past experiences and the statistical structures of the world.

1.2. Predictive Processing

To understand meditation from the framework of predictive processing, we must first understand the general principles of PP. PP postulates that the organism always adheres to the free energy principle, according to which an organism needs to maintain a boundary between itself and the world in order to prevent itself from disintegrating and dying (Friston, 2010). In other words, it aims to resist the second law of thermodynamics (the tendency of isolated systems to become more entropic over time). As the organism is separated from its environment by its boundary, it does not have direct access to its environment, hence it can only make guesses (predictions) about the state of its environment hidden beyond the boundary. In order to maintain its boundary and stay alive, the organism continuously needs to revisit the limited set of states that ensure its integrity and perform actions that minimize entropy (deviations from these expected states), and it uses these predictions while doing so (Friston & Buzsáki, 2016).

In generating these predictions, the organism relies on models of how the world works, which is based on what it has learned over the course of its life. In addition to these high-level models, it has models of the current state of the world, which is based on a combination of the general model and the model of the just-past state of the world. Some models are very strong, thus being difficult or even impossible to change, such as the model that the organism has a body. Such stubborn models might be genetically acquired, instead of just learned (Yon et al., 2019). Other models are much more easily adapted in light of new evidence, such as the believe that the footsteps I hear from coming behind me are my mom's, since I have no information confirming this.

Models are used to predict the hidden causes of the sensory inputs that the organism receives. We can think of the difference between the prediction about the state of the world and the incoming signals from the senses as a prediction error (a form of free energy). In order to make the best guesses about the environment, the brain should minimize the difference between its predictions and the information coming from the senses (Friston, 2010). This is called free energy minimization, or prediction error minimization. Prediction error minimization occurs at all levels of the neural hierarchy (Friston & Stephan, 2007). At the lowest level of the neural hierarchy, input from the senses is compared to a top-down prediction about this incoming signal, and the difference between these two is sent up to the next level in the hierarchy. This prediction error then becomes the input for this second level, and is in turn compared to a prediction from a higher level, and so on, until it is resolved.

This account of cognition is different from many traditional theories such as cognitivism, which take the organism to be a passive observer, that receives input from the environment, processes this in the brain and delivers output in the form of action. According to such views, representations are constructed in a bottom-up fashion, that is, in each neural level, information from the lower neural levels would be integrated into more complex representations. In vision for instance, the inputs from the retina form the building blocks from which edges and orientations are made, which in turn construct different shapes, which are recognized as particular objects in the higher levels of the hierarchy. In PP, bottom-up signals work in concordance with top-down signals. This is a much more efficient way of information processing, as only the prediction error is propagated up the neural hierarchy, instead of the combined input from the neurons one level below, as in the traditional view. In this way, the organism actively contributes to constructing its own experience by anticipating incoming sensory information based on its past experience, rather than passively processing inputs. In that sense, the brain does not only undergo influences from the environment, it also generates its own models from within (Seth, 2021).

When an incoming signal is very different from the predicted signal, the prediction error will be large. The organism can minimize this prediction error in two complementary ways. First of all, it can revise its model of the world, such that the predictions it makes are in line with the incoming signals. Secondly, it can resample its sensory input in such a way that the input becomes more in accordance with its expectations. These two strategies map onto the concepts of perceptual inference and active inference, respectively (Friston & Frith, 2015). In active inference, actions unfold in order to create an experience in line with the expected sensory inputs. As an example, let's consider the case of thirst as a prediction error. The organism has very stubborn expectations regarding its body fluid level, and when these are not met, a strong prediction error emerges in the form of thirst. At a certain point, a series of actions unfold, that facilitate fluid intake, such as going to the kitchen, filling a glass with water and drinking it. This restore the body's fluid level to expected levels, thus minimizing the prediction error caused by the drop in fluid level. In addition, action can update models. For instance, I could turn around (performing an action) in order to see if the footsteps I'm hearing actually come from my mom, or from someone else.

Should an organism always revise its beliefs whenever a prediction error occurs? Wouldn't such flexibility ultimately lead to a highly unstable model of the world, continuously changing in an unexpected fashion? During model updating, it is crucial to take into account the precision of the signal, which is a second order prediction of how reliable the prediction error is given the current environment. Clearly perceived signals have high precision and are assigned strong weight, meaning they strongly influence model revision. On the other hand, noisy and ambiguous signals have low precision and low weight, so they are likely to not be taken into account for model revision. In the latter case, the model will be more based on prior beliefs. In this way, the relative strength of top-down predictions and bottom-up prediction errors is determined by precision weighting (Friston, 2009). To illustrate this with an example, when I enter a dark, unfamiliar room, the visual signals I receive are very noisy and I can only make out vague silhouettes of which I am uncertain what they actually are. Therefore, seeing these silhouettes has very low precision and the prediction errors of this perception are likely to be ignored. However, when I turn on the light, I can clearly see the room with all its furniture, and the precision of my visual input markedly increases.

Both voluntary and involuntary attention are key mechanisms for precision weighting (Feldman & Friston, 2010). Only voluntary attention will be discussed here, since the present thesis only employs voluntary attention in its experimental paradigm. The incoming signals from the attended object are expected to be of high precision. After all, when attention is directed to an object, the noise and ambiguity of that object is reduced and the object is perceived much clearer (Hohwy, 2013). Because of this, less weight is given to incoming signals that are not attended to, making the system less sensitive to other signals (Hohwy, 2013). This is essentially what is thought to occur during FA meditation, as well: voluntary attention directed at the object of meditation upweights its incoming signals, whereas all other inputs are downweighed (Laukkonen & Slagter, 2021). However, as the next section will reveal, there is much more to the predictive processing account of meditation.

1.3. The Many to (N)one Theory

The Many to (n)one theory proposes that deconstructive meditation practices can progressively break down the generative models underlying the predictive mind (Laukkonen & Slagter, 2021), even very stubborn beliefs, such as one's sense of self and subject-object distinction. According to this theory, FA meditation, OM meditation and nondual (ND) meditation (in that order) gradually bring the meditator more and more into the present moment, thereby deconstructing the predictive mind, starting with higher-level and more flexible predictions, all the way down to the lowest levels in the neural hierarchy (Laukkonen & Slagter, 2021).

In short, Laukkonen and Slagter postulate that FA meditation induces a shift from higher-level processes such as thinking to lower-level processes such as sensing by increasing the precision of a single present-moment sensation such as the breath, thereby reducing the precision and frequency of higher-level predictions and breaking down cognition in the higher neural levels. As meditation progresses from FA to OM meditation, selective attention is abolished in favor of nonjudgemental awareness, meaning that all contents of experience have equally low precision and almost no predictions are made. In ND meditation, even the most stubborn predictions such as subject-object dichotomy dissipate.

Let us take a look at each of those steps more deeply. During FA meditation, one particular sensation in the present moment (e.g., the breath) has very high precision due to an extremely strong focus on that sensation, whereas all other sensations have very low precision, as they are not attended to. Furthermore, higher-level temporally-deep predictions such as thoughts and other higher-level mental processes are reduced as attention is directed away from them, which makes that cognition largely occurs in the lower levels of the neural hierarchy. This cessation of thoughts also reduces the influence of prior beliefs on one's experience. In addition, action is radically restricted as the meditator typically maintains a still posture and stable visual input, as their eyes are closed or at least their gaze does not shift in case their eyes are open. This stillness reduces novel sensory input that could otherwise be used to revise one's current model of the world. These factors make that the precision of one specific input lower in the predictive hierarchy is upweighted, and all other inputs are naturally downweighed.

In OM meditation on the other hand, one does not focus on any particular object. Instead, one maintains nonjudgemental awareness, in which all contents of experience have equal precision. Thus, whereas there was still high precision for one particular source of input in FA meditation, this last source of reliable prediction errors is eliminated in OM meditation. In very deep states of OM meditation, nothing is expected, almost no predictions persist, and all prediction errors are very weak due to the lack of selective attention. However, more stubborn predictions, such as subject-object distinction, could still remain.

Whereas in FA and OM practice, there is still the prior belief of an observer (a subject) and what is observed (the object), this duality dissolves in ND meditation. ND meditation aims to show the meditator the illusory nature of the subject-object dichotomy, a very stubborn prediction constructed from past experience. One way to arrive at this ND state is by realizing that subject and object always arise together in consciousness. In ND states, there are no concepts and the experience of time and space could cease. Nothing remains of the most stubborn and basic constructs of consciousness, and thereby all layers of the predictive mind are broken down.

Now we can appreciate what is meant with 'many to (n)one'. The 'many' refers to the higher levels of the predictive brain, in which one abstracts away from the here and now. The (n)one refers to a state in which all phenomenological distinctions stop, namely the nondual state. The hierarchical processes of the predictive mind can be broken down as one shifts from ordinary states such as mind-wandering or task-related thinking, to FA meditation, to OM meditation and lastly, to ND meditation, in which the mind is completely empty. One may expect that these meditation practices can radically change perception through their effects on sensory processing and conceptualization. In the current study, we examine this using binocular rivalry.

1.4. Binocular Rivalry

Binocular rivalry (BR) might appear as a rather elusive phenomenon to one that has not experienced it. Therefore, reading a first-person account might serve the reader. Wheatstone, who already investigated BR as early as 1838, writes about the experience of each eye being presented with a different letter:

> "the letter […] will change alternately from that which would be perceived by the right eye alone to that which would be perceived by the left eye alone. At the moment of change the letter which has just been seen breaks into fragments, while fragments of the letter which is about to appear mingle with them, and are immediately after replaced by the entire letter. [Notably, i]t does not appear to be in the power of the will to determine the appearance of either of the letters," (Wheatstone, 1838, p. 386).

This fragment does not only nicely capture the phenomenology of BR, but it also started a debate that is still continued these days: Can BR be controlled by voluntarily attention? (Paffen & Alais, 2011).

Before we address this question, a few concepts used in the BR literature need to be defined. A 'dominant percept' is a percept in which one BR stimulus is fully in visual awareness, while the other is not in awareness at all. A 'mixed percept' is a percept in which a mix of the two stimuli is being seen. As long as both stimuli are still being perceived, it is considered a mixed percept, even when one of the stimuli prevails. 'Dominance duration' refers to the time that a particular dominant percept is in visual awareness. Dominance duration typically lasts between one and a few seconds (e.g. Paffen & Alais, 2011). 'Switch-rate' is the number of alternations from one dominant percept to the other in a particular time period. Important to note here is that switch-rate includes the time that a mixed percept is being viewed, whereas dominance duration terminates as soon as the percept becomes mixed.

As mentioned before, it has long been debated to what extent voluntary attention can influence BR (for a meta-analysis, see Paffen & Alais, 2011). Helmholtz already argued in 1925 that BR is under volitional control; he even claimed to have full control over the image that he himself saw during BR (Helmholtz, 1925). Based on his observations, Helmholtz concluded that BR must be a higher-level phenomenon, as the viewer should not be able to control BR if a lower-level process determined which image was seen. His view contrasted with that of Breese (1899), who emphasized the role of lower-level processes in determining perceptual dominance. He found that attention did not affect switch-rate and that participants could only lengthen the duration of the dominant percept while making vigorous eye movements, not by merely focussing on the dominant percept (Breese, 1899). This led him to conclude that BR is already determined at the level of the retina, and that eye movements played an important role in dominance duration. Later research by Lack elucidates the matter. In a series of systematically controlled experiments, he found that participants were able to exert a modest degree of attentional control over BR, even when controlled for eye movements, blinking, accommodation and pupillary activity (Lack, 1978). This control could be enhanced with practice, both for speeding up and slowing down the switch-rate of the rivalry stimuli (Lack, 1978). Lack's findings are also in line with the current consensus that BR depends on both lower- and higher-level processes (Blake & Logothetis, 2002).

More recent studies elaborated on these results. Some research indeed confirmed that viewers can deliberately control switch-rate of rivalry stimuli (van Ee et al., 2005; Meng & Tong, 2004). However, the literature remains quite divided about the effect of voluntary attention on dominance duration. Van Ee and colleagues (2005) found that voluntary attention directed at one of the BR stimuli slowed down switches, but no conclusions can be drawn about dominance durations from their study, as participants could only indicate when they were seeing dominant percepts, but not mixed percepts. Meng and Tong (2004) did not find an effect of voluntary attention on dominance duration of the attended stimulus, but rather, they found a decrease in dominance duration of the unattended stimulus. However, another study failed to find such an effect on the unattended stimulus (Chong, et al., 2005). Instead, they found that dominance duration of the attended stimulus was prolonged, but only when participants performed an attentionally demanding task related to the features of that stimulus (Chong, et al., 2005). An experiment in which one eye was presented with a stimulus and the other with a blank screen demonstrated that voluntary attention directed towards the stimulus helped to retain that stimulus in awareness when the blank screen was perturbed with a moving square (Ooi & He, 1999). Notably, attentional control over BR was found to be markedly weaker than over other forms of bistable perception, such as the perception of a Necker cube (van Ee et al., 2005; Meng & Tong, 2004). Taken together, these findings demonstrate that viewers can exert only a marginal degree of control over the temporal dynamics of BR through voluntary attention.

Other studies highlight the importance of attention for the occurrence of rivalry, by making use of dual task paradigms. In these studies, participants reported which stimulus was dominant in addition to performing a concurrent task, such as reporting on peripheral dot motions (Paffen et al., 2006) or auditory cues (Alais et al., 2010). These studies demonstrated that rivalry slows down when attention is withdrawn from the BR stimuli (Paffen et al., 2006; Ooi & He, 1999; Alais et al., 2010), suggesting that switch-rate is tied to the strength of attention on the stimuli. When increasing the difficulty of the concurrent task, switch-rates slowed down even further, although it was still far from halting completely (Paffen et al., 2006). From these studies it remains unclear whether attention can only modulate rivalry, or is essential for rivalry to occur, as some attention still had to be directed to the BR stimuli in order to report stimulus dominance.

In contrast, research using an EEG frequency tagging method to keep track of the percepts being seen, demonstrated that rivalry nearly halted altogether when attention was diverted away and instead, mixed percepts were seen (Zhang et al., 2011). Unlike in most other research, participants did not have to report on the percept being seen in the unattended condition, which made it possible to completely disengage attention from the stimuli (although one cannot be sure if participants did not direct any attention at all to the BR stimuli). The authors concluded that rivalry requires attention to occur (Zhang et al., 2011). All in all, the literature suggests that increased attention on the dominant percept may enhance the relative dominance duration of that percept, whereas decreased attention on the BR stimuli enhances mixed percept duration.

1.5. Binocular Rivalry Explained through Predictive Processing

In order to better understand the PP account of BR, it helps to cast the predictive processing theory in Bayesian terms (Friston & Stephan, 2007). In this view, predictions can be thought of as hypotheses being tested, and the hypothesis with the highest posterior probability (i.e., the most likely hypothesis) determines what is being perceived. The posterior probability depends on the likelihood of the hypothesis given the input and on the prior probability of the hypothesis, independent of the input (Friston, 2002).

