Distinguishing Confounds from True Meditation Effects: Insights from Auditory ERPs

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Declaration of Authorship

I declare that the material presented here is my own original work, except where the work of others has been acknowledged.

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General Abstract

Meditation expertise is associated with improved attention in high-level processes (for example, task switching) and low-level processes (for example, perceptual discrimination). Recent studies provide evidence that meditation affects pre-attentive auditory processing, as measured through auditory event-related potentials (Cahn & Polich, 2009; Delgado-Pastor, Perakakis, Subramanya, Telles, & Vila, 2013). However, meditation effects in these studies are difficult to distinguish from experimental confounds introduced by unequal task requirements in meditation and control conditions, unbalanced condition order, and unmatched lifestyle factors among meditators and non-meditators. The aim of this dissertation is to distinguish between the role of meditation and experimental confounds in a first-time meditation effect, reported in Biedermann et al. (2016): N1 attenuation during first-time meditation, compared to a mind-wandering control condition. Experiment 1 replicated the effect. Experiment 2 tested whether mental state influences on repetition suppression were responsible for the effect. Eliminating the opportunity for mental state-induced differences in short-term repetition suppression did not eliminate the effect. Experiment 3 tested whether tone-related instructions acted as a mediator of mental control in the meditation and mind-wandering conditions. Matching tone-related instructions for both conditions did not eliminate the effect. Experiment 4 replicated the findings of Experiments 2 and 3. The N1 attenuated during the meditation condition (second condition) in Experiments 1-4, as in Biedermann et al. (2016). In Experiment 5, I reversed the condition order established in Biedermann et al. (2016), so that the meditation condition occurred first. The N1 attenuated during the mind-wandering control condition. Thus, I conclude that N1 attenuation during first-time meditation, compared to a mind-wandering control condition, is an effect of condition order. I discuss critical implications of these findings for the design and interpretation of meditation and pre-attentive auditory processing research.

1 Meditation Effects on Auditory ERPs

1.1 Background

Meditation, described as "paying attention on purpose, in the present moment, and non-judgmentally to the unfolding of experience" (Kabat-Zinn, 2003), is gaining research interest as a mediator of brain processes that underlie attention. Attention is involved in a wide range of processes, from sensory processing through to response selection (Correa, Lupiáñez, Madrid, & Tudela, 2006; Downing, 1988). Clinically-focused mindfulness research addresses some interactions between meditation and executive aspects of attention, such as consciously directing focus away from recurring negative thoughts (Bostanov, Keune, Kotchoubey, & Hautzinger, 2012). However, meditation may affect attention at many levels, and in different ways.

Findings so far suggest that meditation may influence the role of attention in both low-level (for example, perceptual discrimination) and high-level (for example, task switching) processes. A recent meta-analysis on the psychological effects of meditation found that meditation is associated with moderate changes in high-level attention (Sedlmeier et al., 2012). These data were drawn from studies of inhibition—measured by colour-word interference in a Stroop task—vigilance, and attention switching. Meditation is also associated with changes in low-level attention, as measured by expert meditators' performance on a perceptual discrimination task (MacLean et al., 2010).

The effect of meditation on attention may operate differently at each level. Many practices include focus on a single sensation (for example, the breath) and non-judgemental awareness of present experiences (for example, noticing the contents of the mind without automatic response). Focus on the breath may train one aspect of attention, such as vigilance. Non-judgmental awareness may train another aspect of attention, such as the ability to inhibit responses. Focused and non-judgemental meditation may train activation at a perceptual level but inhibition at an executive level. Thus, the nature of meditation effects on attention may be best understood by focusing on each level of processing individually.

We can measure low-level attention through auditory event-related potentials, which reflect the synchronous firing of groups of neurons following the onset of a sound. Figure 1 shows a typical auditory-elicited ERP waveform. The degree (amplitude) and speed (latency) of neural responses of long-latency ERP components (50-600 ms post-stimulus-onset) are associated with the facilitation or inhibition of attention. Research tracing amplitudes and latencies under experimental manipulations of stimulus features, task requirements, and participant populations elucidates the conditions to which an ERP peak is sensitive. Table 1 lists long-latency auditory ERP peaks with conditions to which they are sensitive (see Key, Dove, & Maguire, 2005 for a detailed description of each peak). Note that the conditions associated with early peaks differ qualitatively from conditions associated with late peaks, mapping the time-course of low-level attention from sensory gating to semantic processing.

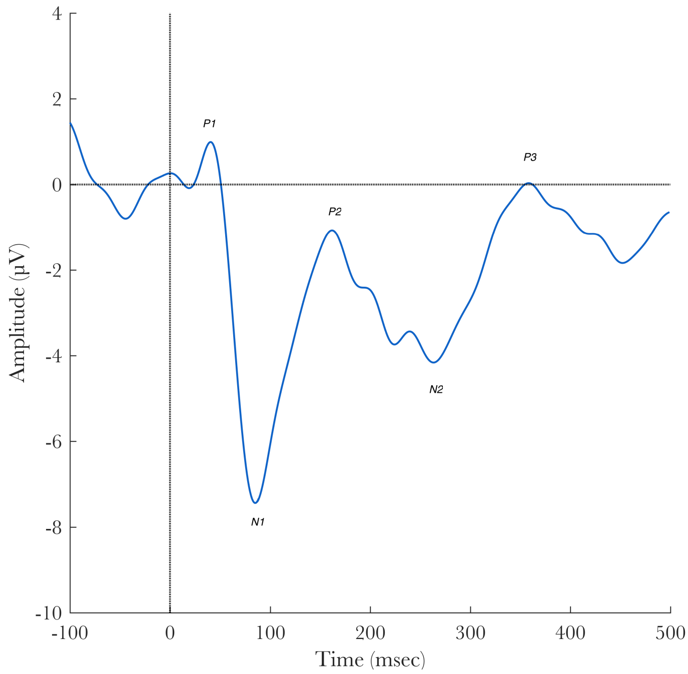

Figure 1. Auditory-elicited ERP for one subject.

Table 1

Long-latency ERP peaks

Peak	Latency (approx.)	Functional association
P1	50 ms	Sensory gating
N1	100 ms	Intentional stimulus discrimination and change detection
P2	150-275 ms	Change detection Amplitude increases with attention to sounds
N2	200 ms	Change detection among attended sounds
P3	300 ms	Elicited by novel, unattended stimuli (P3a) and infrequent, attended stimuli (P3b).
N400	475 ms (auditory)	Semantic deviation
P600	600 ms	Memory and syntactic analysis

Note. Adapted from Key et al. (2005). Auditory ERPs can be recorded actively, with attention directed toward stimuli, or passively, with attention directed away from stimuli. Passive auditory ERPs are especially informative to review, as they can be recorded for stimuli presented during meditation. Other methods, such as behavioural tests and active ERPs, measure meditation effects on low-level attention training immediately after practice or after a training period. However, these rely on carry-over effects from the meditative state, or from meditation training, to a non-meditative task. Meditation effects may not exist after meditation, especially among novice meditators. Passive auditory ERPs provide a unique measurement of meditation effects on low-level attention during meditation.

This review addresses the evidence for meditation effects on low-level attention in the auditory domain, measured by ERPs. The research process is outlined below, followed by a summary of included experiments and a discussion of the findings.

1.2 Methods

The search and screening methods reported below follow a simplified Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) approach (Moher, Liberati, Tetzlaff, Altman, & PRISMA Group, 2009). The recommended search and screening process is included for reference in Figure 2. The search and screening process used in this review is detailed in the following paragraphs.

The PRISMA statement also sets out the details of included studies which should be reported in a review to facilitate a meta-analysis. However, quantitative summaries are appropriate when comparing a homogenous and experimentally controlled group of studies. The field of meditation and auditory ERP research is small, with wide variations in study quality. Consequently, we did not attempt a quantitative analysis or report numerical summaries of included studies.

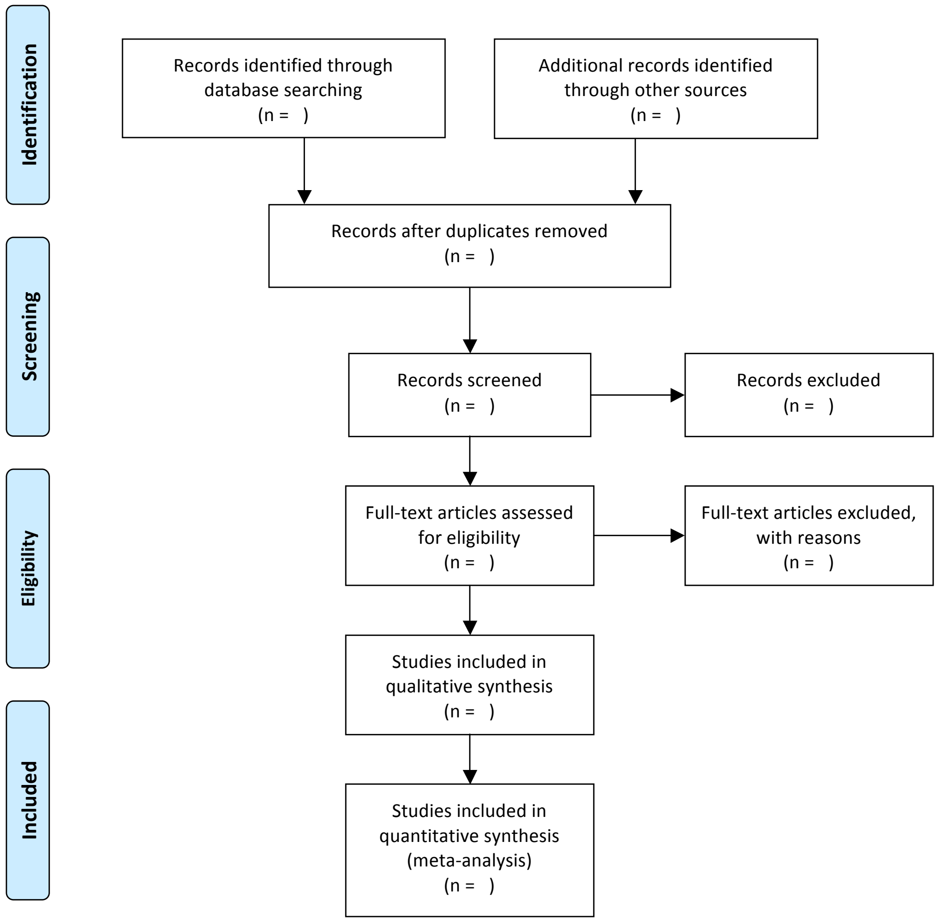

Figure 2. PRISMA process flow chart, taken from Moher et al. (2009).