The rest of this section is based on the paper by Hohwy, Roepstorff and Friston (2008), who propose a predictive processing account of BR in which several factors together determine the dynamics of BR. In daily life, both eyes usually see the same scene, although from a slightly different viewpoint. The brain thus has a very stubborn prior belief, called a hyperprior, that the input of both eyes must be similar. Obviously, this assumption gets violated when exposed to BR stimuli. One way in which the brain deals with this violation, is by selecting one stimulus to be perceived, which becomes the dominant percept. Perceiving one of the two stimuli is more in line with this hyperprior than seeing a mixed percept, which has a much lower prior. However, a mixed percept has a higher likelihood than either dominant percept, because it accounts for much more of the incoming signals than either dominant percept. Mixed percepts occur whenever the likelihood of the mixed percept outweighs the prior of each single dominant percept.

While this hyperprior explains why we do not see a mixed percept the entire time, it cannot account for the flipping between the two stimuli. When one stimulus is dominant, the input from that stimulus matches the prediction for that stimulus being perceived, and thus, prediction error propagating up the hierarchy is very small. This simultaneously results in a large prediction error for the input from the suppressed stimulus, since it does not match the prediction that the dominant percept is being seen. In order to minimize this prediction error, the brain revises its model (perceptual inference) by switching to seeing the suppressed stimulus, which becomes dominant, and suppressing the previously dominant stimulus. This now elicits a prediction error for the currently suppressed stimulus. Because of this continuing imbalance, the stimuli alternate between dominance and suppression.

Another factor that may contribute to the switch in percept is the hyperprior that the world always changes. This hyperprior causes posteriors to decrease in strength over time, as it will be more probable that changes will have occurred in the environment, and that there will be parts of the sensory evidence that are not accounted for by the current posteriors. Therefore, as time passes, the dominant percept becomes more likely to change. This also makes it increasingly difficult to hold on to a dominant percept with one's attention.

As already discussed in the section on PP, attention increases precision weighting, thereby assigning more weight to the incoming signals from the attended stimulus. Thus, when attention is directed to a single BR stimulus, its incoming signals are enhanced and the incoming signals from the other stimulus are reduced, thereby weaking the impetus to switch between percepts and prolonging dominance duration of the attended stimulus. This is how some viewers can influence dominance duration and switch-rate, as was discussed in the previous section.

1.6. A No-Report Measure of Switch-Rate

Most studies on BR make use of button presses to measure switches between percepts. This has a considerable disadvantage, because pressing buttons can influence perception of the BR stimuli and interfere with attention and the meditative state (Laukkonen et al., 2022), as the expert meditators in the study by Carter et al. (2005) also indicated. Besides, self-reported switches suffer from the critiques given to subjective measures, which can be biased (Wenger & Rasche, 2006), subject to social desirability effects (Fisher, 1993) or failures of introspection (Carruthers, 2007; Johansson et al., 2006).

In an attempt to circumvent these issues, the present study implements a no-report paradigm, in which switch-rates are calculated from neural data. This is done by utilizing an EEG frequency tagging method relying on steady-state visual evoked potentials (SSVEPs). An SSVEP is an electrical potential evoked at visual regions in response to a rhythmically presented visual stimulus. The SSVEP oscillates with the same frequency as the frequency with which the stimulus flickers, which makes it possible to track the neural activity induced by the stimulus across the visual cortex. Earlier studies using SSVEPs to investigate BR presented each stimulus with a different flicker frequency and measured how the power of the two SSVEPs changed over time (e.g., Brown & Norcia, 1997). The SSVEPs corresponded to participant's self-reported perception of the stimuli as indicated by button presses, such that the power of the SSVEP elicited by the dominant stimulus was higher than that of the suppressed stimulus (Brown & Norcia, 1997).

The present study uses rhythmic entrainment source separation (RESS, Cohen & Gulbinaite, 2017) to extract SSVEPs from the EEG data to enhance their signal to noise ratio (SNR). Previous studies using RESS in BR research proved that RESS was an adequate method to do so, as RESS-derived switch-rates highly correlated with self-reported switch-rates made with button presses (e.g., Zhang et al., 2011; Laukkonen et al., 2022).

1.7. Aim and Hypotheses

The present thesis aims to investigate the effects of FA and OM meditation on the dynamics of binocular rivalry within the framework of the predictive processing theories of BR and meditation. To this end, experienced meditators were recruited and exposed to BR stimuli during mediation as well as at baseline. Building on the work of Carter and colleagues (2005), the present study measured switch-rate by making use of RESS to extract SSVEPs from EEG data, in addition to recording online self-reports of switches with button presses. Furthermore, questionnaires were administered to further assess perceptual content, meditative state and task performance.

In line with the discussed PP theories, we hypothesized that focussed attention directed towards the dominant percept would upweight the incoming signals from this percept and weaken the incoming signals from the suppressed stimulus. This would most importantly lead to a strong increase in dominance duration, and therefore to a decrease in switch-rate. It is important to note that although prolonged dominance duration would lead to lowered switch-rate, lowered switch-rate could also be a result of prolonged mixed percept duration, and it is therefore crucial to verify the role of both dominant and mixed percept duration in changes in switch-rate. In addition, we expected reduced mixed percept duration and an enhanced feeling of being in control of the transformations of the percept.

In contrast, we hypothesize that neither stimulus is prioritized over the other during OM meditation, meaning that the incoming signals of both stimuli would be equally downweighed. Furthermore, OM meditation is expected to decrease the precision assigned to the priors of the dominant percepts, which makes it more likely that the posterior probability of the mixed percept overrules that of the dominant percepts. Besides, even less predictions persist than in FA meditation, and more stubborn hyperpriors could be weakened, such as the hyperprior that the input of both eyes must be similar and that we cannot perceive two images at the same location. Together, this might lead to a strong increase in mixed percept duration and a decrease in dominance duration, which would also result in a decrease in switch-rate. Like for FA, it needs to be verified if the decrease in switch-rate is due to an increase in mixed percept duration and not due to an increase in dominance duration. In addition, perception of the stimuli was expected to be more instable in OM compared to FA meditation, as OM meditation facilitates quick letting go of the contents of experience, leading to fluctuations in what is perceived, whereas FA meditation would stabilize the attended stimulus by holding on to it.

2. Methods

2.1. Participants

Twelve experienced meditators (6 female and 6 male, mean age = 48.25, range = 27-70) took part in the study. Data collection for the overarching study of which this thesis is part, is still ongoing. Participants were recruited by contacting meditation institutions, as well as via word of mouth. Participants had to meet the following inclusion criteria: aged between 18 and 70 years; fluency in Dutch or English; have (corrected-to-)normal vision; practice meditation regularly; familiarity with FA and OM meditation and participation in at least two intensive meditation retreats in the past two years. Exclusion criteria were color-blindness, migraine, psychiatric or neurological diagnosis, personal or family history of epilepsy, dreadlocks or braids. Inclusion was determined based on an intake survey. We selected participants based on how long they had been meditating, how frequently they meditated, the estimated total hours spent meditating and the number of days spent on retreat. Participants practiced in the Theravada Buddhism tradition, Tibetan Buddhism tradition and/or mindfulness meditation. Self-estimated practice hours ranged from 351 to 17500 , on average 3917 hours, although these numbers are likely incorrect and the true average and maximum probably lie much higher, as some participants' answers were unrealistic (see the discussion section and Table 13). Participants were compensated with 10 euros per hour and their travel costs were reimbursed.

2.2. Experimental Design

The experiment consisted of two experimental conditions, namely focused attention (FA) meditation and open monitoring (OM) meditation, as well as a baseline condition. Participants visited the lab twice. Each session started with a baseline condition followed by one of the two meditation conditions, thus each meditation condition had its own baseline. The order of meditation style across the two session was counterbalances across participants. It was necessary to complete the baseline condition before the meditation condition in order to avoid any leakage of the meditative state into the baseline. Each condition consisted of three blocks with a different trial type: BR no-report trials, BR self-report trials and non-BR trials. Trials occurred always in that specific order, as the instructions for the SR trials are easier to follow if participants first get acquainted with the task in the NR trials. In non-BR trials, the stimuli were presented one at the time, alternatingly. Non-BR trials were used to train a decoder to distinguish between the two BR stimuli. The present thesis does not investigate the non-BR trials.

2.3. Stimuli

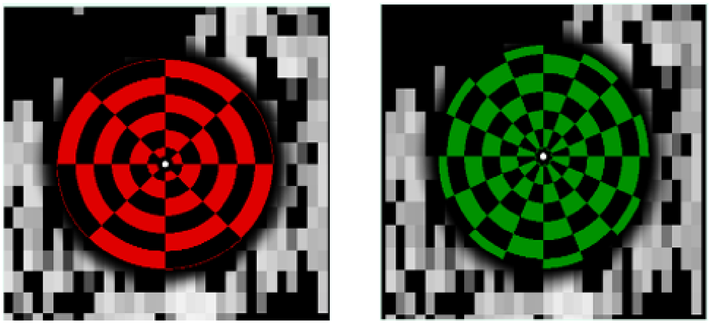
Stimuli were adapted from Zhang et al. (2011). The stimuli were presented on a 23.8-inch Asus ROG Strix XG248Q screen. A mirror stereoscope was used to present each stimulus to a different eye. The stimuli were a red-and-black checkerboard pattern and a green-and-black checkerboard pattern (Figure 2). A white fixation dot was at the center of the stimuli and stimuli were surrounded by black and white gratings. The location of stimuli (right or left) was counterbalanced across participants. The left eye was always presented with a stimulus flickering at 6 Hz and the right eye with a stimulus flickering at 7.5 Hz. While the bandwidth of SSVEPs is generally regarded to range be 3-40 Hz (Vialatte et al., 2010), lower frequencies generally induce stronger SSVEPs, thereby increasing SNR (Zhu et al., 2010; Laukkonen et al., 2022). We also avoided interference with the alpha range (8-12Hz) using these flicker frequencies.

2.4. Questionnaires

The questionnaire consisted of four sections (see Appendix). All questionnaire answers needed to be reported on an Apple iPad using a continuous 7-point Likert scale from 1 (strongly disagree) to 7 (strongly agree), unless otherwise specified. Questions about percept duration were reported as time in seconds.

Figure 2.

Stimuli



Note. Each eye was presented with either a red-and-black or a green-and-black checkerboard pattern. The location of stimuli (right or left) was counterbalanced across participants. The left eye was always presented with a stimulus flickering at 6 Hz and the right eye with a stimulus flickering at 7.5 Hz. Adapted from Zhang et al., (2011).

The phenomenological matrix of mindfulness questionnaire (PMMQ) was adapted from Ghigliotti (2019) and assessed meditative state. Our version consisted of fourteen items in total, covering the seven dimensions identified by Lutz and colleagues (2015): object-orientation, dereification, meta-awareness, aperture, stability, clarity and effort. In addition, it also included two questions on mind-wandering and one on sleepiness. The visual questions consisted of eight questions probing the minimum, maximum and average duration of the mixed and dominant percepts, as well as an item on the proportion of mixed and dominant percepts, and an item on the percept switching characteristic. This was followed by a few questions on task performance and button press interference with perception and attention. Lastly, there were eight questions about the phenomenology of BR, six of which were obtained from Niikawa et al., (2020), the other two being our own addition. We only used questions for which the authors found significant evidence during BR, namely temporal indeterminacy, diachronic spatial indeterminacy, spatial disunity, sensitivity to subject's change and instability (Niikawa et al., 2020). From this last set of questions, the present thesis only investigates the findings pertaining to instability (small and irregular changes such as vibrations, even when a dominant percept is seen) and sensitivity to subject's change (the feeling of being in control of perceptual alternation). There were two versions of the questionnaire, one for the baseline condition and one for the meditation conditions. The latter included a few additional questions specific to the meditation condition, such as whether participants were able to follow the meditation instructions and to what extent the button presses interfered with the meditative state.

2.5. Procedure

The experiment was divided into two sessions that took place on different days (Figure 3). Upon arrival, participants were informed about the experiment and signed an informed consent form. Next, the position of the stimuli on the screen was adjusted for every participant so that participants viewed a single image when looking through the mirror stereoscope, with minimal strain on the eyes. Like this, participants were also familiarized with the stimuli. This was followed by setting-up the EEG electrodes.

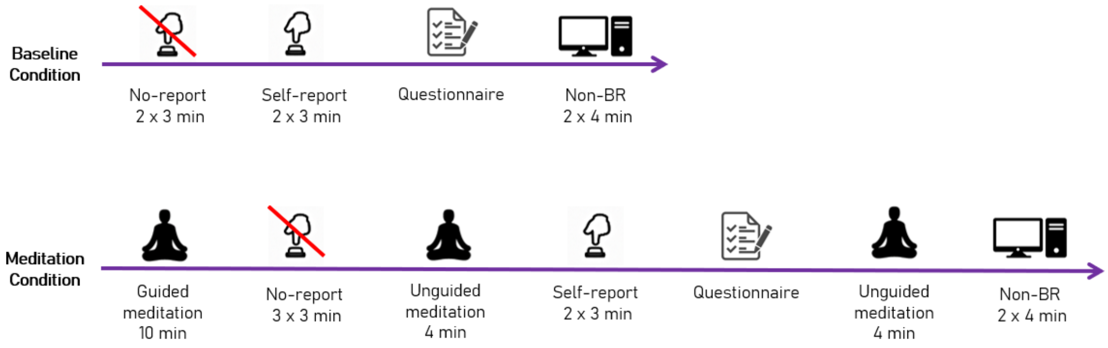
Then the baseline condition started, for which we explicitly instructed participants not to meditate. In the first block, participants completed two no-report trials, during which participants had to simply look at the checkerboard pattern, while keeping their gaze on the fixation cross. In the next block, participants completed two self-report trials, for which they were instructed to press '1' on the keyboard when they saw a completely red-and-black checkerboard pattern and '3' when they saw a completely green-and-black checkerboard pattern. Each no-report and self-report trial lasted 3 minutes. Subsequently, participants filled in the questionnaire, with the questions pertaining to the no-report and self-report trials together (without distinguishing between the two). The last block consisted of two non-BR trials. Every block in the baseline condition started with a practice trial. Participants were offered a break at the end of baseline testing, before starting the meditation condition.

The meditation condition commenced with 10 minutes of either FA or OM guided meditation. At the end of the practice, participants were instructed to apply the meditative state that they had just cultivated to the stimuli. More specifically, in the FA condition participants were instructed to try and hold on to the currently dominant checkerboard pattern with their attention, and when this pattern went out of dominance, to let go of it and hold on to the new dominant pattern. In OM, participants were instructed to look at the stimuli with a nonjudgmental open awareness, without focussing on one or the other.