Eligibility criteria. Journal articles were selected for inclusion in the review if they were published in a scientific journal and reported on a study investigating the effects of meditation on passive and active auditory ERPs. We included active forms of meditation, which combine mental practices with body postures, walking, or controlled breathing exercises, as well as passive forms, which are primarily static. We did not address findings reported in dissertations, conference abstracts, or books, as the quality of these findings has not been assessed through peer review.

Information sources. Articles were discovered through a search of three databases: PubMed, PsycINFO, and Web of Science. Searches were last updated on the 7th October, 2016.

Search. Search terms fell into three categories: meditation terms, ERP terms, and auditory processing terms. The full list of terms is detailed in Table 2.

Table 2

Search strategy

Search	Terms
Search 1	ERPs OR event-related potentials OR N1 OR N100 OR P1 OR P100 OR N2 OR N200 OR P3 OR P300 OR P3a OR P3b OR MMN OR mismatch negativity OR evoked potentials OR auditory evoked potentials OR brain potentials
Search 2	meditation OR mindfulness OR Zen
Search 3	auditory OR attention OR auditory attention OR auditory stimuli OR auditory evoked potentials OR listening OR sound OR tones OR clicks
Search 4	(Search 1) AND (Search 2) AND (Search 3)

Screening. The three databases returned 206 results (PubMed: 59; PsycINFO: 46; and Web of Science: 116). Duplicates were defined as the same publication, or as a re-publication of the same data. Removing duplicates (65: same publication; 4: same data) returned a total of 152 original results. The headings, key words, and abstracts of these 152 articles were screened for relevance by the author of this dissertation. Relevant articles were any reporting on the effect of meditation on passive or active auditory event-related potentials. Seventy-two more articles were excluded, leaving 80 screened articles.

Exclusion. The screened articles were assessed in-depth for reports of meditation effects on auditory ERPs. Sixty-four of the original 80 screened articles were rejected, as they did not report on auditory ERPs. Three of the remaining 16 articles did not report on the effects of meditation. One reported meditation effects and auditory ERP peaks, but did not report the relationship between the two. A full list of the excluded studies with reasons for exclusion is attached in Appendix A.

Accepted articles. Twelve articles were accepted for inclusion in the review. Cited and citing articles for each of the twelve articles were screened to identify any other articles which fit the criteria set out above. Two articles were discovered by this method. Table 3 outlines the authors and key features of the 14 included articles.

Table 3

Key articles

Study	N	ERP	Meditation	Control	Analysis
Atchley (2016)	42 14 Experts 15 Novices 13 Non-meditators	Passive and active N2; P3	Passive Mandala Breath awareness	Group and task	Mixed-design ANOVA followed by paired t-tests for group comparisons
Barwood (1978)	8	Passive P1; N1; P2	Passive Effortless awareness	-	Paired t-tests
Becker (1981)	47 8 Zen Experts 10 Yoga Experts 10 Transcendental Experts 10 "Attend" Non-meditators 9 "Ignore" Non-meditators	Passive N1; P2; P3	Passive Breath awareness Focused awareness Effortless awareness Active Breath control	Group	Repeated measures ANOVA
Biedermann (2016)	26 12 Experts 14 Non-meditators	Passive N1; P2; MMN	Passive Breath awareness	Group and task	Mixed-design ANOVA followed by independent t-tests for group comparisons
Cahn (2009)	16	Passive N1; P2; P3	Passive Body scanning	Task	Repeated measures ANOVA
Chatterjee (2012)	10	Active P3	Passive Focused awareness Effortless awareness Active Breath control	-	Repeated measures ANOVA
Corby (1978)	30 10 Experts 10 Novices 10 Non-meditators	Passive N1; P2; P3	Passive Breath awareness Mantra	Group and task	Mixed-design ANOVA
Delgado-Pastor (2013)	10	Active P3	Passive Breath awareness Body scanning Loving-kindness	Task	Repeated measures ANOVA followed by Bonferroni-adjusted pairwise comparisons
Joshi (2009)	30	Active P3	Passive Breath awareness Active Breath control	-	Repeated measures ANOVA followed by Bonferroni-adjusted pairwise comparisons
Kyizom (2010)	60 30 Novices 30 Non-meditators	Active N2; P3	Active Breath control Body postures	Group	Repeated measures ANOVA followed by Tukey's test for pairwise comparisons
Liu (1990)		Passive P2; N2	Active Body postures	-	Repeated measures ANOVA
Sarang (2006)	42	Active P3	Passive Body awareness Active Body postures	Task	Repeated measures ANOVA followed by paired t-tests
Srinivasan (2007)	20 10 Experts 10 Non-meditators	Passive MMN	Passive Effortless awareness Active Breath control Hand postures	Group	Mixed-design ANOVA followed by planned pairwise comparisons
Telles (2015)	60	Passive N1; P2; N2; P2	Passive Focused awareness Effortless awareness	Task	Repeated measures ANOVA followed by Bonferroni-adjusted pairwise comparisons

1.3 Stimuli and Methods of Included Studies

Five of the included studies used a single repeated stimulus to elicit the ERP. The repeated stimuli were either pure tones, clicks, or a tone bursts. Pure tones are typically formed with rise and fall cycles on either side of a plateau of sine or cosine waves at the frequency of the tone—for example, 10 rise cycles and 50 plateau cycles in Sarang and Telles (2006). The plateau of sine or cosine waves means that the tone has one dominant frequency, while the rise and fall cycles ensure that the tone is perceived as smooth, not abrupt. Clicks have a shorter duration, more abrupt onset, and wider frequency range than pure tones (Stapells, Picton, Perez-Abalo, Read, &

Smith, 1985). Tone bursts are similar to both pure tones and clicks; like pure tones, they are frequency-specific and include rise and fall cycles; like clicks, they are short in duration (Johnson & Brown, 2005).

Abrupt onset and short duration (clicks and tone bursts compared to tones) increase the salience and perceived spacing of stimuli. Widely spaced stimuli may also elicit novelty responses. Identical, repetitive stimuli do not offer insight into change detection or target detection functions of ERP peaks. However, attention can be directed toward or away from the repeated stimuli, providing insight into meditation effects on active or passive ERPs.

Nine of the included studies used a variant of the auditory oddball paradigm to elicit the ERP. This consists of common "standard" sounds and rare "deviant" sounds. Deviants are typically of higher pitch or longer duration than standards. In an active oddball task, deviants serve as targets, which are identified by pressing a button or by silently counting the number of targets and reporting it at the end of the task. In a passive oddball task, standards and deviants are both unattended. The difference between ERPs elicited by standards and deviants in a passive oddball task forms another ERP component, called mismatch negativity (MMN). Figures 3 shows the MMN difference wave alongside waveforms for standards and deviants. The waveforms elicited by standards and deviants diverge to form the MMN component in a similar latency to the N1 (between 150-250 ms; Näätänen, 1992) when the deviant feature is apparent from stimulus onset, or later when the deviant feature is apparent after stimulus onset—for example, in the case of a duration-deviant stimulus (Leitman, Foxe, Sehatpour, Shpaner, & Javitt, 2009). Like the N1, MMN is sensitive to stimulus change. Unlike the N1, MMN is sensitive to the absence of stimuli in a repetitive sequence, suggesting that its change detection function is unique (Tervaniemi, Saarinen, Paavilainen, Danilova, & Näätänen, 1994). Thus, it is used as an index of passive attention or sensory memory (Näätänen, Jacobsen, & Winkler, 2005; Näätänen, Paavilainen, Rinne, & Alho, 2007).

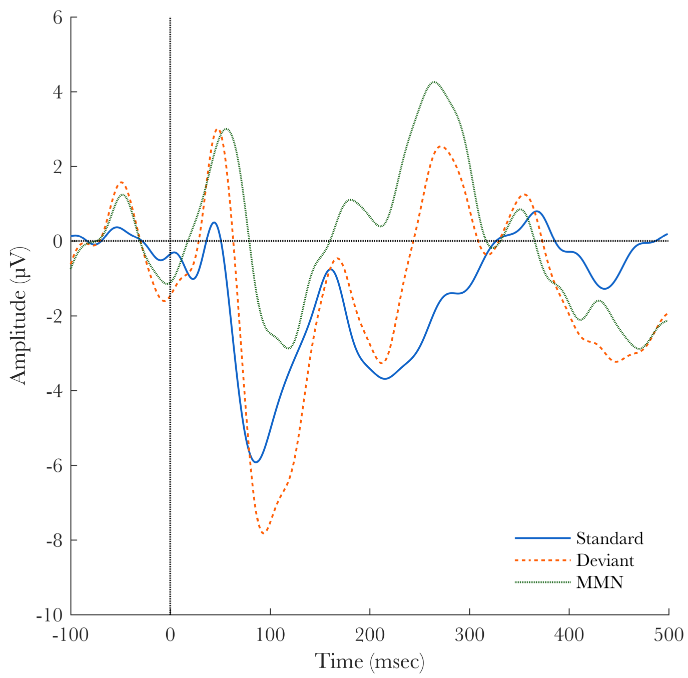

Figure 3. Waveforms elicited by standard and deviant tones, with the MMN difference waveform in green.

Both stimulus type and ERP peak shape the information an experimental design can provide about low-level attention. Attended, infrequent, and target sounds each elicit larger ERP peak amplitudes than unattended, repetitive, and non-target sounds. Standards in a passive oddball task (unattended, repeated, non-target sounds) elicit smaller amplitudes than deviants in an active oddball task (attended, infrequent, target sounds). As shown in Table 1, different ERP peaks are most responsive to stimulus change, attention, and targets: P1 and N2 peaks are strongly responsive to change in stimuli, N1 through to P3 peaks are increasingly responsive to attention, and P3 is sensitive to target stimuli. Thus, the different stimuli and ERP peaks in the reviewed studies offer distinct insights into low-level attention.

1.4 Results

The quality of the included studies varied in two key parameters: the presence of a control task or group, and the directness of the association between meditation and auditory ERPs. The discussion begins by commenting on studies with poor experimental control, and progresses to those which provide stronger grounds for drawing causal links between meditation and auditory ERPs.

1.4.1 Studies with no control condition or group

After meditation. Measurements of meditation effects on auditory ERPs in the reviewed studies varied from direct—during meditation—to indirect—after meditation, or after meditation training. Measuring meditation effects post-practice or post-training separates the outcome—changes in low-level attention—from the presumed antecedent. For example, Chatterjee, Ray, Panjwani, Thakur, and Anand (2012) selected 10 men from the Indian army, with no prior experience of meditation, and trained them in meditation twice daily for two months. Event-related potentials were recorded before and after training, after 24 h and 36 h sleep deprivation and after a recovery sleep. During testing sessions, participants silently counted pitch-deviant click stimuli in an active oddball task (proportions not reported). Amplitudes and latencies of P3 increased after sleep deprivation, compared to a pre-deprivation baseline taken before training. Meditation effects on low-level attention were measured indirectly as modulation of sleep deprivation effects on auditory ERPs. Meditation did not protect against sleep deprivation-induced changes to P3. Pre- to post-meditation training changes in P3 without sleep deprivation were not reported. Thus, this finding has a limited role in forming a theory of meditation effects on low-level attention, as it traces the effect of meditation on attention through another factor. Such an indirect measurement entails complex hypotheses and interpretations. It assumes that sleep deprivation-induced changes in auditory ERPs are attention-related; that meditation affects auditory ERPs; that the effects of meditation on auditory ERPs shape the same attentional mechanism which is presumed to be affected by sleep deprivation; and that the effects of meditation counter-act those induced by sleep deprivation. In this case, the assumption that meditation training modulates brain changes following sleep deprivation was not supported by the findings.

Joshi and Telles (2009) studied experienced yoga meditators after either high-frequency yoga breathing or breath awareness practice. Participants silently counted targets in an active oddball task consisting of standard (80%) and pitch-deviant (20%) pure tones before and after their practice. Unlike Chatterjee et al. (2012), Joshi and Telles (2009) found statistically reliable changes in P3 amplitude and latency after meditation, compared to the pre-condition baseline. Changes were differentiable between the two practice types; P3 latency decreased only after the high-frequency yoga breathing condition, whereas P3 amplitude increased only after the breath awareness condition. The authors do not specify whether comparisons were conducted among P3 elicited by standards or by deviants, so we cannot comment on the relevance of these findings to target detection.

Measuring ERPs after meditation complicates attempts to attribute the observed effects to meditation. Meditation does not necessarily induce a meditative state that continues after practice, particularly among novice meditators. Observed changes in P3 do not necessarily reflect carry-over of the meditative state. Distance between the theorised cause and effect in these two studies limits the extent to which these findings can be integrated in a theory addressing the mechanism of meditation's effect on low-level attention.

During meditation. Barwood, Empson, Lister, and Tilley (1978) measured expert meditators' auditory ERPs before, during, and after meditation. In this study, meditation effects on auditory ERPs were measured directly—during meditation—as well as indirectly. There was no evidence of a meditation-related change during or after meditation, compared to the pre-meditation baseline. While the approach to testing meditation effects on auditory ERPs was more direct than in the previous two studies, this study may not have had power to identify real effects; data from eight participants, with only 50 trials per condition, may not be sensitive enough to show meditation effects. The lack of effect does not provide evidence against meditation effects on auditory ERPs.

Liu, Cui, Li, and Huang (1990) also measured meditation effects on auditory ERPs before, during, and after meditation. Experienced Qigong meditators were presented with tone bursts while their attention was directed away from the tones. In contrast to Barwood et al. (1978), this study showed evidence of P2 amplitude decrease during meditation, compared to the pre-meditation baseline.

While the studies reported in Barwood et al. (1978) and Liu et al. (1990) do well to measure auditory ERPs during meditation, they, like the studies reported in Chatterjee et al. (2012) and Joshi and Telles (2009), do not include a control condition. The lack of a control condition makes it difficult to distinguish between meditation effects and changes which may occur across time regardless of whether participants meditate; this would only be possible with a non-meditative control condition.

1.4.2 Studies with a control condition

The studies reported in this section include a non-meditative condition to control for effects confounded with meditation effects in the previous studies: physiological changes which naturally occur over time; increased exposure to stimuli; and, in studies with an active auditory task, practice effects from repeating the task.

After meditation. Sarang and Telles (2006) compared pre- to post-meditation auditory ERPs for two conditions: a cyclic meditation practice, and a period of supine rest. Expert meditators silently counted pitch-deviant pure tones in an active oddball task (80% standards; 20% deviants) before and after each condition. P3 latencies to standard tones decreased following both conditions. P3 amplitude increased after meditation, but not after supine rest. While the study included a control condition, the researchers did not conduct statistical comparisons between the two conditions. Thus, we cannot conclude that the change from pre- to post-condition was reliably different between meditation and rest.

In contrast, Delgado-Pastor et al. (2013) compared P3 for silently counted pitch-deviant pure tones in an active oddball task (80% standards; 20% deviants) after meditation and a random thinking control task. Amplitude of midline P3 for both standard and target tones increased following meditation, compared to random thinking. Although this study does not offer direct insight into what happens during meditation, the comparison task allows us to distinguish meditation effects from changes which occur over time or with repeated exposure to stimuli, which may have influenced the outcome of some earlier studies.

During meditation. Telles, Deepeshwar, Naveen, and Pailoor (2015) compared expert meditators' passive auditory ERPs to clicks presented before, during, and after four conditions: focused *OM* meditation (looking at and visualising the Sanskrit syllable), effortless *OM* meditation (reflecting on the subtle characteristics of the Sanskrit syllable), random thinking, and non-meditative focusing. During focused *OM* meditation, attention is consciously directed toward the syllable *OM*. During effortless *OM* meditation, the object of meditation remains in focus without effortful redirection of attention. Comparisons with the pre-meditation baseline showed decreased P2 latency during the first stage of effortless meditation, as well as after effortless meditation. Average P1, P2, and N2 peak amplitudes decreased only during the non-meditative tasks, compared to the pre-task baseline. Differences between pre- or post-meditation ERPs and during-meditation ERPs could be due to the addition of a primary task, whether meditative or non-meditative, which more effectively drew attention away from the click stimuli. In the absence of a control condition, meditation effects and primary task effects would always occur together, creating a confound. Thus, comparisons between conditions are more informative than pre- to during-meditation comparisons.

Cahn and Polich (2009) excluded pre- to during-meditation comparisons entirely by basing their calculation of meditation effects on passive ERP differences between meditation and a mind-wandering control condition. Expert meditators completed the conditions in random order, with a passive oddball task presented throughout the conditions. Oddball stimuli were a standard pure tone (80%), a pitch-deviant pure tone (10%), and a white noise burst (10%). They found evidence of N1, P2, and P3 attenuation to rare white noise bursts during meditation, compared to the mind-wandering control condition. These methods harness the power of within-subject comparisons, which have less variability than between-group comparisons, to highlight the different changes in low-level attention during meditation practice and during a comparable task.

Studies with a control group

However, meditation practice may affect attention even when the expert meditator is not meditating. This is especially likely during tasks that resemble meditation, such as those used in non-meditative control conditions. The following studies used a group of non-meditators as a baseline to control for ingrained "trait" effects of meditation among expert meditators which may have formed a confound in the control conditions of the previous studies.

After meditation. Kyizom, Singh, Singh, Tandon, and Kumar (2010) circumvented the problem of meditation trait effects in the control condition by using a control group of non-meditators. Participants with no prior meditation experience were allocated to a meditation training group or a no-training wait-list group. They completed an active oddball task with button press responses to target stimuli (proportions, stimulus type, and deviance type not reported) before and after the training or wait period. Average N2 and P3 latency to standard stimuli decreased, while amplitude increased, from pre- to post-training only in the meditation group. The control group showed no evidence of ERP change. As with Chatterjee et al. (2012), meditation training was presumed to have observable carry-over effects to non-meditative tasks. For Kyizom et al. (2010), however, the presence of a control group who were exposed to the same time-gap and repeated testing as meditators supports attribution of group differences to the meditation training.

Srinivasan and Baijal (2007) measured meditation effects on auditory ERPs based on differences between meditators and non-meditators after meditative or non-meditative conditions. Expert mediators completed hand postures, controlled breathing, and effortless awareness meditation practice. Non-meditators read a book in three sessions of the same duration as the meditators' three practices. Before and after each session, both groups were presented with standard and pitch-deviant pure tones (80% standards; 20% deviants) forming a passive oddball task to elicit an MMN component. Mismatch negativity amplitude did not change from pre- to post-task among controls after any session, or among meditators after hand postures or controlled breathing. However, MMN amplitude increased among expert meditators after effortless awareness meditation compared to the precondition baseline.

During meditation. Becker and Shapiro (1981) also used group comparisons to study meditation effects on auditory ERPs. They selected groups of Zen meditators, yoga meditators, transcendental meditators, and two control groups of non-meditators. One control group was instructed to ignore click stimuli; the other control group was instructed to silently count click stimuli. Expert meditators carried out their usual meditation practice while clicks played in the background. Meditators' N1 and P2 peak amplitudes were attenuated compared to the attend-to-click controls, but were not different to N1 and P2 amplitudes among ignore-click controls. The meditation effects were comparable to ignoring the clicks. Meditators' attention was drawn away from the clicks by their practice, which may account for the similarity between meditators' and ignore-click controls' N1 and P2 amplitudes.

Three recent findings include a control condition in which non-meditators follow meditation instructions. These studies offer valuable insight into effects of the meditative *state* and effects of meditation experience, or *trait*, as well as interactions between meditation trait and state effects. Atchley et al. (2016) compared expert meditators, novice meditators, and non-meditators in active oddball and breath-counting meditation tasks. Oddball stimuli were presented in blocks of 10 tones: standards (80%), pitch-deviant non-targets (low pitch; 10%), and pitch-deviant targets (high pitch; 10%). The same stimuli were presented passively during the breath-counting meditation task. Meditators had greater target-elicited N2 and P3 amplitudes than non-meditators when asked to attend to tones, and smaller N2 and P3 amplitudes than non-meditators when asked to ignore tones, suggesting an interaction between meditation experience and deliberate attention to sounds.

Corby, Roth, Zarcone, and Kopell (1978) compared expert, novice, and non-meditators' ERPs to passive oddball stimuli in three conditions: rest, breath awareness, and mantra repetition. Oddball stimuli were pure tones (standard: 93%; deviant: 7%), with four white noise bursts presented during the 10 minute sequence of tones to obtain an orienting response. Amplitude of the N1 elicited by standards and deviants decreased across conditions. Amplitude of P2 and P3 to deviants decreased across conditions, whereas amplitude of P2 and P3 to standards increased across conditions. However, the authors suggest that these findings are best explained as typical decreases in the evoked response over repeated stimulation, and as the result of reduced attention to tones during meditation compared to rest. Reduced attention to tones during meditation may reflect the presence of a primary task—breath awareness or mantra repetition—which cannot be called a meditation effect. There was no evidence of a meditation expertise effect on ERPs, reinforcing the interpretation of findings as due to stimulus features and task demands.