After the guided meditation, participants again performed a no-report block (this time with three trials), followed by a self-report block and a non-BR block. They filled out the questionnaire after the self-report block. Prior to the self-report block and the non-BR block, participants meditated for a four minutes (without guidance), in order to refresh their meditative state. Each session lasted about four hours.

Figure 3.

Experimental procedure



Note. Each session started with a baseline condition, which consisted of two no-report trials, followed by two self-report trials, a questionnaire and then two non-BR trials. Hereafter, the meditation condition took place, which commenced with a guided meditation (in either the FA or OM style) and was followed by three no-report trials, an unguided meditation, two self-report trials, a questionnaire, another unguided meditation and lastly two non-BR trials.

2.6. EEG

EEG data were recorded with a BioSemi Active 2 system with 64 electrodes at a sampling rate of 512 Hz. Preprocessing was done using EEGLAB 2023.0 in Matlab R2023a . Data was re-referenced to the average of the external electrodes placed on the earlobes and then high pass filtered at 0.1 Hz. Next, a cleanline filter was used to remove 50 Hz line noise from the signal. Subsequently, external channels were removed, as well as the first and last 1.5 seconds of each trial, as these were before and after stimulus onset and tended to be very noisy. Excessively noisy channels were removed, by visual inspection. Lastly, the trials of each block were concatenated to form a single data file per trial type for each participant. No further preprocessing steps were carried out, since interpolating electrodes and performing ICA could interfere with the performance of the RESS-filter (Cohen & Gulbinaite, 2017).

2.7. Neural Data Analysis

Only neural data analysis will be described in this section. The description of the statistical analysis is included in the results section for the sake of clarity and brevity.

2.7.1. Rhythmic Entrainments Source Separation

First, the concatenated trials were temporally filtered at the stimulus' flicker frequencies (6 Hz and 7.5 Hz) as well as two neighboring frequencies (± 1 Hz) by applying a Fourier transform to the EEG time series data and multiplying the result by a Gaussian. The full width at half maximum (FWHM) of the Gaussian was 0.5 at the flicker frequencies and 2.5 at the neighboring frequencies. These FWHM values were chosen, because they produced the maximum SNR and were similar to values used in previous research (Vissers et al., 2017; Cohen & Gulbinaite, 2017). Next, the data was converted back to time domain by applying an inverse Fourier transform. Subsequently, covariance matrices were generated for the frequencies of interest and the neighboring frequencies, which were then used to compute generalized eigendecompositions. These generalized eigendecompositions were employed to find the eigenvector with the largest eigenvalue that maximally differentiates the frequencies of interest from the neighboring frequencies. The time series data were then multiplied by the eigenvalues to generate the RESS component. Hereafter, a Hilbert transform was applied to this RESS component, which yielded a RESS power time series of the two frequencies of interest, for each trial block. The SNR spectrum and topoplot were also calculated for each trial block. We decided to keep in trials with low SNR, as the sample size was already low.

2.7.2 Calculating Switch-Rates

The RESS power time series were used to determine when switches occurred. Following the same protocol as Laukkonen et al. (2022), we identified turning points in the time series by making use of a moving slope function, which calculated the difference between the two gradients within a five data point window, across each RESS power time series. This five-point window enhanced robustness against noisy data sequences and made it less likely that points of spurious inflection were included in the switch-rate calculation. In this way, a vector of gradients was obtained for each frequency. For each vector, it was calculated how many successive date points changed from positive to negative or vice versa, which indicated a turning point in the time series. Switch-rate was then determined by calculating the mean per minute of these four variables (positive-to-negative and negative-to-positive turning points for the two frequencies) for each block.

3. Results

Whenever Mauchly's test of sphericity is violated, Huyn-Feldt corrected p-values are reported.

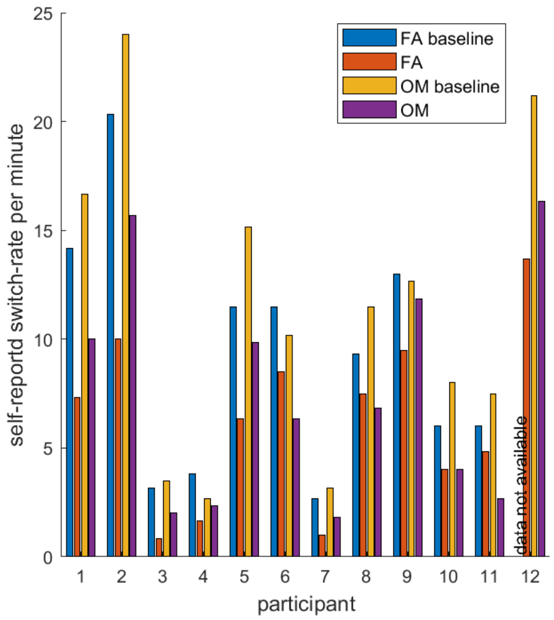
3.1. Behavioral Results

The button presses that the participants made in the SR blocks were used to calculate switch-rate (the total number of switches per minute) for each trial, separately per condition. As mentioned before, our main hypotheses predict prolonged perception of the dominant percept in the FA condition (compared to baseline and OM conditions) and prolonged mixed percept duration in the OM condition (compared to baseline and FA conditions), both in turn leading to decreased switch-rate in the meditation conditions compared to baseline.

In line with our expectations, participants had lower switch-rates in the meditation conditions compared to its baseline (Figure 4, Table 1). Interestingly, it can be observed that there were considerable differences between participants in self-reported switch-rate, with a few participants (namely participant 3, 4 and 7) reporting strikingly low values across conditions.

Figure 4.

Self-reported swich-rates of individual participants



Note. There is considerable variation in self-reported switch-rate across participants. Every participant had a lower switch-rate in the meditation conditions compared to its baseline.

Table 1.

Descriptive statistics of self-reported switch-rate

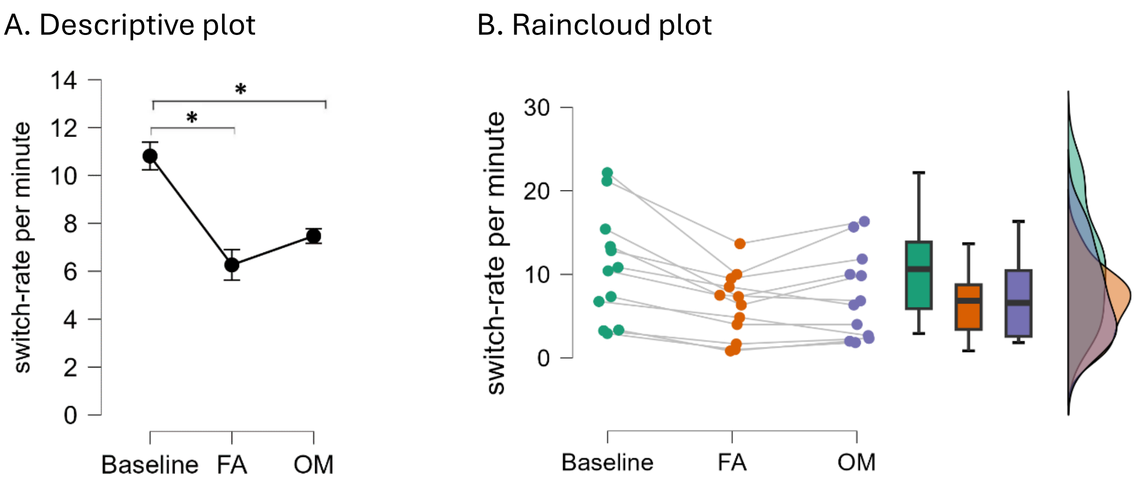
Statistic	Baseline	FA	OM
N	12	12	12
Mean	10.813	6.264	7.472
SE	1.891	1.143	1.512
95% CI upper	14.974	8.779	10.799
95% CI lower	6.651	3.748	4.145
SD	6.551	3.959	5.237
Minimum	2.917	0.833	1.833
Maximum	22.167	13.667	16.333

Note. N = sample size, SE = standard error, SD = standard deviation, CI = confidence interval from the mean.

In order to directly compare the switch-rate for the two meditation conditions, we first needed to verify if the switch-rate for the baseline conditions across the two sessions were similar. If not, we would first need to subtract the baselines from the meditation conditions, which could introduce noise. A repeated measures ANOVA assessing the effect of baseline condition on self-reported switch-rate showed no significant difference between baselines $F(1,10) = 0.422$, $p = 0.531$, with a very small effect size, $\omega^2 = 0.000$, meaning we could average the two baseline for comparisons. Subsequently, another repeated measures ANOVA was conducted, comparing the switch-rates between FA, OM and average baseline condition. A highly significant difference between conditions was found (Figure 5), $F(1.484,16.326) = 19.945$, $p < 0.001$, with a large effect size, $\omega^2 = 0.109$. Post-hoc tests showed that switch-rate was significantly lower for FA compared to baseline, $t = -6.097$, $p < 0.001$; and also significantly lower for OM compared to baseline, $t = -4.477$, $p < 0.001$. No significant difference was observed between FA and OM, $t = -1.620$, $p = 0.120$.

Figure 5.

Self-reported switch-rate across conditions



Note. A. Self-reported switch-rate is significantly lower for FA and OM compared to baseline. Asterisks indicate significant differences. Error bars represent standard error. B. Individual values for each participant, boxplots and distribution plots are displayed. Baseline is the average baseline of the two sessions. Error bars represent confidence intervals.

3.2. Neural Results

3.2.1 Switch-Rate

Our predictions for RESS-derived switch-rate remain similar to self-reported switch-rate. Once again, we first verified baseline similarity. A two-way repeated measures ANOVA was performed, with condition as a factor with the two baseline conditions as levels, and with trial type as a second factor with NR and SR as levels. There was no significant difference in switch-rate between the two baselines $F(1,11) = 0.029$, $p = 0.868$ with a very small effect size, $\omega^2 = 0.000$. No significant difference in switch-rate between trial types, $F(1,11) = 9.005\text{x}10^{-4}$, $p = 0.977$, $\omega^2 = 0.000$, and no interaction effect, $F(1,11) = 0.150$, $p = 0.706$, $\omega^2 = 0.000$, were observed.

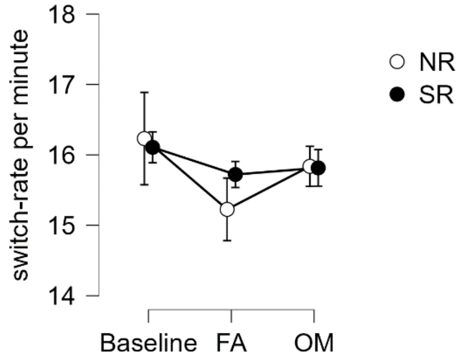
As there was no significant difference between baselines, baselines were averaged for the subsequent analysis. A two-way RM ANOVA was conducted, with condition as a factor with average baseline, FA and OM as levels; and with trial type as a second factor with NR and SR as levels. Unlike hypothesized, there was no significant effect of condition on switch-rate as measured by RESS, $F(2,22) = 1.613$, $p = 0.222$, and the effect size was very small, $\omega^2 = 0.015$ (see Figure 6 and Table 2). There was also no effect of trial type, $(F1,11) = 0.138$, $p = 0.717$, $\omega^2 = 0.000$, nor was there an interaction between condition and trial type, $F(2,22) = 0.410$, $p = 0.668$, $\omega^2 = 0.000$, as expected.

Furthermore, it needed to be verified if switch-rate can be reliably derived from the RESS signal, as was the case for Laukkonen and colleagues (2022). A Pearson's correlation between the self-reported switch-rate and the RESS-derived switch-rate of the SR trials collapsed across all conditions was carried out. Contrary to our expectation, a nonsignificant small negative correlation was found between the two, $r(45) = -0.223$, $p = -0.133$ (Figure 7). After splitting by condition, anticorrelations for baseline, $r(20) = -0.222$, $p = 0.321$; and FA, $r(10) = -0.172$, $p = 0.594$, were small and nonsignificant, and moderate and not significant for OM, $r(10) = -0.478$, $p = 0.116$.

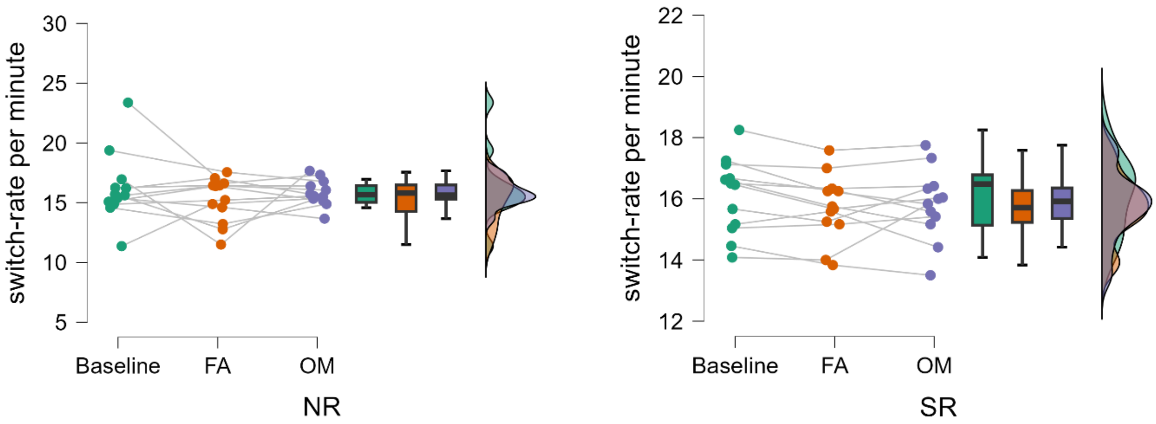
Figure 6.

RESS derived switch-rate across conditions

A. Descriptive plot



B. Raincloud plots for no-report and self-report trials



Note. A. RESS-derived switch-rate remains similar across conditions for both SR and NR trials. Error bars represent standard error. B. Individual values for each participant, boxplots and distribution plots are displayed separately for the NR and SR trial types. Baseline is the average baseline of the two sessions. Error bars represent confidence intervals.

Table 2.