In the most recent study using auditory ERPs to examine the association between meditation and low-level attention, Biedermann et al. (2016) compared expert meditators' and non-meditators' ERPs elicited by a passive oddball task during meditation and a mind-wandering control condition. Stimuli were pure tones: 85% standards, and 15% raised-pitch deviants. The mind-wandering control task allows for a trait comparison between meditators' and non-meditators' low-level attention. The meditation task allows for measurement of meditation state effects across both groups, as well as state-trait interactions in meditators during meditation. Meditators showed evidence of a trait effect in the form of a larger MMN compared to non-meditators, regardless of task. There was also evidence of a trait-state interaction: a positive shift in standard-elicited N1-P2 amplitude during meditation among non-meditators, with no change among meditators. However, the tone-related instructions changed from "ignore the tones" for the mind-wandering task to "notice the tones, but do not attend to them" for the meditation task, possibly triggering differential direction of attention. Further, the tasks were always completed in the same order to prevent carry-over of meditation effects among expert meditation. Factors that co-vary with condition order, such as fatigue or increased exposure to stimuli may be at work, as suggested by Corby et al. (1978) with regard to their own study. Alternately, the attenuated N1 during first-time meditation may reflect reduced attention to tones due to the difficulty of meditation for novices.

1.5 Conclusions and Future Directions

The reviewed papers validate the use of auditory ERPs as a measurement of meditation effects. Meditation is associated with changes in ERP peaks, even in studies with stringent experimental controls. Amplitude of N1, P2, N2, and P3 peaks elicited by distracting sounds typically decreased during meditation among meditators. Amplitude of N2 and P3 (active) and MMN (passive) typically increased among meditators following meditation, and among meditators compared to non-meditators, suggesting meditation has both state and trait effects on these components. Latencies of P3 (active) and P2 (passive) peaks elicited by repetitive stimuli decreased after meditation among meditators; latencies of active N2 and P3 peaks also decreased following meditation training. Further, meditation-related changes in low-level attention suggest that the role of meditation in shaping attention may be more than a change in attitude or executive processing.

However, meditation effects on auditory ERPs were obscured by confounds. Differences between meditation types reported in Joshi and Telles (2009) may reflect the physical demands of the practices: an active practice, associated with reduced P3 latency; and a passive practice, associated with increased P3 amplitude. Some studies compared meditation to pre-task rest baselines, so that baseline-to-meditation comparisons may reflect the introduction of an engaging primary task. If this is the case, reduced standard-elicited N1 and P2 amplitudes and target-elicited N2 and P3 amplitudes found in these studies may similarly be obtained by comparing a rest baseline to a non-meditative primary task. Changes naturally occurring over time may explain apparent meditation effects; even studies including control tasks and groups did not always counterbalance conditions, introducing stimulus repetition, fatigue, and relaxation as confounds.

The apparent state effect of meditation among controls but not among meditators in Biedermann et al. (2016) raises further questions about possible immediate effects of meditation on first-time meditators. There are three plausible explanations for a first-time meditation effect: first, that it is an artefact of experiment design (for example, an order effect); second, that it is a common feature of early meditation training; and third, that it is a true effect of the meditation condition, but not a common feature of early meditation training (for example, due to low physiological activation when focusing on breath). Each of these explanations has implications for designing and interpreting meditation studies which include non-meditators.

1.5.1 Aims of the current dissertation

The following chapters address the question of whether a state effect of meditation in first-time meditators, as reported in Biedermann et al. (2016), is a true effect of meditation or an artefact of experiment design. My first aim is to measure the reliability of the effect: N1 attenuation to standard tones during first-time meditation, compared to a mind-wandering control condition (Chapter Two). Second, I aim to test if an effect of mental state on repetition suppression could explain the reduced N1 (Chapters Three and Five). Third, I aim to investigate whether the effect could be explained by condition differences unique to the situation: differences in mental control induced by opposing sets of tone-related instructions for the meditation and control conditions (Chapters Four and Five). Fourth, I aim to test the role of condition order in the observed effect (Chapter Six).

2 Experiment 1. Replication

2.1 Background

This experiment was designed to test the replicability of N1 changes in first-time meditators during meditation, as reported in Biedermann et al. (2016). The methods reported in the current study were the same as those in Biedermann et al. (2016), with four exceptions. First, Biedermann et al. (2016) found that N1 amplitude was attenuated (more positive) and P2 mean amplitude was enhanced (more positive) during first-time meditation compared to a mind-wandering control condition. The fact that N1 and P2 were both more positive during meditation than during the control condition suggested that both effects originated at the earlier time point (N1). Thus, the current study focused on N1 rather than N1 and P2. Descriptive and inferential statistics for P2 (Appendix B) are provided for reference.

Second, Biedermann et al. (2016) measured MMN as well as N1 and P2 in their study. They found that the MMN was larger in experienced meditators than in first-time meditators (trait effect), but found no reliable effect of condition (state effect) on MMN among either group. Thus, this study—which addresses a state effect in first-time meditators—did not focus on the MMN. This decision was supported by descriptive and inferential statistics for the MMN (Appendix B) which substantiate the Biedermann et al. (2016) finding that the MMN is not affected by meditation in first-time meditators.

Third, Biedermann et al. (2016) analysed data collected from the parietal and frontal midline electrode sites, Pz and Fz. Pz showed differences between meditators and non-meditators most clearly. However, the condition effect on non-meditators' N1 was largest at the frontal midline electrode, Fz.

Thus, this study reports findings based on data collected at Fz.

Fourth, unlike Biedermann et al. (2016), I used a Bayesian analysis paradigm, similar to that described in Wagenmakers et al. (2015), to detect statistically significant effects. The Bayes Factor (*B*)reflects whether the effects in experimental conditions or groups fit with effects predicted by the hypothesis. The fit of the data to hypothesised effects is weighted against the fit of the data to effects predicted by a typical spread of effect sizes, called the prior distribution. If the data are a better fit for the hypothesised model than the null model (the prior distribution of effect sizes), the data is taken as evidence for the hypothesis. If the data are a better fit for the null model, they are taken as evidence against the hypothesis. This critical feature of Bayesian data analysis—the weighting of the hypothesised model against the null model—serves two key functions. First, it offers differentiation between null results which are due to insensitive data, and null results due to a lack of effect by providing a continuum of evidence for and against a hypothesis (Dienes, 2014). Findings at the mid-point of the continuum ($B = 1$) do not offer conclusive evidence in either direction. Findings away from the mid-point offer increasingly strong evidence for ($B > 1$) or against ($B < 1$) a hypothesis. As the evidence for or against a hypothesis is greater as *B* moves away from 1, we can set a cut-off range within which the data are considered to be inconclusive. The recommended cutoff is a *B* of 3 (evidence for) or .3 (evidence against) (Dienes, 2014). Second, monitoring *B* provides a stopping rule which terminates testing when a statistically significant outcome is reached, without biasing studies towards false positive findings (Rouder, 2014). Continuous sampling with frequentist statistics violates the assumption that each sample used for inference is independent of other samples used to address the same question. Analysing data from a sample, adding to the sample, and re-analysing the data increases the rate of Type 1 error: the probability of finding evidence for an effect when there is no real effect (Yu, Sprenger, Thomas, & Dougherty, 2013). Bayesian data analysis does not assume independent samples. Adding to the sample increases the strength of evidence for one theory over the other, leading to either a positive or a negative result. Thus, we can monitor *B* after testing each subject, and terminate testing when there is strong evidence for or against the hypothesis, without increasing the probability of a Type 1 error. This is particularly useful when a null effect is predicted, or when a power analysis is difficult. Even in cases where the information needed for a power analysis is possible, as in this experiment, the Bayesian stopping rule is more economical for strong effects and clear null effects (Wagenmakers et al., 2015). Details of the stopping criteria, analysis, and interpretation are included in the following sections.

2.2 Methods

2.2.1 Participants

Participants were recruited from a pool of undergraduate psychology students at Macquarie University. Selection criteria were (a) no prior meditation experience, including active meditation in yoga classes; (b) normal hearing; and (c), no history of ADHD or epilepsy. Prospective participants were informed of the selection criteria, aims of the study, and the procedure through a research participation website. Participants gave informed consent prior to data collection. They received course credit for their participation. The study was approved by the Macquarie University Human Research Ethics Committee (reference number 5201500921; approval letter in Appendix C).

The number of participants recruited was decided by a Bayesian stopping rule, in which the sample size is contingent on the evidence for or against a hypothesis (indexed by *B*), with more noise in the data requiring more extensive testing. The Bayes Factor can be spuriously significant for very small samples. Conversely, one of the benefits of the Bayesian stopping rule is its economy with strong effect sizes, such as that found by Biedermann et al. (2016) for N1 attenuation during first-time meditation. I set a minimum number of participants to limit the risk of obtaining a spuriously significant outcome. I set the minimum number below that used in Biedermann et al. (2016) (n = 14) and the conservative sample size produced by a power analysis (n = 20; based on Biedermann et al., 2016), to harness the power of the Bayesian stopping rule to prevent unnecessary testing if the effect was larger than predicted. Thus, the sampling rule was a minimum of 8 participants, plus the number needed to achieve conclusive evidence for or against N1 attenuation during meditation compared to a mind-wandering control condition. I defined conclusive evidence as *B* greater than 3 or less than .3, as recommended in Dienes (2014). Bayesian data analysis does not assume that samples are independent, so these stopping criteria do not increase the likelihood of Type 1 error. I did not base decisions about sample size on Student's *t*-test outcomes, as this can distort the likelihood of producing a statistically significant result when there is no real effect. For this experiment, I tested eight participants (6 females), with a mean age of 20 (SD = 0.76, range = 19-21 years).

2.2.2 Conditions

Mind-wandering condition. Participants were first asked to spend 15 minutes thinking about how they would build a tree house. They were told that tones would begin to play through headphones, but were asked to ignore the tones and continue building the tree house. This condition was designed to mirror the meditation condition for posture (static, eyes closed) and maintain consistency across participants, while allowing the participant's mind to wander from the present moment. Note that mind-wandering and cross-participant consistency are somewhat in conflict with each other. This is why I neither directed participants to let their minds wander, as in Cahn and Polich (2009), nor provided stricter task boundaries.

Meditation condition. Participants were asked to spend the next 15 minutes focusing on the inhalation and exhalation of their breath, counting each exhalation from one to 10, and beginning again at one. Similar practices have been recorded as part of meditation as far back as c. 430 AD (Levinson, Stoll, Kindy, Merry, & Davidson, 2014), and are still common as a beginner technique (Cahn & Polich, 2006). Unlike the instructions to ignore the tones in the mind-wandering condition, participants were instructed here to notice the sounds, but gently let them go. Verbatim instructions for both conditions are included in Appendix D.

2.2.3 Stimuli

Auditory stimuli were blocks of 666 pure tones, presented binaurally through Sennheiser HD 280 Pro headphones. Each block consisted of pseudorandomly sequenced frequent 1000 Hz tones (n = 566; 85% of trials) and infrequent 1200 Hz tones (n = 100; 15% of trials), forming a passive auditory oddball paradigm. Deviants were never among the first three stimuli, separated by fewer than three standards, or separated by more than 35 standards. This pseudorandom order was generated for each condition and participant. Stimulus duration was 175 ms, with sigmoidal ramps over 10 ms rise and fall times. Stimulus onset was jittered within a range of 900 to 1100 ms to prevent any confounding effects related to temporal expectation of sounds or artefacts from one tone consistently carrying over to the next. Stimuli were created in and presented through MATLAB R2012b (MathWorks, 2012) and Psychtoolbox version 3.0.12 (Brainard, 1997; Pelli, 1997). The stimulus presentation computer was a Dell Optiplex GX990, with a Creative Sound Blaster X-Fi Titanium HD audio card. The order of oddball stimuli was different for each condition and participant.

2.2.4 Procedure

Electroencephalogram (EEG) set-up. Electrode sites around the eyes and mastoids were cleaned with an alcohol wipe and exfoliant. Eye movement and mastoid electrodes were placed on these sites and connected to the skin with Signa electrolyte gel. An appropriate EEG cap was selected to match each participant's head size (small, medium, or large). The participant's scalp was combed before fitting the cap to reduce impedances (Mahajan & McArthur, 2010). Electrodes in the cap were connected to the scalp with Signa gel. All electrodes were then plugged into the amplifier.

Equipment. The cap was an EasyCap, with 11 electrodes positioned according to the International 10-20 system (FP1, FP2, Fz, FCz, Cz, CPz, Pz, Oz, O1, O2, and ground at AFz). Data were referenced to the left and right mastoids (10-20 system locations M1 and M2). I included eye movement channels to account for ocular artefacts. Horizontal bipolar electrodes were placed adjacent to the outer canthi of both eyes, with vertical movement bipolar electrodes centred above and below the left eye. EEG data were collected via Neuroscan Synamps2 and Acquire software at a 1000 Hz sampling rate, with an online bandpass filter of 0.05-200 Hz. EEG data were recorded and stored for offline processing.

Testing. Participants wore headphones and sat in a comfortable chair. Pre-recorded instructions were presented through the headphones (see Appendix D). The mind-wandering condition was always completed before the meditation condition described above, as in Biedermann et al. (2016). There was a short break between conditions, during which participants drew the tree house they had been imagining. Participants were asked to answer questions regarding their focus and general awareness for each condition (Appendix E), for purposes not related to this dissertation. Participants filled out the questionnaire after both conditions were completed, prior to any discussion with the tester about the experiment.

EEG pre-processing. Each subject's EEG data was processed by a MATLAB script, using EEGLAB version 13.5.4b (Delorme & Makeig, 2004). Each data file was high-pass filtered at 0.1 Hz and low-pass filtered at 30 Hz. Continuous data were epoched from -100 to 500 ms relative to the onset of each stimulus (tone), and baseline corrected from -100 to 0 ms. Epochs with values beyond ±150 µV from 0 were rejected. No more than 10% of the 666 epochs were rejected in any case (mean accepted = 99.70%; SD = 0.01%). Average waveforms were calculated for each condition (control and meditation) for each tone type (standard and deviant) for each individual. Data from the frontal midline electrode (Fz) were analysed, as Cahn and Polich (2009) and Biedermann et al. (2016) found an attenuated N1 during meditation at this site.

N1 amplitude. The N1 was identified as the first clear negative peak between 50 and 150 ms from stimulus onset. Automatic peak amplitude extraction was manually reviewed to ensure accurate selection of the N1 peak. No manual adjustments were made.

Analyses. The first-time meditation effect in Biedermann et al. (2016) was among the N1 elicited by standard tones. Consequently, I focused on the condition effect of first-time meditation on the standard-elicited N1. Descriptive and inferential statistics for the deviant-elicited N1 are in Appendix B. Planned pairwise comparisons of standard-elicited N1 peak amplitude between conditions were based on the hypothesis that N1 amplitude is reduced during first-time meditation, compared to a mind-wandering control task. The primary statistic of interest was the Bayesian measure of effect size, *B*. The Bayes Factor reflects whether the differences between conditions fit with effects predicted by the hypothesis compared to those predicted by a typical spread of effect sizes, called the prior distribution. I used a Cauchy distribution to generate a typical spread of effect sizes, as this is more robust (less likely to be skewed by new data points) than a normal distribution (Gelman, Jakulin, Pittau, & Su, 2008). The Cauchy distribution was one-tailed, indicating that the hypothesis for this experiment did not predict effects in the opposite direction to Biedermann et al. (2016) (i.e. N1 greater during meditation). Cauchy prior width—the interquartile range for the prior distribution of effect sizes—was set at 0.71 (compare Wagenmakers et al., 2015: Cauchy prior width of 1). The width of the prior affects whether the observed effect in the data is considered to be consistent with the prior distribution of effect sizes. A prior width of 1 extends the range of effects which fit (i.e. will be judged consistent with) the prior distribution, whereas a prior width of .5 reduced the range of effects which fit the prior distribution. In turn, this affects the magnitude of *B*. Strong effects are robust to small changes in the prior distribution width. Plotting the magnitude of *B* produced by a range of prior widths shows whether the finding is robust to changes in prior width. Tests for the robustness of *B* across a range of prior widths (Appendix F) substantiate the evidence offered by *B* for the selected prior width. I also calculated Student's *t* and Cohen's *d* to facilitate direct comparisons between this experiment and Biedermann et al. (2016). Statistical analyses were conducted using the open-source program JASP version 0.7.5.5 (Love et al., 2015).

2.3 Results and Discussion

Across participants, the mean N1 amplitude to standard tones was reduced in the meditation condition at the frontal midline electrode (Fz) compared to the mind-wandering control condition. This effect was statistically reliable (B = 10.84). Figure 4 contrasts grand mean waveforms for the two conditions. The Bayes Factor reflects whether the differences between conditions fit with effects predicted by the hypothesis compared to those predicted by a typical spread of effect sizes, called the prior distribution. I use a Cauchy distribution to generate a typical spread of effect sizes, as this is more robust (less likely to be skewed by new data points) than a normal distribution. The alternate hypothesis was that N1 attenuates during meditation compared to the control condition. The magnitude of *B* reflects to what extent the theorised distribution of effect sizes, as generated by the hypothesis and by the Cauchy distribution of effect sizes, fits the data. A *B* of 1 reflects an equal fit of the hypothesised and null models to the data. A *B* of 10.84 for the hypothesis that N1 attenuates during meditation compared to the control condition reflects a 10-times better fit of the data to the hypothesised model than to the null model. Table 4 sets out descriptive statistics for each condition, with Bayesian and Student's *t*-test outcomes for pairwise comparisons.

These findings are consistent with previous findings reported in Biedermann et al. (2016). The state effect of meditation on N1 amplitude was replicable with a small sample of non-meditators. This suggests that the first-time meditation effect reported in Biedermann et al. (2016) was not an anomalous finding, or due to unique characteristics of their non-meditator group. Thus, we can conclude that the first-time meditation effect in Biedermann et al. (2016) and in this experiment reflect a real-world effect. Establishing that this effect is reliable allows us to address a deeper question: where does the effect come from? The findings of Biedermann et al. (2016) and this experiment do not clarify whether the observed changes in N1 amplitude during first-time meditation are due to meditation or to confounding factors. Non-meditative aspects of the conditions, such as mental state induced by the task, mental control induced by tone-related instructions, and order effects, may explain the attenuated N1. In the following chapter, I will focus on the role of mental state in N1 attenuation during first-time meditation.

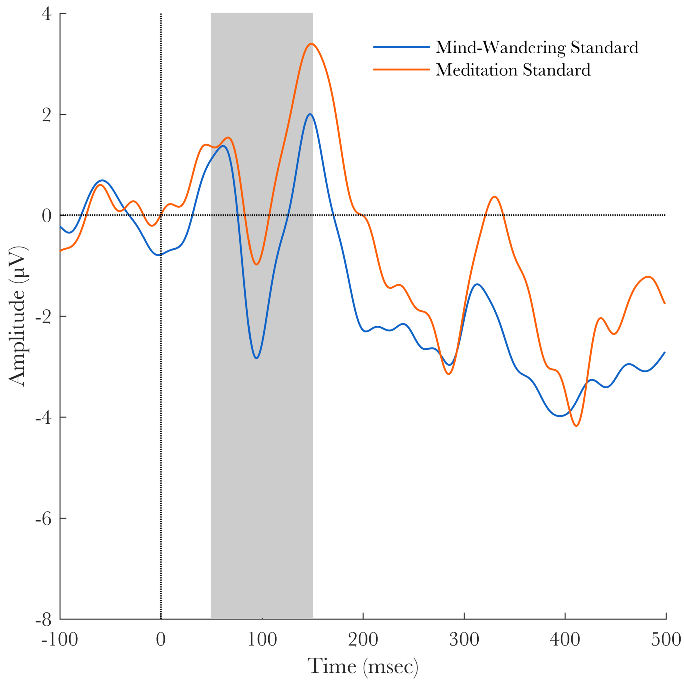

Figure 4. Experiment 1 condition (mind-wandering vs meditation) average waveform, amplitude (µV) by time (ms), for standard and deviant tones at Fz. Stimulus onset is marked by a vertical dotted line. The N1 selection range (50-150 ms) is blocked in grey.

Table 4

Descriptive statistics for N1 amplitude, and inferential statistics for N1 difference between mind-wandering and meditation conditions.

	Mean (µV)	Range (µV)	SD	*B*	error %	Student's *t*	Cohen's *d*
Mind-wandering	-4.72	-6.97,-2.70	1.72				
Meditation	-3.31	-6.02,-0.37	2.19	10.84	1.18e-6	-3.34**	-1.18

Note. **=p<.01.

Note. Alternate hypothesis: N1 amplitude is greater (more negative) during the mind-wandering condition than during meditation.

Note. Cauchy prior width =.71, one-tailed distribution, for the Bayesian *t*-test.

3 Experiment 2. Mental State and Repetition Suppression

3.1 Background

Experiment 1 (Chapter 2) suggested that the Biedermann et al. (2016) finding that the N1 is attenuated during meditation relative to mind-wandering is a reliable effect. As outlined in Chapter 2, while this effect may indeed be a product of meditation, it may also have been a product of experimental confounding factors, including mental state effects on repetition suppression, tone-related instruction effects on mental control, and condition order. The aim of Experiment 2 was to test if the first of these—effect of mental state on repetition suppression—was responsible for the attenuation of N1 in first-time meditators during meditation.

The N1 ERP typically attenuates under repeated stimulation. This decrement in response, called repetition suppression, is similar to refractory effects observed in single unit recordings (Baldeweg, 2006). Activated single neurons depolarise at the cell membrane to reach an activation threshold; they then enter a period of hyperpolarisation during which the electrical charge around the membrane is further from the activation threshold, and the neuron is less likely to fire. At the level of neural populations, auditory ERP repetition suppression could reflect widespread reduction of neural responsiveness following the synchronised firing required to produce the initial response (Budd, Barry, Gordon, Rennie, & Michie, 1998).