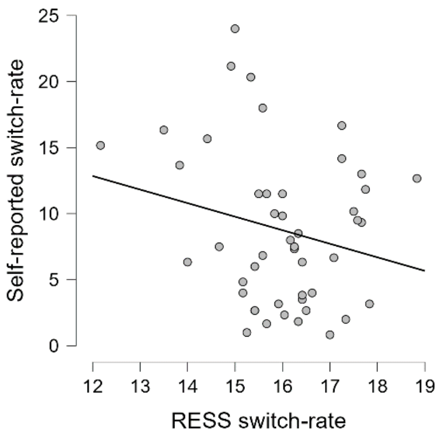
Descriptive statistics of RESS-derived switch-rate

Statistic	Baseline NR	Baseline SR	FA NR	FA SR	OM NR	OM SR
N	12	12	12	12	12	12
Mean	16.232	16.108	15.227	15.722	15.838	15.816
SE	0.836	0.357	0.546	0.315	0.318	0.334
95% CI upper	18.073	16.893	16.429	16.416	16.538	16.551
95% CI lower	14.391	15.322	14.024	15.028	15.138	15.081
STD	2.897	1.237	1.893	1.092	1.101	1.157
Minimum	11.369	14.083	11.500	13.833	13.667	13.500
Maximum	23.375	18.250	17.556	17.583	17.667	17.750

Note. N = sample size, SE = standard error, SD = standard deviation, CI = confidence interval from the mean.

Figure 7.

Correlation between RESS-derived and self-reported switch-rate



Note. There is a nonsignificant anticorrelation between the two switch-rates. Values for all conditions and participants are displayed.

3.2.2. SNR

We subsequently looked at the SNR values of the two stimulus frequencies for different trial types and conditions. It was expected that the SNR would be higher for the FA condition, since attention is expected to be strongest during FA, and prior research suggested attention enhances SNR (Briggs et al., 2013). A two-way RM ANOVA was conducted, estimating the effect of condition and trial type on SNR, collapsing across frequencies. No significant effect was found for condition $F(1.351,31.069) = 0.526$, $p = 0.526$, $\omega^2 = 0.000$; nor for trial type, $F(1,23) = 1.116$, $p = 0.302$, $\omega^2 = 0.001$, and also not for the interaction between condition and trial type, $F(2,46) = 2.571$, $p = 0.087$, $\omega^2 = 0.010$. SNR happened to vary quite a lot between participants, and was in general very low (Figure 8, Table 3).

Table 3.

Descriptive statistics of SNR

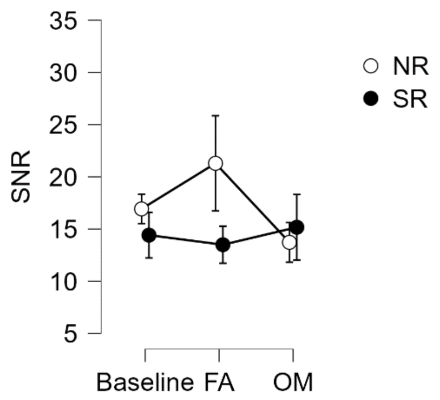
Statistic	Baseline NR	Baseline SR	FA NR	FA SR	OM NR	OM SR
N	48	48	24	24	24	24
Mean	14.303	13.096	21.295	13.504	13.732	15.175
SE	2.236	1.326	6.068	2.177	3.001	3.721
95% CI upper	18.801	15.763	33.847	18.008	19.939	22.873
95% CI lower	9.805	10.428	8.743	9.001	7.525	7.477
SD	15.490	9.188	29.725	10.665	14.699	18.230
Minimum	0.299	2.498	0.170	0.133	0.290	1.360
Maximum	69.106	42.030	135.448	38.083	55.968	85.181

Note. N = sample size, SE = standard error, SD = standard deviation, CI = confidence interval from the mean.

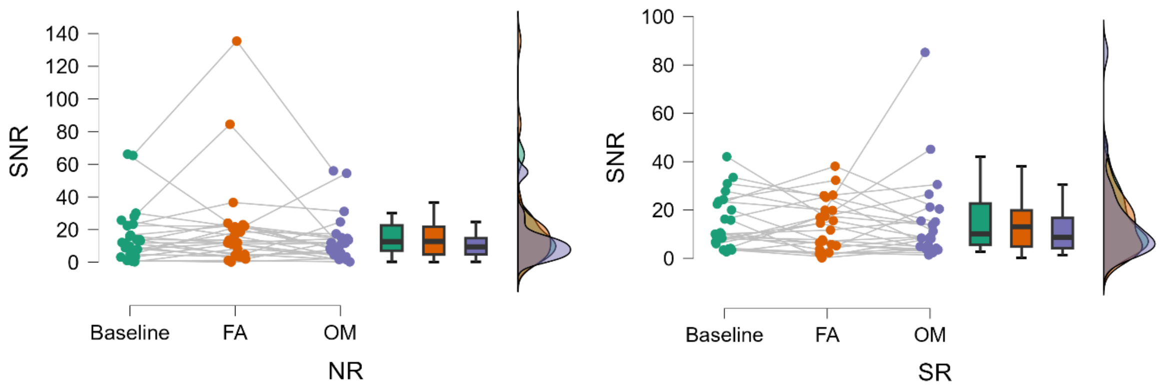
Figure 8.

SNR across conditions and trial types

A. Descriptive plot SNR



B. Raincloud plots SNR for no-report and self-report trials



Note. SNR across conditions and trial types, together for both frequencies. Baseline is the average baseline of the two sessions. A. No significant differences can be observed. Error bars represent standard error. B. Individual values for each participant, boxplots and distribution plots are displayed. The slightly increased value for FA in the NR condition was driven by two participants. Error bars represent confidence intervals.

3.3. Questionnaire Results

3.3.1. Comparing Baselines

Baselines were compared for the relevant questionnaire items assessing perception of the dominant and the mixed percept. These were question 13, 16, 17, 19, 20, 25, 28 (see

Appendix). For this, repeated measures ANOVA were conducted, to compare the effect of the two baseline conditions on percept durations and questionnaire scores. Baselines were not different for any item and all statistical tests showed small or very small effect sizes (question 13 (assessing maximum dominance duration), $F(1,11) = 2.882$, $p = 0.118$, $\omega^2 = 0.007$; question 16 (assessing average dominance duration), $F(1,9) = 4.203$, $p = 0.071$, $\omega^2 = 0.027$; question 17 (assessing the ratio of dominant and mixed percepts), $F(1,11) = 0.148$, $p = 0.708$, $\omega^2 = 0.000$; question 19 (assessing maximum duration of the mixed percept), $F(1,11) = 0.228$, $p = 0.643$, $\omega^2 = 0.000$; question 20 (assessing average duration of the mixed percept), $F(1,10) = 1.957$, $p = 0.192$, $\omega^2 = 0.020$; question 25 (assessing instability of the percept), $F(1,11) = 0.199$, $p = 0.664$, $\omega^2 = 0.000$; and question 28 (assessing control over perceptual transformation of the checkerboard pattern), $F(1,11) = 1.657$, $p = 0.224$, $\omega^2 = 0.018$). Thereafter, we computed the average of the baseline values for each trial and used this to compare to the values for the FA and OM conditions in the subsequent statistical tests.

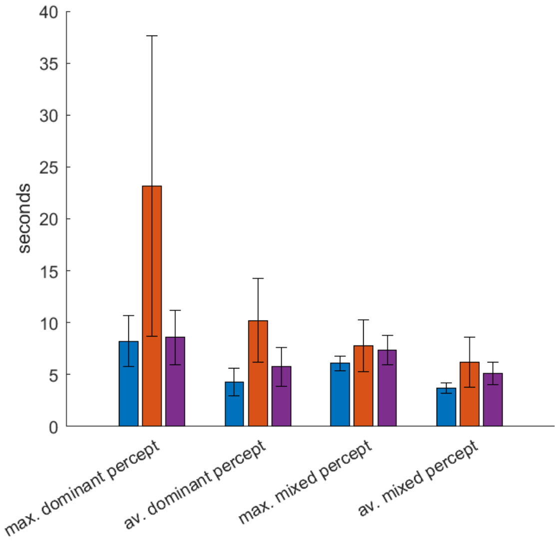
3.3.2. Perception of the Dominant Percept

In order to test whether experienced meditators can modulate perceptual dominance, an RM ANOVA was computed for question 13, 16, 17 and 28, assessing the effect of condition on the percept durations and questionnaire scores. α was adjusted to 0.0125 to correct for multiple comparisons. Bar charts with mean results of these items are shown in Figure 9 and descriptive statistics can be found in Table 6-9. There were no significant differences between conditions and effect sizes were small for maximum dominance duration, $F(1.004, 11.047) = 1.421$, $p = 0.258$, $\omega^2 = 0.016$; average dominance duration, $F(1.056, 9.508) = 3.137$, $p = 0.107$, $\omega^2 = 0.049$; and the item measuring the ratio of dominant to mixed perception, $F(1.452, 15.969) = 1.677$, $p = 0.219$, $\omega^2 = 0.035$. In line with our expectations, the RM ANOVA for question 28, assessing if participants felt to be in control of the transformations of the checkerboard pattern, showed a significant difference between conditions and a large effect size, F(2,22) = 10.048, $p < 0.001$, $\omega^2 = 0.276$. More specifically, post-hoc tests showed that participants felt more in control during the FA condition, compared to OM, t = 4.239, $p < 0.001$, and baseline, t = 3.383, p = 0.005. No significant differences were found between OM and baseline, t = 0.856, p = 0.401.

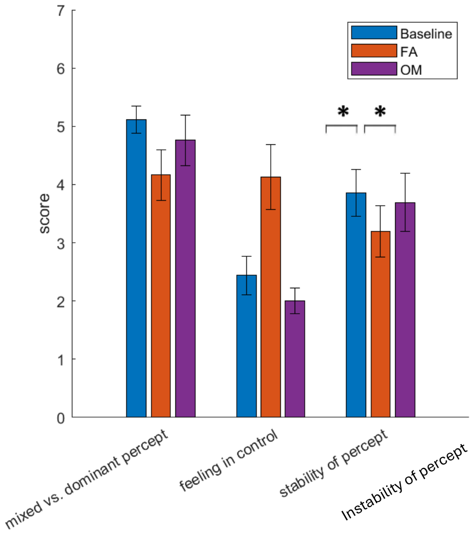
Figure 9.

Means of percept durations and other visual items

A. Mean percept durations



B. Means for perception of the BR stimuli



Note. A. Although not statistically significant, FA seems to be higher for the dominance durations, compared to OM and baseline. B. Items assessed whether participants saw mostly mixed (7) or dominant (1) percepts; to what extent they felt in control of the transformations of the stimuli (with higher scores corresponding to feeling more in control); and the instability of the percept (with higher scores signifying more instability). Participants felt significantly more in control during the FA condition, compared to OM and baseline. Scores were given on a 7-point Likert-scale. Error bars represent standard error. Asterisks indicate significant differences. Max. = maximum, av. = average

Table 6.

Descriptive statistics of average dominance duration

Statistic	Baseline	FA	OM
N	12	11	11
Mean	4.604	10.227	5.773
SE	1.305	3.996	1.875
95% CI upper	7.476	19.131	9.950
95% CI lower	1.733	1.323	1.595
SD	4.519	13.254	6.218
Minimum	1.250	1.500	1.000
Maximum	15.000	45.000	20.000

Note. N = sample size, SE = standard error, SD = standard deviation, CI = confidence interval from the mean.

Table 7.

Descriptive statistics of maximum dominance duration

Statistic	Baseline	FA	OM
N	12	12	12
Mean	8.208	23.167	8.583
SE	2.441	14.453	2.630
95% CI upper	13.582	54.977	14.372
95% CI lower	2.835	-8.643	2.795
SD	8.457	50.065	9.110
Minimum	2.500	1.000	2.000
Maximum	30.000	180.000	30.000

Note. N = sample size, SE = standard error, SD = standard deviation, CI = confidence interval from the mean.

Table 8.

Descriptive statistics of mixed vs. dominant occurrence

Statistic	Baseline	FA	OM
N	12	12	12
Mean	5.112	4.167	4.758
SE	0.230	0.433	0.435
95% CI upper	5.619	5.120	5.716
95% CI lower	4.606	3.213	3.801
SD	0.797	1.501	1.507

Note. N = sample size, SE = standard error, SD = standard deviation, CI = confidence interval from the mean.

Table 9.

Descriptive statistics of control over perceptual transformation

Statistic	Baseline	FA	OM
N	12	12	12
Mean	2.438	4.133	2.008
SE	0.336	0.579	0.220
95% CI upper	3.177	5.407	2.493
95% CI lower	1.698	2.860	1.524
SD	1.164	2.004	0.762

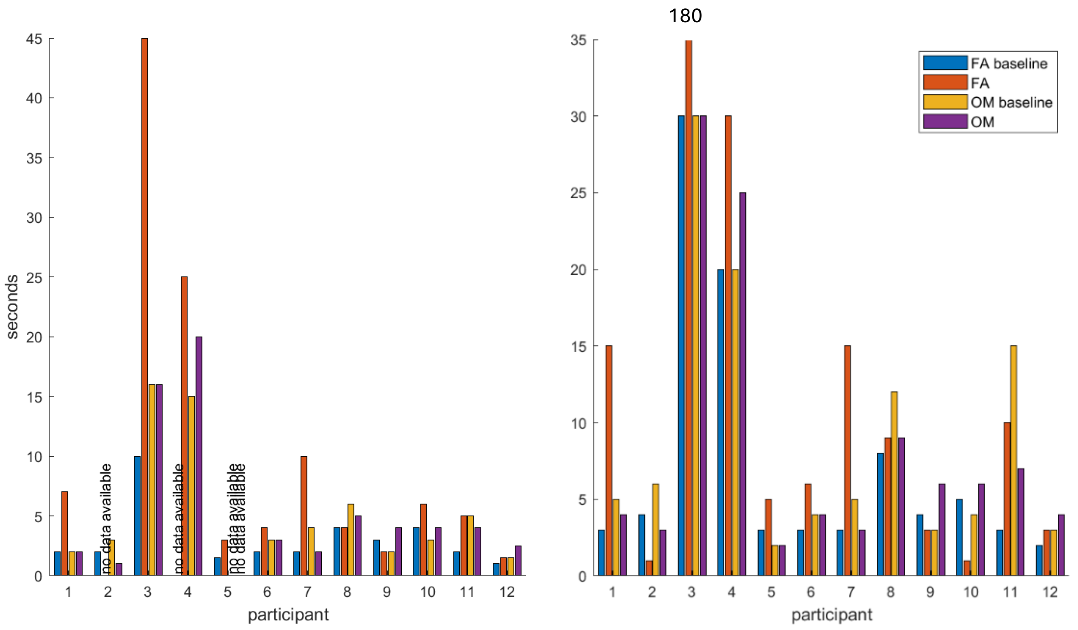
Note. N = sample size, SE = standard error, SD = standard deviation, CI = confidence interval from the mean.