For the N1, repetition suppression is greater at short inter-stimulus intervals (ISIs) than at long ISIs. For example, Rosburg, Zimmerer, and Huonker (2010) found that for trains of five pure tones, N1 attenuated from the first to the second tone. Inter-stimulus intervals of 1800, 1200, and 600 ms resulted in greater repetition suppression—a greater amplitude difference between first and second tones—as the gap between stimuli decreased. The effect plateaued after the second tone; third to fifth tones elicited an N1 amplitude similar to that elicited by the second tone. Magnetoencephalogram (MEG) data, useful for its sensitivity to cortical activity and reduced smear of signals at the scalp compared to EEG (Huotilainen et al., 1998), has reinforced the finding that N1 magnitude attenuated for the second stimulus but not beyond. This and similar findings (Cowper-Smith, Green, Maessen, Bance, & Newman, 2013; Gilley, Sharma, Dorman, & Martin, 2005) give rise to the theory that N1 repetition suppression reflects a recovery or "refractory" period for neural populations generating the N1.

According to habituation theory, the attenuation of brain responses across repeated stimuli (response decrement) can be reversed if the sequence is broken by a new stimulus (dishabituation), or if a previously habituated stimulus is presented after a new stimulus (response recovery). Budd et al. (1998) tested the refractoriness explanation against the habituation theory of N1 repetition suppression. They used sequences of seven repeated tones and ISIs of 1, 3, or 10 s for each seven-tone sequence. The sixth tone in each train was higher in pitch (1500 Hz compared to 1000 Hz). This provided a measurement of response recovery in terms of N1 amplitude to the new high-pitch tone, and dishabituation in terms of N1 amplitude at previously habituated low-pitch tone. N1 amplitude reduced from the first to second stimulus at ISIs of 1 and 3 s, but not 10 s. There was no evidence of graded N1 decrement from second to fifth stimuli. There was also no evidence to suggest response recovery in terms of increased N1 amplitude from the fifth to sixth stimulus, or dishabituation in terms of increased N1 amplitude from the fifth to seventh stimulus. The dependence of N1 repetition suppression on ISI, coupled with the lack of evidence for response recovery and dishabituation, support the refractoriness explanation of N1 repetition suppression.

In contrast, Brattico, Tervaniemi, and Picton (2003) offer evidence for some degree of response recovery. They introduced rare, perceptually similar tones to a stream of repeated 1000 Hz tones. Rare tones were selected from a range between 800 and 1200 Hz. Increasing the frequency difference between the repeated and rare tones increased the N1 response recovery. This pitch similarity modulation of N1 repetition suppression suggests that refractoriness is specific to the perceptual features of repeated stimuli. Response recovery of N1 to perceptually dissimilar tones suggests some involvement of habituation in N1 repetition suppression.

Other studies have found that repetition suppression varies with a person's mental state, including intoxication. A study of alcohol consumption and repetition suppression found that N1 amplitude for unattended tones spaced at 2400 ms ISIs decreased among subjects who consumed low (0.55 g/kg body weight) and high (0.85 g/kg body weight) doses of ethanol alcohol, compared to placebo controls (Jääskeläinen, Pekkonen, Hirvonen, Sillanaukee, & Näätänen, 1996). Subjects who consumed ethyl alcohol showed no change at short ISIs (800 ms), suggesting there is no global increase in the magnitude of refractoriness after alcohol intake. Reduced N1 amplitude among experimental alcohol groups compared to placebo controls at 2400 ms ISIs, but not 800 ms ISIs, may reflect an increase in the latency of recovery of neural populations generating the N1. Repetition suppression is greater at short ISIs compared to long ISIs within the range of 0.3-12 s, and recovers quickly between 0.5 s and 3 s (Budd et al., 1998). Alcohol-induced N1 attenuation at long ISIs may demonstrate that the recovery rate is slowed, showing refractory effects at 2400 ms which would typically only be observed at shorter ISIs.

Like the Jääskeläinen et al. (1996) paradigm, the Biedermann et al. (2016) paradigm might have been prone to repetition suppression effects resulting from differences in a person's mental state—in this case meditation rather than intoxication. In Biedermann et al. (2016) and in Experiment 1 of this dissertation, first-time meditators were asked to focus on their breath. Unattended breathing at rest is typically short and shallow. Directing attention toward the breath may have induced atypically slow breathing, resulting in a physiological change similar to that induced by alcohol: lower overall physiological activation and subsequently a longer refractory period. This is consistent with the finding of a reduced N1 in the breath-counting meditation condition.

In the current study, I investigated if an effect of mental state on repetition suppression could explain the reduced N1 amplitude in first-time meditators during meditation compared to a mind wandering control condition. In Jääskeläinen et al. (1996), alcohol-induced differences in refractory effects disappeared at 800 ms ISIs. I attempted to eliminate the possible influence of meditation on an extended recovery period at 925-1125 ms ISIs (used in Experiment 1) by reducing the ISI to 725-925 ms. Changes in ISI within the range of .5 to 2 s have strong effects on N1 refractoriness (Budd et al., 1998). I consequently predicted that if N1-attenuation in first-time meditators was caused by the effect of mental state on repetition suppression, then reducing the ISI to 725-925 ms would eliminate this effect.

3.2 Methods

I tested 11 participants (8 females), with a mean age of 20 (SD = 1.92; range = 19,24). None of the participants included in this experiment had taken part in Experiment 1. The set-up and conditions were identical to those used in Experiment 1, except for the reduced ISI, which was jittered randomly between 725 and 925 ms across trials. Analyses were identical to those used in Experiment 1, except for the shape of the Cauchy prior distribution; I used a two-tailed prior distribution of effect sizes to compare against the findings, as the alternate hypothesis—any difference between conditions—does rule out effects in either direction. I include the directional test for the hypothesis that N1 reduces during meditation compared to mind-wandering, to facilitate comparison across experiments.

3.3 Results and Discussion

Across participants, the mean N1 amplitude to standard tones differed systematically across mind-wandering and meditation conditions. This effect was statistically reliable (B_{01} = 0.15). A B_{01} less than 1 reflects stronger evidence for the alternate hypothesis than for the null hypothesis. The B_{01} of 0.15 is below the .3 critical cutoff, and can be taken as conclusive evidence against the hypothesis of no difference. The B_{10} of 6.50 (1/0.15) reflects a 6.5-times better fit of the data to the alternate hypothesis (N1 different for mind-wandering and meditation conditions) than the null hypothesis. Figure 5 contrasts grand mean waveforms for the conditions. Table 5 sets out descriptive and inferential statistics for each condition.

The hypothesis used in Experiment 1—N1 attenuates during meditation compared to the mind-wandering control condition—produced a B of 12.91 (one-tailed Cauchy prior distribution). This reflects a 13-times better fit of the data to the model for the alternate hypothesis, that N1 attenuates during meditation compared to a mind-wandering control condition, than to the null model.

Contrary to the prediction, the shorter jittered ISIs did not eliminate condition differences in N1 amplitude. Rather, this experiment found that N1 attenuates during meditation compared to mind-wandering in first-time meditators, replicating the findings in Biedermann et al. (2016) and in Experiment 1. The discovery of an attenuation of the N1 during meditation in first-time meditators in three studies—Biedermann et al. (2016), Experiment 1, and Experiment 2—that have used shorter and longer ISIs suggests that N1 amplitude reduction during first-time meditation is not solely explained by effect of mental state of repetition repression.

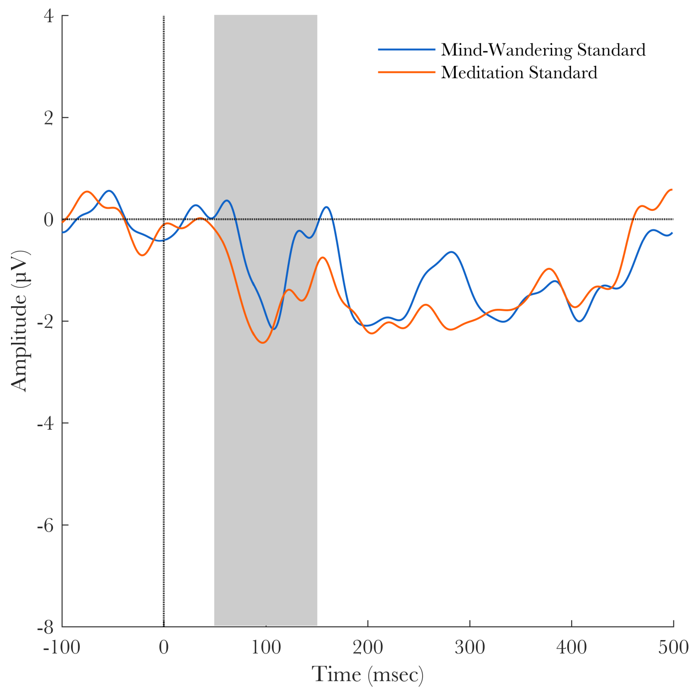

Figure 5. Experiment 2 condition (mind-wandering vs meditation) average waveform, amplitude (μV) by time (ms), for standard and deviant tones at Fz. Stimulus onset is marked by a vertical dotted line. The N1 selection range (50-150 ms) is blocked in grey.

Table 5

Descriptive statistics for N1 amplitude, and inferential statistics for N1 difference between mind-wandering and meditation conditions.

	Mean (μV)	Range (μV)	SD	B_{10}	B_{01}	error %	Student's t	Cohen's d
Mind-wandering	-4.50	-10.38,-0.85	2.06					
Meditation	-3.30	-7.67,-0.21	2.11	6.50	0.15	1.54e-6	-3.22**	-0.97

Note. **=p<.01.
Note. Alternate hypothesis: N1 during the mind-wandering condition does not equal N1 during meditation.
Note. Cauchy prior width =.71, two-tailed distribution, for the Bayesian t-test.

4 Experiment 3. Mental Control and Tone-Related Instructions

4.1 Background

N1 amplitude is modulated by the direction of attention toward or away from stimuli; attention directed toward stimuli is associated with an increase in N1 amplitude (Maclean, Öhman, & Lader, 1975). In Biedermann et al. (2016) and Experiments 1 and 2, the instructions for the direction of attention differed for the meditation and mind-wandering control conditions. For the mind-wandering condition, participants were told to "ignore the tones", while for the meditation condition, they were told to "notice the tones; do not attend to them; gently let them go". While both phrases instruct participants to direct their attention away from the tones, they were not consistent, and may have introduced attention-related effects on the size of the N1.

The two sets of instructions also altered the nature of participant's mental control in each condition. Wegner (1994) presented evidence for two opposing processes in mental control. The first process promotes availability of stimuli which are relevant to the task. The second process monitors task-irrelevant information to assess whether the first process should continue to operate. Under stress, the findings of the monitoring process become more accessible than those promoted by the task-relevant search. Exerting control over mental state in high-demand circumstances can bring task-irrelevant information into focus.