There is a lot of inter-individual variability in percept durations, especially in the average and maximum dominance duration (Figure 10). When observing this figure, it becomes clear that there were a few participants that reported exceptionally long dominance durations, especially during the FA condition. These were participants 3 and 4, and to a lesser degree participant 1 and 7. Particularly striking was the maximum dominance duration of participant 3 in the FA condition, who reported to see a dominant percept for 3 minutes long (the duration of a complete trial).

Figure 10.

Dominance duration for individual participants

A. Average dominance duration B. Maximum dominance duration (zoomed-in)



Note. There is a lot of variation between participants in both average and maximum dominance duration, with a few participant reporting exceptionally long percept durations. A. Unfortunately, some values are missing, because they were not filled in by the participant. B. The bar chart is zoomed in because participant 3 reported a duration of 180 seconds for the FA condition, which would make all other values indistinct if shown fully.

3.3.3. Perception of the Mixed Percept

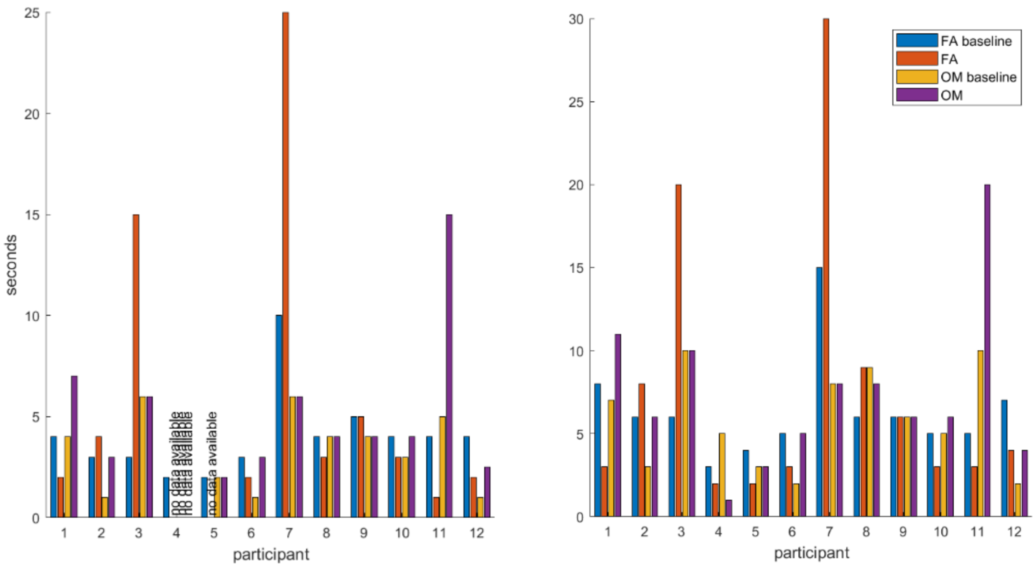
In order to investigate whether participants see mixed percepts more often and for a longer duration during OM meditation, the items about the maximum and average duration of the mixed percept were used, as well as the item about the instability of the checkerboard pattern (question 19, 20, 25, respectively). In the previous section, a statistical test was already performed on the item assessing whether the mixed or the dominant percept was seen mostly (question 13), and these results were also used to test the current hypothesis. Bar charts with mean results of these items are shown in Figure 9. The descriptive statistics for these items can be found in Table 8, 10, 11 and 12. α was again adjusted to 0.0125 to correct for multiple comparisons.

RM ANOVAs revealed nonsignificant very small effects of condition on maximum mixed percept duration, $F(1.273, 13.998) = 0.360$, $p = 0.609$, $\omega^2 = 0.000$; average mixed percept duration, $F(1.230, 11.068) = 0.622$, $p = 0.479$, $\omega^2 = 0.000$; and instability of the perceived checkerboard pattern, $F(2,22) = 0.634$, $p = 0.540$, $\omega^2 = 0.000$. Individual results of average and maximum mixed percept duration are displayed in Figure 11. Participant 3 and 7 reported prolonged mixed percept durations, especially in the FA condition, and participant 11 reported prolonged mixed percept duration in the OM condition.

Figure 11.

Mixed percept duration for individual participants

A. Average mixed percept duration B. Maximum mixed percept duration



Note. Participant 3, 7 and 11 report exceptionally long mixed percept durations. A. Here too, quite some values are missing.

Table 10.

Descriptive statistics of average mixed percept duration

Statistic	Baseline	FA	OM
N	12	10	11
Mean	3.625	6.200	5.136
SE	0.504	2.444	1.096
95% CI upper	4.735	11.729	7.578
95% CI lower	2.515	0.671	2.695
SD	1.747	7.729	3.634
Minimum	2.000	1.000	2.000
Maximum	8.000	25.000	15.000

Note. N = sample size, SE = standard error, SD = standard deviation, CI = confidence interval from the mean.

Table 11.

Descriptive statistics of maximum mixed percept duration

Statistic	Baseline	FA	OM
N	12	12	12
Mean	6.083	7.750	7.333
SE	0.690	2.493	1.411
95% CI upper	7.603	13.237	10.438
95% CI lower	4.564	2.263	4.229
SD	2.392	8.635	4.887
Minimum	3.500	2.000	1.000
Maximum	11.500	30.000	20.000

Note. N = sample size, SE = standard error, SD = standard deviation, CI = confidence interval from the mean.

Table 12.

Descriptive statistics of instability of the percept

Statistic	Baseline	FA	OM
N	12	12	12
Mean	3.854	3.192	3.692
SE	0.404	0.460	0.499
95% CI upper	4.744	4.203	4.791
95% CI lower	2.964	2.180	2.592
SD	1.400	1.592	1.730

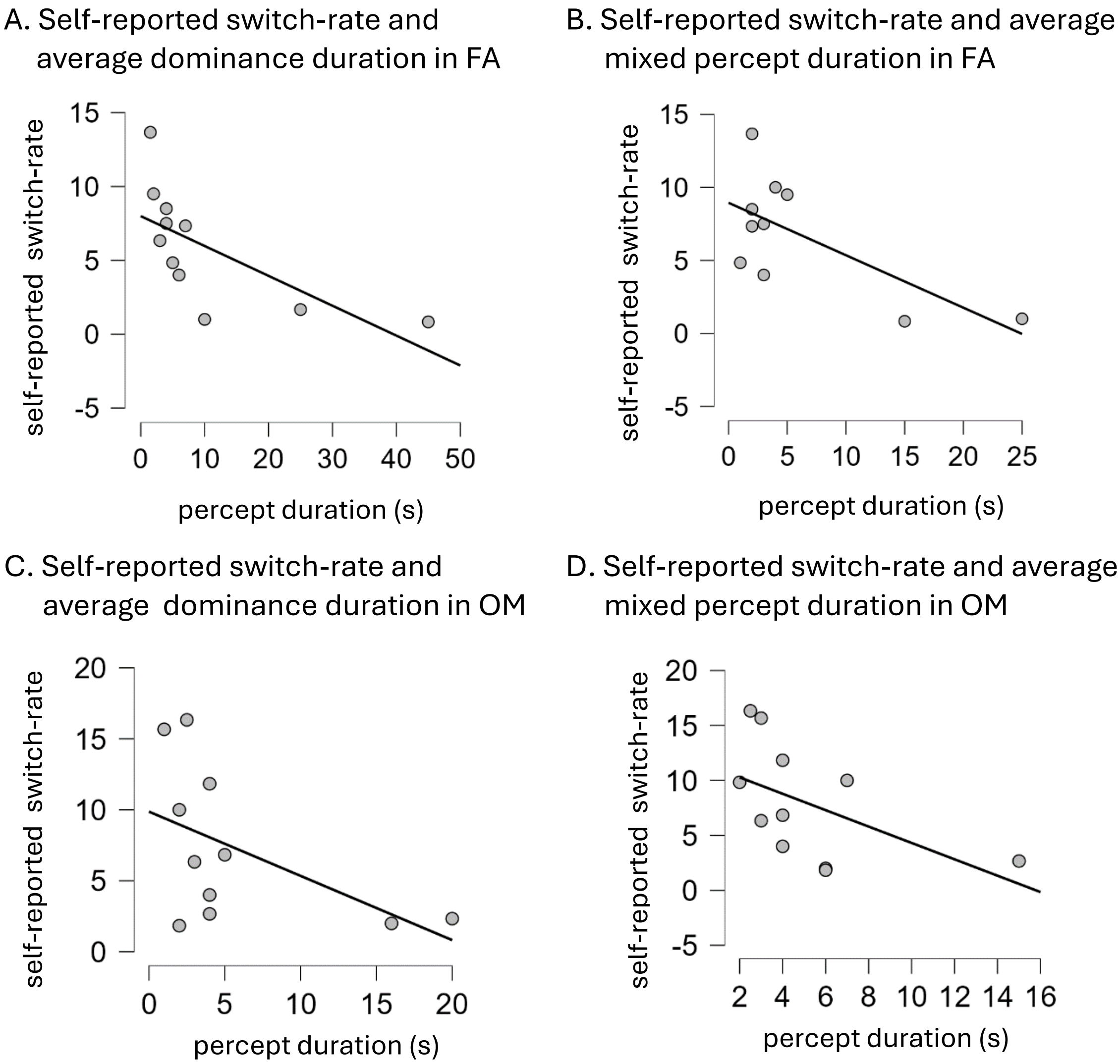
Note. N = sample size, SE = standard error, SD = standard deviation, CI = confidence interval from the mean.

3.4. Relating Dominant and Mixed Percept Durations to Self-Reported Switch-Rate

Next, it was verified whether the decrease in self-reported switch-rate in the meditation conditions is due to increases in dominance duration or mixed percept duration, by correlating switch-rate with percept duration (Figure 12). For the FA condition, Spearman's rank correlation revealed a strong and highly significant anticorrelation between self-reported switch-rate and average dominance duration, $\rho(9) = -0.888$, $p < 0.001$, but not for average mixed percept duration, $\rho(8) = -0.332$, $p = 0.348$, exactly as expected. For the OM condition, Spearman's rank correlation showed a marginally significant anticorrelation for average mixed percept duration $\rho(9) = -0.571$, $p < 0.066$, and no significant correlation for average dominance duration, $\rho(9) = -0.437$, $p < 0.179$, in line with our expectations.

Figure 12.

Correlations between self-reported switch-rate and percept durations in FA and OM



Note. All plots show negative correlations between self-reported switch-rate and average percept durations. A. A strong anticorrelation was present for self-reported switch-rate with dominance duration in FA. B. No significant correlation is found between self-reported switch-rate and mixed percept duration in FA. C. No significant correlation is found between self-reported switch-rate and dominance duration in OM. D. There is a strong and marginally significant anticorrelation between self-reported switch-rate and mixed percept duration in OM.

3.5. Controlling Results

3.5.1. Quality of the Meditative State

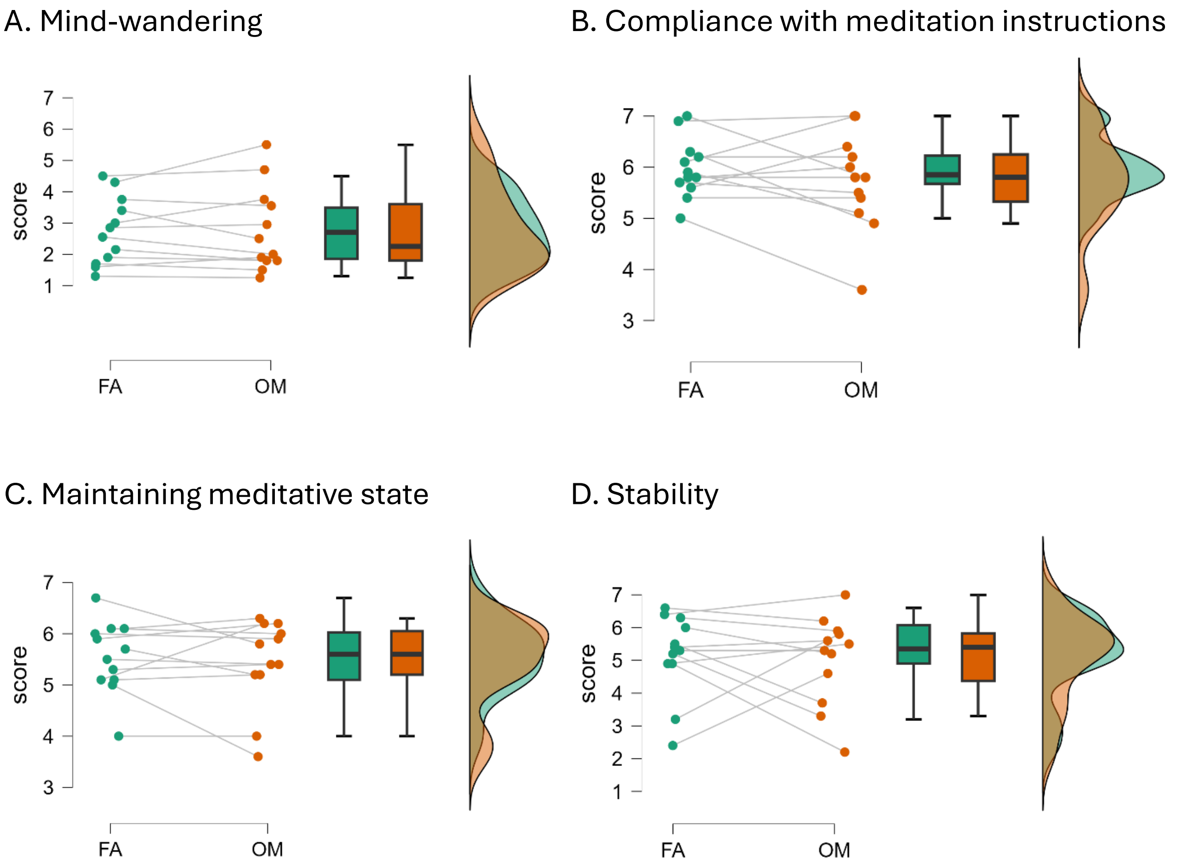
We then assessed the quality of the meditative state during the experimental conditions. To do so, we first needed to establish that participants were in a meditative state during the meditation conditions, using questionnaire items on mind-wandering (question 2 and 10); compliance with meditation instructions (question 32); maintenance of meditative state while performing the task (question 34); and stability of experience (question 5). Visual examination of scores (displayed in Figure 13) suggests that participants did in fact enter a meditative state. Most participants had low to medium scores on mind-wandering. Participants generally scored high for following the meditation instructions and maintaining a meditative state during the rivalry task. Most participants scored high on stability, with a few exceptions.

Secondly, it was examined if participants were actually in a focussed attention state in the FA condition, and in an open awareness state during the OM condition. This was evaluated by how their scores on object orientation (question 1 and 3), aperture (question 4 and 6) and meta-awareness (question 12) differed between these two conditions, as these are the dimensions on which these two styles of meditation differ most strongly (Lutz et al., 2015). For this, three repeated measures ANOVAs were conducted with condition as a factor and FA and OM as the two levels of that factor (Figure 14). As three statistical tests are used to assess if participants were in the desired meditation state, a Bonferroni corrected α of 0.05 / 3 = 0.0167 was used to correct for multiple comparisons.