In the mind-wandering control condition, participants were given instructions to ignore the tones, indicating that these would be task-irrelevant stimuli throughout the treehouse building task. In the meditation condition, participants were instructed to notice the tones, but gently let them go. This may have removed anxiety about task performance and the cognitive demand of inhibiting responses to the tones. Thus, the balance of task-relevant focus and task-irrelevant monitoring would more effectively reduced low-level attentional responses to task-irrelevant stimuli in the meditation condition.

The aim of the current experiment was to remove the influence of differences in attention or mental state between the mind wandering control condition and the meditation condition by providing the same set of instructions for both conditions. If attention of mental state was responsible for the first-time meditator's N1 attenuation during meditation, then we would no longer find a larger N1 in first-time meditators to standard tones in the meditation condition compared to the mind-wandering control condition.

4.2 Methods

The methods for this experiment were identical to Experiment 1, except for the instructions. In both meditation and control conditions, participants were instructed as follows:

Mind-wandering. *Please close your eyes, and keep them closed until I ask you to open them. Throughout this experiment, sit comfortably and relax, with your back straight and both feet flat on the floor. I would like you to think about how to build a tree house. Think about a suitable location. What type of tree might you use? Would it be in Australia, or somewhere else? How might you get to the tree house? What materials would you use? What kinds of things would you fill it with? Think about the steps involved from beginning to end. After some time building your tree house, some tones will start to play through the headphones. Just notice them, do not attend to them. Gently let them go, and continue building your tree house. At the end of this task, I am going to ask you to draw or describe your tree house to me. Just keep your eyes closed, and remember: do not open them until I let you know.*

Meditation. *Please close your eyes again, and keep them closed until I let you know. Concentrate now on your breath: slowly breathing in, and slowly breathing out. With the first exhalation, count "one"; with the second exhalation, count "two"; and so on, until you reach 10. Then, start again at one. If you lose count, just start with the count of "one" on* *your next exhalation. Focus on your breath. When a thought arises, just notice it, let it go, and come back to your breath. After some time counting your breath, some tones will start to play through the headphones. Just notice them, do not attend to them. Gently let them go, and continue counting your breath. Please do not open your eyes until I come in and let you know, even if the tones stop.*

The analyses were identical to Experiment 2. I tested 12 participants (9 females) with a mean age of 24 (SD = 10.69; range = 18,52). None of the participants included in this experiment had taken part in Experiment 1 or 2.

4.3 Results and Discussion

Across participants, the mean N1 amplitude to standard tones at Fz differed systematically between mind-wandering and meditation conditions. This effect was statistically reliable (B_{01} = 0.03). The B_{01} of 0.03 reflects conclusive evidence against the hypothesis of no difference. The B_{10} of 37.90 (1/0.03) reflects a 38-times better fit of the data to the alternate hypothesis (N1 different for mind-wandering and meditation conditions) than the null hypothesis. Figure 6 contrasts grand mean waveforms for the conditions. Table 5 sets out descriptive and inferential statistics for each condition.

As in Biedermann et al. (2016) and Experiment 1 and Experiment 2, the mean N1 amplitude to standard tones was reduced in the meditation condition at the frontal midline electrode (Fz) compared to the mind-wandering control condition. This effect was statistically reliable (B = 75.72), based on the hypothesis that N1 attenuates during meditation compared to the mind-wandering control condition (one-tailed Cauchy prior distribution). The B of 75.72 for the hypothesis that N1 attenuates during meditation compared to the control condition reflects a 76-times better fit of the data to the hypothesised model than to the null model. Note that the magnitude of B reflects both the noise in the data and the size of the effect. Cohen's d shows an effect size of -1.27, similar to those found in Experiment 1 and Experiment 2, which suggests that the large B compared to the previous experiments reflects reduced noise in the data. This is reinforced by the strong trend toward a evidence for the alternate hypothesis in the sequential analysis of B, which plots B magnitude as each data point is added (Figure 7).

These findings suggest that instruction-induced differences in attention or mental state between the meditation and control conditions cannot fully explain the N1 attenuation during meditation compared to mind-wandering in first-time meditators. I did not test for systematic differences in effect size between experiments, and so cannot comment on any minor role tone-related instructions may have in the N1 attenuation. However, the N1 attenuation effect size was large (d = -1.27) and comparable to those found in Experiment 1 (d = -1.18) and Experiment 2 (d = -0.97). Thus, if there was an instruction-related effect on the outcomes of Biedermann et al. (2016) and Experiments 1, 2, and 3, the evidence suggests that this effect would have been small as well as non-significant.

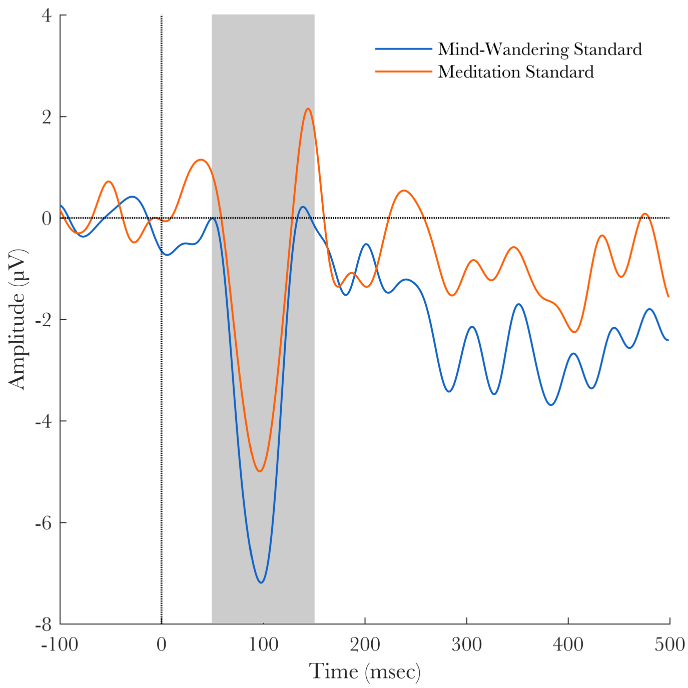

Figure 6. Experiment 3 condition (mind-wandering vs meditation) average waveform, amplitude (µV) by time (ms), for standard and deviant tones at Fz. Stimulus onset is marked by a vertical dotted line. The N1 selection range (50-150 ms) is blocked in grey.

Table 6

Descriptive statistics for N1 amplitude, and inferential statistics for N1 difference between mind-wandering and meditation conditions.

	Mean (µV)	Range (µV)	SD	B_{10}	B_{01}	error %	Student's *t*	Cohen's *d*
Mind-wandering	-5.17	-12.88,-1.42	3.26					
Meditation	-4.06	-10.59, 0.03	2.96	37.90	0.03	2.20e-7	-4.40**	-1.27

Note. **=p<.01.
Note. Alternate hypothesis: N1 during the mind-wandering condition does not equal N1 during meditation.
Note. Cauchy prior width =.71, two-tailed distribution, for the Bayesian *t*-test.

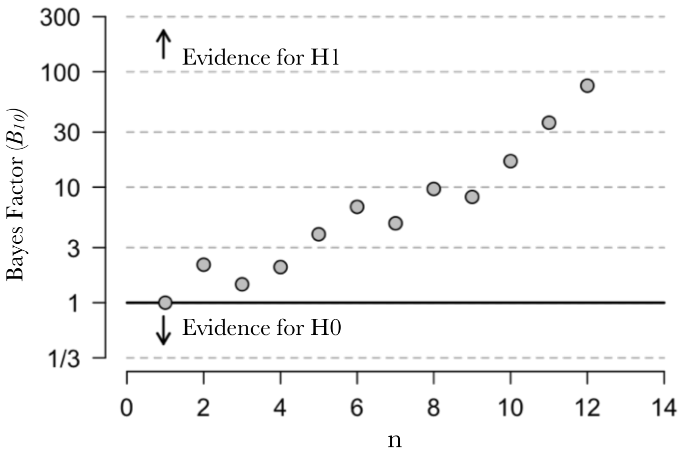

Figure 7. Sequential analysis of evidence for H1 and H0 (represented by *B*) with the addition of each participant.

5 Experiment 4. Reliability of Experiment 2 and Experiment 3

5.1 Background

This experiment was designed to test the reliability of findings in Experiment 2 and Experiment 3 of this dissertation. Experiment 2 found that N1 attenuation during meditation compared to a mind-wandering control condition was not dependent on the effect of mental state on repetition suppression, as demonstrated by a reduction in ISI. Experiment 3 found that N1 attenuation during meditation was a result of instruction-induced differences in attention or mental control, as demonstrated by a set of uniform instructions. In this experiment, Experiment 4, I tested the reliability of these findings in conjunction by using both a reduced ISI and uniform instructions in a new group of participants. Based on the outcomes of Experiment 2 and Experiment 3, I predicted an attenuated N1 during the meditation condition relative to the mind-wandering control condition in first-time meditators.

5.2 Methods

Methods were identical to those used in Experiment 1, except for changes in stimulus timing and tone-related instructions. Stimuli were presented at an ISI jittered between 725 and 925 ms, as used in Experiment 2. Instructions were the same for each condition ("notice the tones; do not attend to them"), as used in Experiment 3. I tested eight participants (6 females), with a mean age of 21.13 (SD=4.82, range=19, 33). None of the participants included in this experiment had taken part in Experiments 1-3.

5.3 Results and Discussion

As in Experiments 1-3, the mean N1 amplitude to standard tones across participants was reduced in the meditation condition at the frontal midline electrode (Fz) compared to the mind-wandering control condition. This effect was statistically reliable (B = 83.90). Figure 8 contrasts grand mean waveforms for the two conditions. The B of 83.90 for the hypothesis that N1 attenuates during meditation compared to the control condition reflects a 84-times better fit of the data to the hypothesised model than to the null model. Table 7 sets out descriptive statistics for each condition, with Bayesian and Student's t-test outcomes for pairwise comparisons.

As predicted, the first-time meditation effect was present despite the simultaneous use of a shorter ISI and uniform instructions between conditions. These findings do not rule out the possibility that conditions varied in refractory effects or effectiveness of mental control. However, they do suggest that N1 attenuation during first-time meditation, compared to a mind-wandering control condition, has little dependency on these factors. There is no trend toward a decrease in effect size from Experiments 2 and 3 to Experiment 4, as might be expected if ISI or tone-related instructions drove the N1 attenuation; the effect size of -1.92 for this experiment was greater than that elicited by Experiment 2 (d = -0.97) or Experiment 3 (d = -1.27).