In line with our expectations, object orientation was found to be significantly higher for FA compared to OM, $F(1,11) = 10.733$, $p < 0.001$, $\omega^2 = 0.379$, and aperture was significantly higher for OM compared to FA, $F(1,11) = 11.865$, $p = 0.005$, $\omega^2 = 0.369$; and both had large effect sizes. However, there was no significant difference between conditions for meta-awareness and the effect size was very small, $F(1,11) = 1.065$, $p = 0.324$, $\omega^2 = 0.003$, although the results go into the expected direction.

Figure 13.

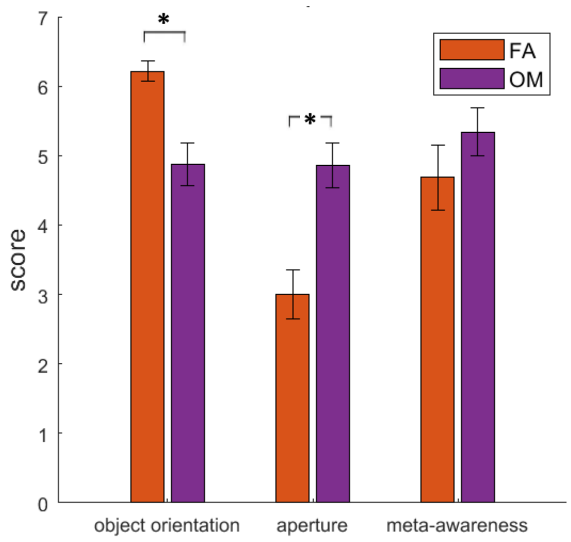
Quality of the meditative state



Note. Individual values for each participant, boxplots and distribution plots are displayed for the FA and OM conditions. Scores are on a 7-point Likert scale. Error bars represent confidence intervals. Items pertained to whether: A. participants were mind-wandering during the task; B. participants succeeded in following the meditation instructions while performing the task; C. participants managed to maintain a meditative state during the task; D. participants' meditative state was stable.

Figure 14.

PMMQ means for meditation conditions



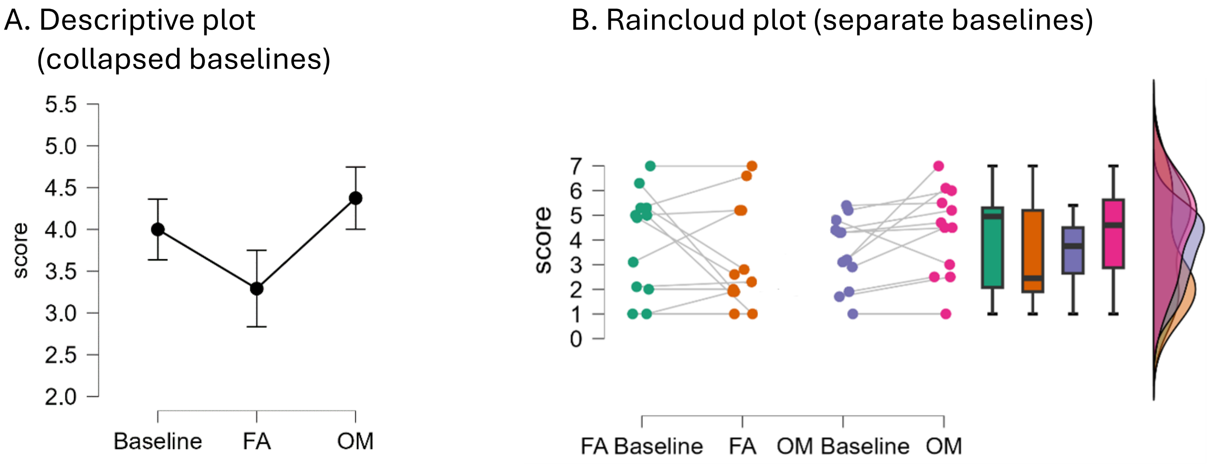
Note. Object orientation is significantly higher in FA, whereas aperture is significantly higher in OM. Meta-awareness is higher in OM, although this difference is not significant. Scores are on a 7-point Likert scale. All differences are in the expected direction. Asterisks indicate significant differences. Error bars represent standard errors.

5.5.2. Sleepiness

Furthermore, it needed to be checked if participants were not too sleepy (assessed with question 9) while viewing the BR stimuli, as sleepiness can reduce attention and the meditative state. Besides, as the meditation condition always came after the baseline condition, it could have been the case that participants were more sleepy during the meditation condition, and we need to ensure this is not the case. A repeated measures ANOVA revealed no significant difference in sleepiness between baseline, FA and OM and the effect size was small, $F(2,22) = 1.894$, $p = 0.174$, $\omega^2 = 0.023$. However, quite some participants have high values for sleepiness, especially in the OM condition, which is rather concerning (Figure 15).

Figure 15.

Sleepiness across conditions



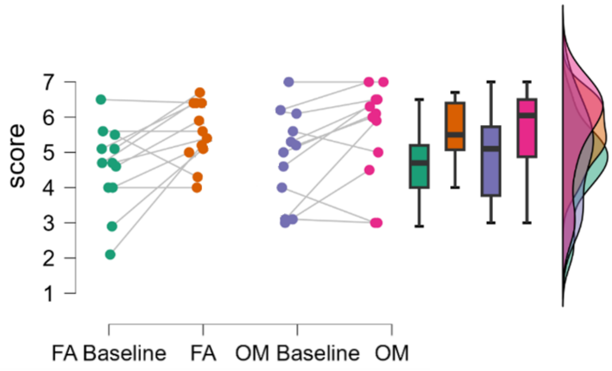
Note. Scores were measured on a 7-point Likert scale. Overall, sleepiness was quite high. A. No significant difference in sleepiness can be observed across conditions. Error bars represent standard errors. B. Changes in sleepiness from baseline to meditation condition within one session are displayed for individual participants, next to boxplots and distribution plots. A number of participants reported an decrease in sleepiness from baseline to FA and an increase from baseline to OM. One should note that the reported statistical analysis does not pertain to this subfigure. Error bars represent confidence intervals.

3.5.3. Baseline Mental State

As experienced meditators tend to have enhanced trait mindfulness (Wheeler et al., 2017), we had to verify if participants were not in a meditative state during baseline conditions, otherwise the baselines cannot be considered to be true baselines. To this end, a raincloud plot of the item assessing to what extent the participant felt like being in a meditative state (question 2) was visually examined (Figure 16). While most participants felt more like being in a meditative state during the meditation conditions compared to baseline, there were some cases where baseline scores were equal to or even greater than meditation conditions, and baseline scores in general were already quite high.

Figure 16.

Meditative state from baseline to meditation

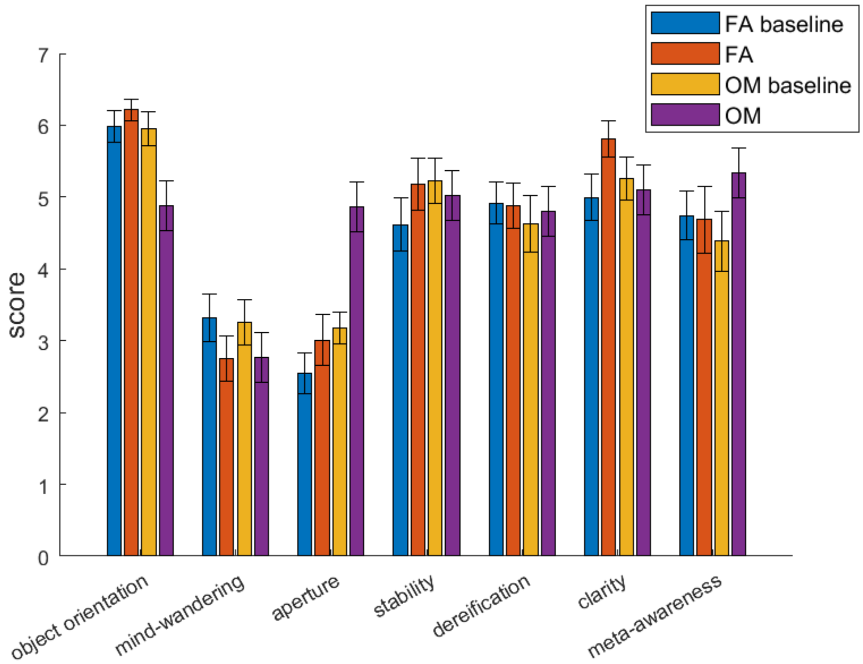


Note. Changes in meditative state from baseline to meditation condition within one session are displayed for individual participants, next to boxplots and distribution plots. Scores were measured on a 7-point Likert scale. Participants were more in a meditative state during the FA and OM condition, but many participants also reported to be in a state resembling meditation during the baselines. Error bars represent confidence intervals.

Next, in order to ensure that baseline mental state was not too similar to the mental state during (one of the) meditation conditions, the mean scores of the PMMQ dimensions (see Figure 17) were also object to visual examination. Overall, differences between meditation conditions and baselines are quite small, apart from the difference between OM and its baseline for object-orientation, aperture and meta-awareness, as was reported earlier. Note that 'effort' is not part of the presented PMMQ dimensions, as this item was only assessed during the meditation conditions.

Figure 17.

PMMQ mean values across conditions



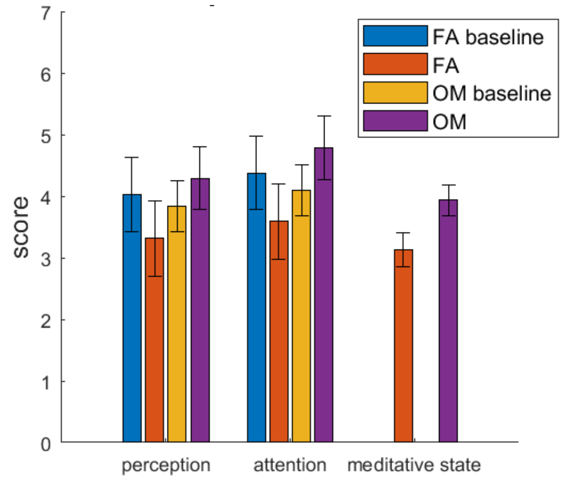
Note. Means for the PMMQ dimensions are displayed for the two baseline conditions, as well as the FA and OM condition. Overall, scores are fairly similar between conditions, apart from the scores for OM condition on object orientation, aperture and meta awareness, and the difference between meditation and baseline conditions for mind-wandering. Error bars represent standard errors.

3.5.4. Button Press Interference

Furthermore, we investigated if the button presses during self-report trials interfere with participant's attention, perception of the images and meditative state during the meditation conditions. For this, mean scores on question 29, 30 and 35 respectively were visually examined (Figure 18). It can be observed that the self-report task interfered considerably with participants' perception, attention and meditative state in all conditions, and seems to be more pronounced in the OM condition and relatively weaker in the FA condition.

Figure 18.

Button press interference with perception, attention and the meditative state



Note. Means of button press interferences with perception, attention and the meditative state across conditions are displayed. Button presses interfered considerably for all three variables. The effect seems to be a bit stronger for the OM condition and weaker for the FA condition. As button presses could interfere with the meditative state only during the meditation conditions, this question was not asked for baseline conditions. Error bars represent the standard error.

3.6. Meditation Experience

As mentioned before, there were quite some differences between participants in how much meditation experience they had. It is plausible that more experienced participants could have entered deeper meditative states and consequently experienced less switches and longer percept durations compared to less experienced meditators. In order to investigate this, participants were divided into two groups with different levels of meditation experience, namely intermediate and expert, depending on a selection of answers they gave on the intake survey. The answers pertained to the number of years in which they practiced meditation; how often they meditated; the estimated number of hours spent meditating and the total number of days spent on retreat. An overview of the answers on these four questions of each participant can be found in Table 13.

Table 13.

Meditation experience of individual participants

Meditation experience	Participant number	Number of years practicing meditation	Meditation frequency	Estimated total number of hours spent meditating	Total number of days spent on retreat
Expert	1	24 years	daily	1500?*	1000
	3	40 years	daily	17500**	7500**
	7	23 years	daily	7000	14
	9	18 years	daily	10000	1400
	11	around 25 years	almost daily	1520*	505
Intermediate	2	6 years	Changes from daily to once or twice per week; but preferably a short time daily.	351	42
	4	More than 8 years	2-3 times per week	100*	No idea, 100
	5	18 years	Weekly	4000	150
	6	5 years	for 2 hours daily (since this year), before sporadically	-	35
	8	5 years	daily	1000	35
	10	2 years	daily 45 minutes	540	14
	12	8 years	daily	3500	63

Note. *These answer are likely to be unrealistic and the actual values probably lie much higher.

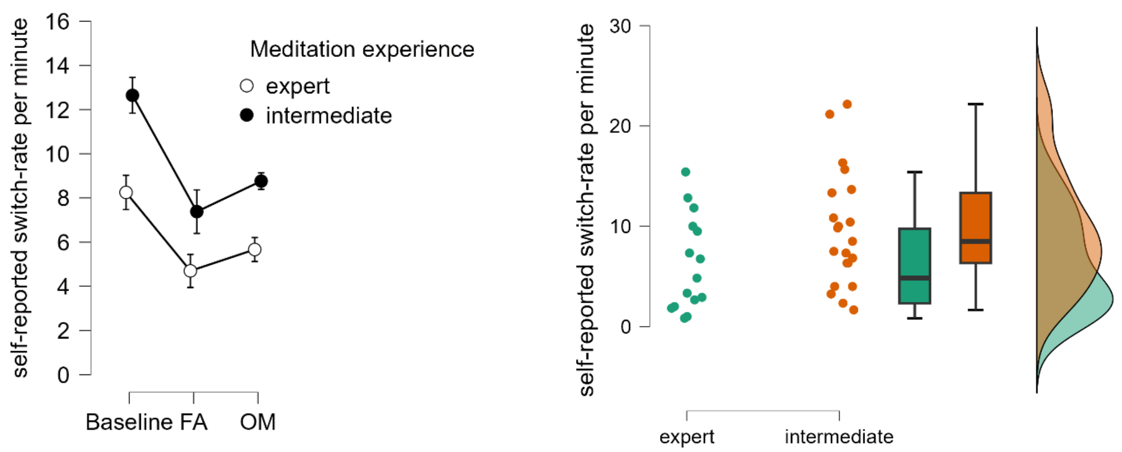
**Either of these answers is inaccurate, because taken together it would mean that this participant spent less than two hours maximum per day meditating on retreats.

A repeated measures ANOVA was used to estimate the effect of meditation experience on self-reported switch-rate, which turned out to be insignificant, $F(1,10) = 1.302$, $p = 0.208$, $\omega^2 = 0.014$. There was also no significant interaction between condition and meditation experience, $F(2,20) = 0.676$, $p = 0.520$, $\omega^2 = 0.000$. Nonetheless, from the plots (Figure 19), it can be observed that on average, switch-rate is lower for participants with the most meditation experience, compared to people with less experience.

Figure 19.

Self-reported switch-rate in participants with different levels of meditation experience

A. Descriptive plot *B. Raincloud plot*



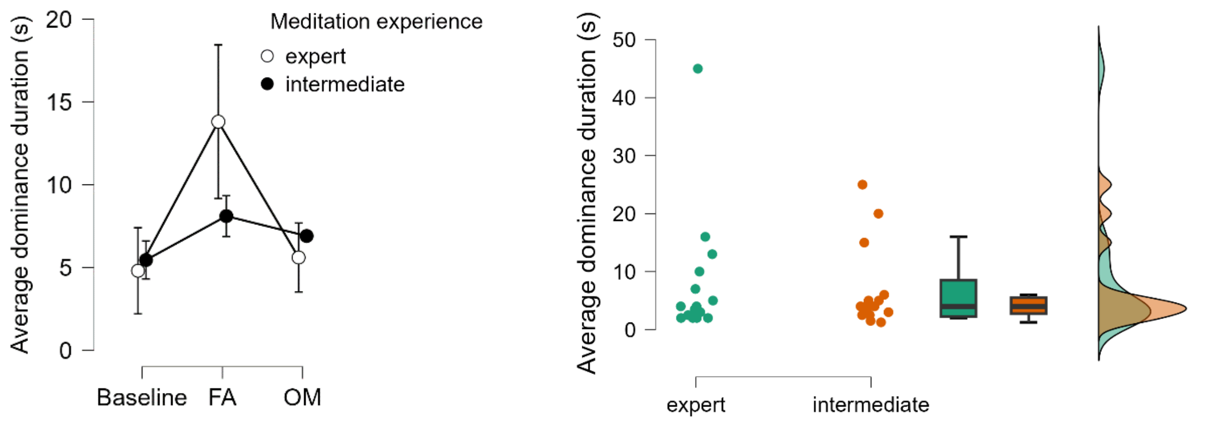
Note. A. Expert meditators had lower self-reported switch-rate on average for each condition, although this effect was not significant. Baseline is the average baseline of the two sessions. Error bars represent standard errors. B. Individual values for each participant, boxplots and distribution plots are displayed. Self-reported switch-rate (across conditions) still varied considerably between participants within the same level of meditation experience. Error bars represent confidence intervals.

Furthermore, a repeated measures ANOVA (Figure 20) revealed that there was an insignificant small effect of meditation experience on average dominance duration, $F(1,8) = 0.055$, $p = 0.821$, $\omega^2 = 0.000$. There was also no significant interaction effect between average condition and meditation experience, $F(1.055,8.444) = 1.265$, $p = 0.295$, $\omega^2 = 0.006$.

Figure 20.

Average dominance duration in participants with different levels of meditation experience.

A. Descriptive plot B. Raincloud plot



Note. A. No significant differences in meditation experience can be observed. Baseline is the average baseline of the two sessions. Error bars represent standard errors. B. Individual values for each participant, boxplots and distribution plots are displayed. The increase in average dominance duration of the FA condition in expert meditators is driven by a single participant. Error bars represent confidence intervals.

4. Discussion

This study investigated the effects of focussed attention and open monitoring meditation on the dynamics of binocular rivalry in experienced meditators. Switches between BR stimuli were measured using two complementary approaches: button presses indicating which of the two stimuli was perceived, and steady-state visual evoked potentials (SSVEPs) computed from the neural data. The neural data was filtered using RESS in order extract SSVEPs in the flicker frequency corresponding to each stimulus, so as to enable perceptual tracking (Cohen & Gulbinaite, 2017). In addition to behavioral and neural measures, a questionnaire was used to assess percept durations, perceptual content, meditative state and task performance.

4.1. FA Meditation Decreases Self-Reported Switch-Rate and Prolongs Dominance Duration, Although This Is not Reflected in the RESS-Derived Switch-Rate

In line with our hypothesis, we found a significant decrease in self-reported switch-rate for the FA condition compared to baseline. Furthermore, the questionnaire data revealed that maximum and average dominance duration were increased for the FA condition compared to OM and baseline, although these results did not reach significance, probably due to small sample size. These findings are in line with those of Carter and colleagues (2005), who also found reduced switch-rate and enhanced dominance duration in experienced meditators, as indicated by their self-reports after the task. However, our findings go beyond those of Carter et al., (2005), as we measured switch-rate during the task. Besides, participants reported to feel significantly more in control of the transformations of the percepts during the FA condition, compared to OM and baseline. Together, these findings lend credence to our idea from predictive processing that FA meditation upweights the incoming signals from the dominant stimulus and weakens the incoming signals of the suppressed stimulus.

The correlations between self-reported switch-rate and percept durations show that the decrease in self-reported switch-rate in the FA condition is related to an increase in dominance duration, as expected. However, some participants also reported long mixed percept durations for the FA condition. This can be accounted for if FA meditation also slows down the transition from one percept to the other, as one continues to hold on to the initially dominant percept, or if participants inadvertently held on to the mixed percepts, too.

Contrary to what was expected, RESS-derived switch-rates did not differ between FA and baseline for both trial types. Remarkably, RESS-derived switch-rate even anticorrelated (although nonsignificantly, see Figure 7) with self-reported switch-rate across conditions, even though a positive correlation was expected, as they are in theory different methods to measure the same variable. This stands in contrast to previous studies, which found a strong positive correlation between RESS-derived switch-rate and self-reported switch-rate (Laukkonen et al., 2022; Zhang et al., 2011). Furthermore, RESS also consistently overestimates switch-rate compared to self-reported switch-rate across conditions, which was also reported in the study by Laukkonen et al. (2022), albeit to a lesser extent. Thus, not only are the RESS results not as hypothesized, the way RESS-derived switch-rate is currently calculated in our research is potentially inaccurate and invalid.

Nonetheless, when examining the relation between the two measures of switch-rate more closely, it becomes clear that the two seem merely unrelated and that the anticorrelation is most likely accidental. First of all, the correlation plot (Figure 7) shows rather dispersed dots, which indicates that there are many trials for which the anticorrelation does not hold (which is also why it is insignificant). Secondly, it is likely that the anticorrelation is driven by a few trials with very low self-reported switch-rate for which RESS-derived switch-rate is average.

One potential explanation for this inaccuracy could be that the way in which switch-rate was derived by RESS cannot be used for experienced meditators. More specifically, meditation might only have an effect higher up in the neural hierarchy, such that SSVEPs that would normally indicate perceptual switches persist at the lower levels, even though no switches occur at the conscious level. In other words, RESS may reflect bottom-up signals more than the top-down signals generated by meditation. It has indeed been shown that SSVEPs capture very early visual cortical responses (Sanchez-Lopez et al., 2019; Jiang et al., 2018). This could explain the disconnect between this “objective” measure and the self-reports. This is supported by our finding that RESS least aligns when self-reported switch-rates are low, which is also when the effect of meditation is strongest. Furthermore, this interference of meditation with switch-rate computation might also be present during baseline, as quite some participants reported to be in a meditative state during baseline and trait mindfulness is likely to be high in our sample. If this explanation holds, it would highlight the remarkable effects of extensive meditation practice on the brain. Yet, at present, this possibility is speculative and warrants further investigation.

Another potential explanation for our neural findings is simply that there was (almost) no effect of meditation on switch-rate, which would imply that our self-report measures are invalid. This alternative explanation is supported by our finding that many participants reported to be in a meditative state already during baseline, which resembled their meditative state during the meditation conditions (Figure 16).

4.2. OM Meditation Decreases Self-Reported, but not RESS-Derived Switch-Rate and Does not Increase Mixed Percept Duration

Self-reported switch-rate was significantly reduced for the OM condition compared to baseline, as expected. Unlike hypothesized, no significant difference in RESS-derived switch-rate was found between OM and baseline for SR as well as NR trials, again pointing to a discrepancy between the neural and behavioral data.

Furthermore, the questionnaire data showed no increase in mixed percept duration for the OM condition, contrary to what was expected. Nonetheless, the correlations between self-reported switch-rate and percept durations demonstrate that the decrease in self-reported switch-rate for the OM condition was related to increases in mixed percept duration but not to increases in dominance duration. Besides, there was no decrease in dominance duration for the OM condition and the reported stability of the percept did not differ significantly from the other conditions. Importantly, it should be kept in mind that we only expected a reduction in switch-rate for the OM condition as a result of prolonged mixed percept duration, which we failed to find. Together, these findings fail to support our initial idea that OM meditation downweighs the incoming signals of both BR stimuli to an equal degree. There are several potential explanations for this.

Firstly, for some participants, the effect of OM meditation on BR dynamics seems to be similar to that of FA meditation, although less pronounced. Enhanced awareness in combination with maintaining one's gaze at central fixation, might have resembled focussing one's attention to the stimulus too much, even if participants were not trying to hold on to the dominant percept. From Figure 14, it can indeed be seen that object orientation was still quite high in the OM condition.

Secondly, the judgemental nature of the button press task might have interfered with the participant's ability to maintain the nonjudgemental stance characteristic of OM, which prevented them from equally downweighing the incoming signals. Figure 18 indeed shows that button presses interfered considerably with OM meditation. This problem may be circumvented by utilizing adequate no-report measures, as we aimed to do with this study. Yet, we did not obtain evidence for reduced switch-rates in our neural measure during NR trials.

Thirdly, our sample might not contain sufficient expert meditators who practice OM meditation as their primary practice - we only had four, although a few other participants indicated having both FA and OM meditation as their main practices. These meditators might be able to better maintain a more nonjudgemental stance that is less like FA meditation. In fact, from Figure 11 it can be seen that participant 12, who was an expert OM meditator, indeed had prolonged mixed percept durations during the OM condition, on average lasting

15 seconds, which was much more than in the other conditions. Therefore, it is recommended to recruit more expert OM meditators for the overarching research of which this thesis is part.

A fourth possibility is that the OM condition resembled the baseline condition too much, which could account for the absence of increased mixed percept duration compared to baseline. After all, experienced meditators often have high trait mindfulness. From Figure 16 it can indeed be observed that participants did not report to be much more in a meditative state during the OM condition than during its baseline, and Figure 17 shows that the OM condition did not differ much from its baseline on most dimensions of the PMMQ. This may have also contributed to our inability to observe an effect of OM on our RESS-derived switch-rate.

4.3. Differences in Meditation Experience

The group of expert meditators seemed to have lower self-reported switch-rates and increased dominance duration during the FA condition compared to the intermediate group, although these findings were not statistically significant. Furthermore, it must be noted that each group had very low sample size and that expert meditators showed a lot of variability in their reported dominance duration for the FA condition, thus these interpretations remain very speculative. Nonetheless, these findings might indicate that having only an intermediate level meditation experience (as was classified here) may not be sufficient for the kind of abilities that the present study is looking for. On the other hand, there was still one expert meditator in our sample for which there was no effect of meditation on self-reported switch-rate and percept duration, but this was similar to Carter and colleagues (2005), who found an effect in about half of their sample.

As can be observed from Figure 10 and 11, there are considerable differences between participants in self-reported switch-rates and percept durations. In particular, there are a few participants (namely participant 1, 3, 4, 7, and 11) that have very low self-reported switch-rates and report long percept durations, on some or all conditions. One participant (participant

3) even reported to have seen a dominant percept for a full trial in the FA condition. This participant also had very low self-reported switch-rates across conditions, although their RESS-derived switch-rate were among the highest for the meditation condition, and they had rather typical SNR values. As reported in section 10 of the results, participant 1, 3, 7, and 11 were classified as expert meditators, and participant 4 was classified as a meditator with an intermediate level of experience. Participant 3, a meditation teacher, stood out as having the most meditation experience, with 40 years of practice. The findings of participant 3 are on par with the best performances of the monks from the study by Carter and colleagues (2005), who also reported to have seen a single percept for several minutes at length.

4.4. Experienced Meditators Might Be Able to Influence Switch-Rate and Dominance Duration

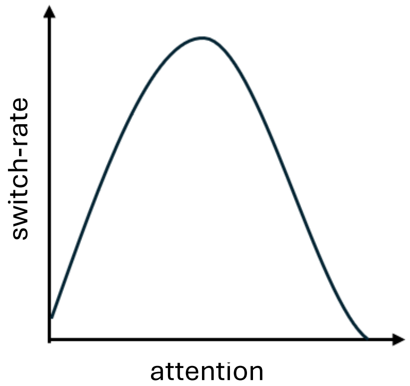
Taken together, our results remain inconclusive about the extent to which experienced meditators can influence BR perception. On the one hand, our results of self-reported switch-rate and estimates of dominance duration indicate that this influence might be quite profound. On the other hand, it should be kept in mind that our objective measure of switch-rate fails to support this claim. Nonetheless, comparing our self-report findings to other studies, meditators might be able to influence switch-rate much more than non-meditators, who can only exert limited influence (van Ee et al., 2005; Meng & Tong, 2004; Ooi & He, 1999), even after training (Lack, 1978). Even during baseline, some of our participants reported very few switches, which stands in sharp contrast with typical participants, for whom a switch takes place every few seconds (Paffen & Alais, 2011). In comparison, Zhang and colleagues (2011), who used the same stimuli and similar flicker frequencies (6.6 and 7.5 Hz) in their research on non-meditators, found a mean self-reported switch-rate of 24.5 per minute, which is much higher than the 6.26 and 8.09 switches per minute we found in the FA and OM condition, respectively, and still much higher than the 10.81 switches per minute we found during baseline. Interestingly, the self-reported switch-rate found by Zhang and colleagues (2011) is also much higher than our neurally-derived switch-rate, which ranged from 15.23-16.23 per minute on average, across conditions. Unfortunately, Zhang et al. (2011) did not report dominance duration of their objective measure of switch-rate. Thus, our neural findings may also support the idea that meditators have lower switch-rates in general, although this remains very speculative, as our RESS findings may be inaccurate and no statistical comparison was made between our findings and those of other studies.

4.5. Revisiting the Role of Attention in BR Perception

At first sight, our results that enhanced attention during meditation decreases switch-rate seem to contradict findings from dual task studies, which found that switch-rate slows down or even might cease altogether when attention is diverted away from the BR stimuli (Paffen et al, 2006; Ooi & He, 1999; Alais et al., 2010; Zhang et al., 2011). These studies claim that attention directed to the BR stimuli speeds up switching. However, these findings might be reconciled if we think of the relationship between attention and switch-rate as a curve with an inverted u-shape, with minimal attention needed for rivalry to occur, ‘ordinary’ attention (such as seen in non-meditators) directed to the stimuli increasing switch-rate, but particular strong attention such as seen in experienced meditators again reducing switch-rate (Figure 21). In other words, increased attention on the dominant percept may enhance the dominance duration of that percept, whereas decreased attention on the BR stimuli enhances mixed percept duration, both resulting in reduced switch-rate.

Figure 21.

The proposed relationship between switch-rate and attention



Note. The relationship between switch-rate and attention is proposed to have the form of an inverted u-shape. Minimal attention is needed for rivalry to occur, switch-rate increases as more attention is directed towards the stimuli, but when attention gets particularly strong, switch-rate again declines.

This could be explained through different mechanisms within the predictive processing framework. When attention is withdrawn from the stimuli, almost no weight is given to the incoming signals of either stimulus and the prior probabilities of the dominant percepts are very low, such that the likelihood of the mixed percept overrules that of the dominant percepts, and consequently, mixed percepts are seen for prolonged durations. This is essentially also what we expected to happen during OM meditation, although it happens through disengagement of attention rather than through nonjudgemental observation of the stimuli. However, there are some subtle differences between these two states pertaining to how they affect the PP mechanisms of BR. OM meditation was also thought to extinguish the hyperprior that expected the input of both eyes to be similar, which would facilitate the perception of mixed percept, which is not the case when attention is withdrawn from the stimuli.

Directing ordinary attention to the BR stimuli would then increase the prior probability of seeing a dominant percept. As detailed in the introduction, the dominant stimulus elicits a small prediction error, whereas the suppressed stimulus induces a large prediction error. In order to minimize prediction error, the suppressed stimulus becomes dominant by the mechanism of perceptual inference, and as this imbalance persists, the dominant percepts continue to alternate (Hohwy et al., 2008). Deliberately enhancing attention with the purpose of holding on to a dominant percept can in some cases already slightly diminish switch-rate by upweighting the incoming signals from the dominant stimulus, but is not sufficiently strong to continue to overrule the prediction error arising from the suppressed stimulus. This might be due to the predicting hierarchy still being in place and higher level mental actions such as thoughts still being abundant and interfering with attention. During deep states of FA meditation, in which attention is exceptionally strong, the predicting hierarchy breaks down and almost no interfering thoughts are formed, the incoming signals from the dominant stimulus are upweighted to the extent that they can overrule the prediction error from the suppressed stimulus for extended periods of time. In this way, predictive processing can unite our findings of self-reported switch-rate and dominance duration with those of earlier studies on non-meditators.

4.7. Limitations and Future Research

The possible inaccuracy of RESS-derived switch-rate is the most important limitation of the present thesis. The continuing overarching research of which this thesis is part should improve RESS-derived switch-rate, so it can be used as a no-report measure. There are several ways in which this can be attempted.

First of all, mixed percepts might have interfered with the ability of the RESS method to determine switch-rate. Zhang et al., (2011) found that the anticorrelation between the RESS signal of the two flicker frequencies falls away when mixed percepts are being perceived, yielding ambiguous input for the switch-rate calculation. It might have been the case that the RESS method falsely identified switches due to this ambiguity, especially in participants who reported frequent mixed percepts or long mixed percept durations. A solution would be to use the RESS method for determining when mixed percepts are perceived. It is known that mixed percepts produce nonlinear intermodulation frequencies (Baitch & Levi, 1988; Brown et al., 1999; Sutoyo & Srinivasan, 2009), which can be used to identify periods of mixed percept perception. In order to verify the accuracy of RESS-derived mixed percept perception, participants should also indicate when a mixed percept is being seen in the self-report task.

Secondly, switch-rate should be calculated from SSVEPs of only a few electrodes, as this was recommended by Cohen and Gulbinaite (2017). Ideally, these should be electrodes recording SSVEPs that reflect conscious perception. This might be done by selecting electrodes that may more likely include higher-order visual regions, and by discarding electrodes that are more likely recording from primary visual areas, as these are found to respond strongly to subliminal stimuli (de Heering et al., 2019). However, it should be noted that one can really not be sure where the EEG signal is coming from, and this suggestion is therefore very unsubstantiated.

Thirdly, SNR should be improved, as it was low for many trials in the present research. It is unclear why SNR was so low for some trials, but potential causes are noisy recordings, sleepiness, reduced attention, and the presence of mixed percepts, amongst other factors. Earlier studies found that SSVEPs are not present in everyone (Norcia et al., 2015; Vialatte et al., 2010), which might form an additional explanation for low SNR in some of our participants. SNR could be improved by applying stricter rules to electrode rejection and discarding trials with very low SNR. Optionally, an algorithm could be written to go over the electrodes and find the ones with the highest SNR in the regions of interest, although it should be noted that SNR might only have a small effect on the accuracy of RESS-derived switch-rate (Cohen & Gulbinaite, 2017).

Fourthly, the parameters that are used for computing switch-rate need to be optimized, without overfitting. There are several parameters that can be tweaked, such as the peak width of the Gaussian of the frequencies of interest; the distance of the neighboring frequencies from the frequencies of interest; the width of the Gaussian of those neighboring frequencies; the parameters of the Hilbert transform; and the parameters of the moving slope function that is used to determine when a switch occurs. Lastly, researchers working on the overarching study are currently training a decoder to use the RESS filtered data to determine which percept is dominant, which should improve switch-rate accuracy. This decoder might also be utilized to facilitate mixed percept identification.

A number of limitations of the present research pertain to the particularities of the study design. For instance, the experiment took place in a fixed order: the baseline always preceded the meditation condition and the NR trials occurred before the SR trials. This makes that participants knew better what was expected from them after the first baseline condition, which might have influenced their perception, ability to do the button press task, or questionnaire answers. However, as mentioned in the methods section, it was necessary to have the baseline before the meditation condition in order to avoid any leakage of the meditative state into the baseline, and it is easier for participants to follow our instructions for the SR trials if they first get acquainted with the task in the NR trials.

Moreover, participants reported to be quite sleepy while watching the BR stimuli across conditions (Figure 15). Sleepiness was nonsignificantly enhanced during OM and nonsignificantly reduced during FA, compared to baseline, indicating that the fact that the meditation condition always occurred after the baseline did fortunately not result in enhanced sleepiness during the second half of the session overall. The nature of the two meditation styles might explain this difference in sleepiness, as the sharp focus typical of FA meditation might have energized participants, whereas the more relaxed state of OM could have made participants sleepier. The latter also could have interfered with reporting switch-rate and might have contributed to the lowered switch-rate in the OM condition in some participants.

Furthermore, most participants reported considerable interference of button pressing with perception, attention and their meditative state. In turn, the button presses might not be a very reliable measure of switch-rate, as participants might have missed some switches or were unsure of whether a switch took place. Some participants indeed reported to have difficulty with the button press task. This highlights the importance of making use of a no-report paradigm for research on binocular rivalry and in contemplative neuroscience more in general.

Enhanced demand characteristics are a limitation particular to all studies on experienced meditators: participants expect meditation to have an effect on their experience, even without being aware of this expectation. We attempted to deal with this by comparing two different meditation styles for which we initially had different expectations, as demand characteristics would apply to both meditation styles. Nonetheless, demand characteristics might have been particularly enhanced during the FA condition, because the expected effect of meditation on perception was more explicit in the instructions, as participants were asked to hold on to the dominant percept by using FA meditation, whereas no particular change in perception could be expected from the instructions of the OM condition. It is possible that this difference in demand characteristics played a role in the enhanced effects of meditation seen in the FA condition, compared to OM.

On another note, the instruction given in the FA condition was perhaps asynchronous with the practice of FA, as FA usually does not insist on holding on to the object of meditation. Rather, FA practices aim to observe how the object changes from moment to moment without clinging to how they initially appear to be, which is facilitated by sharp and stable attention.

Another limitation was that questionnaire reports could be biased or inaccurate, as they could be subject to failures of introspection (Carruthers, 2007; Johansson et al., 2006) or questions might be misunderstood. Furthermore, participants reported that it was quite difficult to estimate percept durations, so these should be interpreted with caution. The question of whether participants felt to be in control could be particularly subject to demand characteristics in the FA condition, as the instructions asked the participants to control their perception. Some questions from the intake survey that were used to classify the level of meditation experience might also have been difficult to answer, especially the estimated hours of meditation experience, so it remains unclear how much experience our participants exactly had.

Some participants reported (extremely) long percept durations and few switches already during the baseline condition. This questions if the baseline condition can even be regarded as a baseline, as the ‘baseline’ mental state of experienced meditators might be characterized by heightened mindfulness by default. One might think that the present study would have benefited from a control group, so conditions could be compared between groups. However, we deliberately chose to use a within-subject design, because it is virtually impossible to find a matching control group for experienced meditators, as they differ in many respects from non-meditators.

An additional limitation is low sample size, which is a likely reason for why almost no significant results were found for the questionnaire data and the differences in meditation experience. Fortunately, more data will be collected for the overarching study that this thesis is part of.

Future research investigating the effect of meditation on BR should recruit more experienced meditators, as no differences between meditation and baseline could be observed in any of the participants with only an intermediate level of meditation experience in the present study. It would be especially interesting to investigate BR in expert OM meditators, in order to see if our initial hypotheses about the effect of OM meditation on BR dynamics still holds.

5. Conclusion

The present thesis investigated the effects of focussed attention and open monitoring meditation on binocular rivalry dynamics in experienced meditators. Building on the work of Carter et al. (2005) and Laukkonen et al. (2022), we made use of SSVEPs and self-reports to measure switches between dominant percepts in a well-controlled setting. We found that self-reported switch-rate was diminished in both meditation conditions compared to baseline. A few highly experienced meditators showed exceptionally low switch-rates and long percept durations, especially during the FA condition. These results support our predictive processing account of FA meditation upweighting the incoming signals from the dominant percept and downweighing the incoming signals of the suppressed stimulus. However, no support was found for our initial idea that OM meditation would equally downweigh the signals from both stimuli, thereby prolonging mixed percept duration. Moreover, our objective neurally-derived measure of switch-rate indicated no difference in perception as a function of meditation, showing a disconnect with the subjective reports. On the basis of the current data, we can hence not with certainty conclude that extensive meditation practice can have a profound effect on fundamental processes of perception, but further analyses and future studies may reveal which aspects of our perception are automatic and can in fact be controlled by expert meditators, and may thus not be that automatic after all.

6. The Interdisciplinary Aspect of the Thesis and Its Relevance for Cognitive Science

The interdisciplinarity of this research is underlined by combining insights from predictive processing and contemplative practices with neuroscientific and self-report methods, within a research paradigm that is widely used in experimental psychology. It draws on the literature from cognitive neuroscience, cognitive psychology and philosophy of mind, which are all disciplines that fall under cognitive science. Furthermore, programming and statistics are used for data analysis. This thesis is relevant to cognitive science, as it investigates how perception and attention can be altered by contemplative practices. Thereby, it sheds light on the plasticity of the brain and the capabilities of the mind.

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Appendix

Table 14.

Questionnaire

Question number	Measure of	Question formulation
PMMQ*		
1	Object-orientation	I did not direct my attention to anything other than the checkerboard pattern
2*	Mind-wandering	I felt like I entered a meditative state
3	Object-orientation	I actively directed my attention to the checkerboard pattern
4	Aperture	My scope of awareness was wide
5	Stability	The quality of my attention was stable over time
6	Aperture	My attention was focused on one object
7	Dereification	I was not caught up by my thoughts, feelings and experiences
8	Dereification	I felt a distance between myself and my thoughts, feelings and experiences
10	Mind-wandering	I noticed myself mind-wandering often
11	Clarity	My experience was vivid and clear
12	Meta-awareness	I felt like I was monitoring the contents of my experience
Questions about viewing mixed and complete percepts		

13	Proportion seeing mixed vs. complete percept	I saw a combination of multiple checkerboard patterns… Never (1) – Most of the time (7)
14	Gradual vs. instantaneous transition	I experienced the transition from one complete checkerboard pattern to another… Gradually (1) – Instantaneously (7)
15	Minimum complete percept duration	Periods of seeing complete checkerboard patterns lasted between ... seconds
16	Maximum complete percept duration	and ... seconds
17	Average complete percept duration	on average ... seconds
18	Minimum mixed percept duration	Periods of seeing combinations of multiple checkerboard patterns lasted between ... seconds
19	Maximum mixed percept duration	and ... seconds
20	Average mixed percept duration	on average ... seconds
Phenomenology questions		
21	Reversing transformation	I saw one complete checkerboard pattern starting to change to the other, but then it stopped and reversed back to the original pattern
22	Color blending	I saw the red and green colors of the pattern as… clearly distinct colors (1) – a blend between red and green (7)

23***	Temporal indeterminacy	I was uncertain when the transition of a complete checkerboard pattern started and ended
24***	Spatial diachronic indeterminacy	The shapes and directions of transformation of the checkerboard patterns were obscure
25***	Instability	The checkerboard patterns constantly continued to change in an unstable manner
26***	Spatial disunity	It felt like there were several checkerboard patterns not integrated very well within the same space
27***	Sensitivity to subject's change	I could determine in advance how the checkerboard patterns would transform
28***	Sensitivity to subject's change	I could control the transformation of the checkerboard patterns
Performance questions		
9****	Sleepiness	I felt sleepy during the task
29	Button press interference with perception	The button presses influenced my perception of the images
30	Button press interference with attention	The button presses influenced my attention

Note. *Adapted from Ghigliotti (2019).

**This question was also used separately in the analysis, as to determine whether participants felt to be in a meditative state.

***Taken from (Niikawa et al., 2020).

****This question was originally part of the PMMQ, but is most useful to the present study as a performance question, rather than a question assessing mind-wandering.

Table 15.

Questions specific for meditation condition

Question number	Placed after question	Measures of	Question formulation
31†	5	Effort	It took a lot of effort for me to follow the meditation instructions
32†	11	Following meditation instructions	I felt like I succeeded in following the meditation instructions
33††	12	Following meditation instructions	I followed the meditation instructions during the guided meditation
34	12	Maintaining meditative state	I managed to maintain a meditative state during the visual task
35	28	Button press interference with meditative state	The button presses interfered with my meditative state

Note. These questions were only asked after the meditation condition and not after the baseline condition. They are referred to in the results section by their question number, even though they were inserted at different places in the original questionnaire, as to group them with similar questions.

† These questions were part of the PMMQ, adapted from Ghigliotti (2019).

† † This question was not used, as 'following meditation instructions' was already assessed in the PMMQ. This question should have been removed from the questionnaire data before data acquisition started.