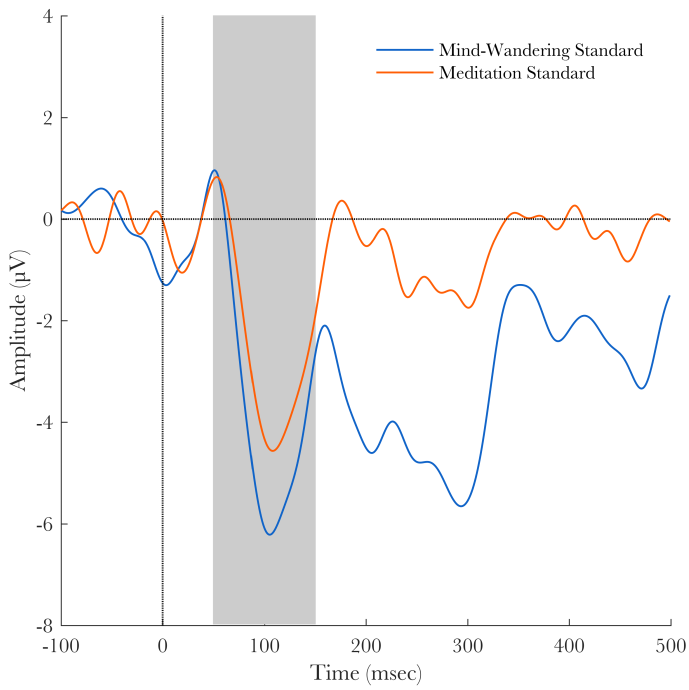

Figure 8. Experiment 4 condition (mind-wandering vs meditation) average waveform, amplitude (µV) by time (ms), for standard and deviant tones at Fz. Stimulus onset is marked by a vertical dotted line. The N1 selection range (50-150 ms) is blocked in grey.

Table 7

Descriptive statistics for N1 amplitude, and inferential statistics for N1 difference between mind-wandering and meditation conditions.

	Mean (µV)	Range (µV)	SD	*B*	error %	Student's *t*	Cohen's *d*
Mind-wandering	-4.59	-6.22, -2.91	1.19				
Meditation	-2.79	-4.57, 0.84	1.73	83.90	<0.01	-5.43**	-1.92

Note. **=p<.01.
Note. Alternate hypothesis: N1 amplitude is greater (more negative) during the mind-wandering condition than during meditation.
Note. Cauchy prior width =.71, one-tailed distribution, for the Bayesian *t*-test.

6 Experiment 5. Condition Order

6.1 Background

In addition to arousal effects on refractory periods, and instruction effects on mental control, order-of-condition effects might be responsible for the attenuation of N1 in first-time meditators during meditation, compared to a mind-wandering control condition. Long-term habituation is confounded with meditation effects in other studies which did not counterbalance condition order or include a control task (see Biedermann et al., 2016; Barwood et al., 1978; Becker & Shapiro, 1981; Corby et al., 1978; Joshi & Telles, 2009). Specifically, Biedermann et al. (2016) and all the previous experiments in this dissertation presented the meditation and control conditions in a fixed order, with the mind-wandering control condition always preceding the meditation condition. This means that the N1 attenuation during meditation could have been driven by extended exposure to stimuli, fatigue, or reduced test anxiety during meditation (second condition) compared to the control condition (first condition). The following experiment tests the effect of condition order on the N1 in first-time meditators.

6.2 Methods

This experiment was designed to investigate whether the attenuated N1 during meditation was due to, or mediated by, the order of conditions. The methods were the same as for Experiment 3, except that I reversed the order of conditions so that the meditation condition preceded the mind-wandering control condition. Tone-related instructions were matched across conditions to improve experimental control, as findings from Experiments 3 and 4 suggested that tone-related instructions did not drive the N1 attenuation during meditation. Participants drew the treehouse they had been imagining in the mind-wandering condition once both conditions were completed. They were given a short break between conditions to keep the spacing of conditions matched across experiments. I tested eight participants (6 females), with a mean age of 28 (SD = 13.21; range = 18,52). None of the participants included in this experiment had taken part in Experiments 1-4.

6.3 Results and Discussion

In contrast to Experiments 1-4, N1 amplitudes were reduced in the mind-wandering control condition compared to the meditation condition. This condition order effect was statistically reliable ($B = 5.18$). Figure 9 contrasts grand mean waveforms for the two conditions. Table 8 sets out descriptive statistics for each condition, with Bayesian and Student's *t*-test outcomes for pairwise comparisons. The Bayes Factor of 5.18 for the condition comparison at Fz represents a 5-times better fit for the data under the hypothesised order model than under the model for no difference. This model posits that N1 peak amplitude in the first condition (now meditation) is greater than that in the second condition (now mind-wandering). Note that the magnitude of *B* reflects both the size of the effect and the noise in the data. Whereas the *B* in this experiment is smaller than that found in Experiment 3, the effect size is large ($d = -0.94$), suggesting that the difference in *B* between experiments reflects more noise in the Experiment 5 data rather than a smaller effect.

The N1 attenuation during the second condition (mind-wandering) in this experiment suggests that condition order in Biedermann et al. (2016) and the previous experiments in this dissertation was responsible for N1 attenuation during the meditation condition, which always occurred second. Corby et al. (1978) came to a similar conclusion about N1 decrement across conditions in their study. They considered condition order essential to their study, as their second condition was designed to allow meditators to prepare for meditation and must occur before the meditation condition. Consequently, they did not randomise order. The N1 attenuated across conditions, as in Biedermann et al. (2016) and the experiments in this dissertation. The authors attribute this attenuation to inherent properties of N1, rather than to any effect of meditation. The findings of the current experiment further suggest that N1 attenuation across conditions is not a meditation effect among people who are meditating for the first time.

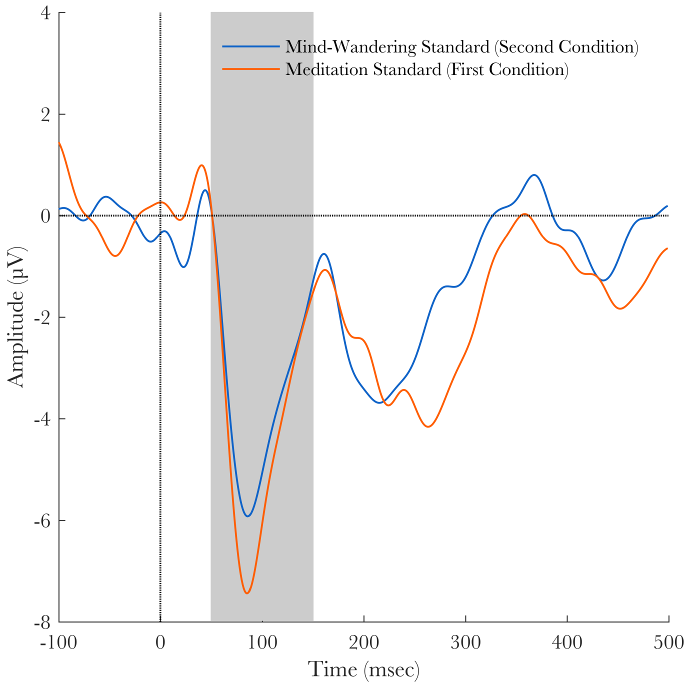

Figure 9. Experiment 5 condition (mind-wandering vs meditation) average waveform, amplitude (µV) by time (ms), for standard and deviant tones at Fz. Stimulus onset is marked by a vertical dotted line. The N1 selection range (50-150 ms) is blocked in grey.

Table 8

Descriptive statistics for N1 amplitude, and inferential statistics for N1 difference between mind-wandering and meditation conditions.

	Mean (µV)	Range (µV)	SD	*B*	error %	Student's *t*	Cohen's *d*
Mind-wandering	-4.75	-8.36, -1.71	2.54				
Meditation	-5.87	-8.61, -3.71	1.80	5.18	8.39e-6	-2.67*	-0.94

Note. *=p<.05; **=p<.01
Note. Alternate hypothesis: N1 amplitude is greater (more negative) during the first condition than during the second condition.
Note. Cauchy prior width =.71, one-tailed distribution, for the Bayesian *t*-test.

7 General Discussion

Meditation is associated with changes in low-level auditory attention, which can be measured through auditory ERPs. Meditation has both state effects on low-level attention, demonstrated in studies with control tasks (see Cahn & Polich, 2009; Delgado-Pastor et al., 2013), and trait effects on low-level attention, demonstrated by studies with a control group of non-meditators (see Atchley et al., 2016; Biedermann et al., 2016; Srinivasan & Baijal, 2007). However, meditation effects on low-level auditory attention may be obscured by confounds of experimental design which limit the clarity of comparisons between conditions or groups. Thus, the aim of this dissertation was to distinguish between confounds and true meditation effects on the auditory N1.

Specifically, we investigated a first-time meditation state effect of N1 attenuation, compared to a mind-wandering control task (Biedermann et al., 2016). State effects of meditation for first-time meditators in Biedermann et al. (2016) occurred in absence of a state effect for meditators, creating an interaction between meditation state and trait effects on low-level attention as measured by the N1. The interaction between condition (state) and group (trait) effects could reflect a true first-time meditation effect. That is, the N1 attenuation may have reflected effort experienced during early meditation training. In this case, N1 magnitude may serve as an index of basic meditation expertise. Alternately, the N1 attenuation during meditation compared to a mind-wandering control condition in first-time meditators could have resulted from an experimental confound which correlated with the meditation condition in non-meditators. The interaction between meditators' and non-meditators' N1 magnitude could then be interpreted in two ways: first, that non-meditators are susceptible to the confound, but meditators are not; second, that non-meditators and meditators are susceptible to the confound, but the effect of the confound on meditators was masked by an opposing meditation state effect. Each of these explanations has implications for interpreting comparisons between meditators and non-meditators, and for designing meditation research.

I designed five experiments to test whether an attenuated auditory N1 during first-time meditation could be called a meditation state effect, or whether it was driven by experimental confounds. The aim of Experiment 1 (Chapter 2) was to test the reliability of findings reported in Biedermann et al. (2016). I replicated the first-time meditation effect in Biedermann et al. (2016), with N1 peak amplitude attenuated during meditation. The aim of Experiment 2 (Chapter 3) was to test whether the influence of mental state on N1 refractoriness could explain the effect. I found no evidence for an effect of mental state on refractoriness in each condition, as estimated by reducing the ISI. The aim of Experiment 3 (Chapter 4) was to investigate the role of mental control induced by tone-related instructions in the first-time meditation effect. I found no evidence for an effect of mental control induced by different tone-related instructions for each condition; the first-time meditation effect remained when tone-related instructions were identical. Experiment 4 (Chapter 5) reinforced the findings of Experiment 2 and Experiment 3 by replicating the first-time meditation effect at short ISIs and with uniform tone-related instructions for each condition. The aim of Experiment 5 was to investigate the role of condition order in the first-time meditation effect. Biedermann et al. (2016) did not counterbalance condition order, as they were concerned that meditation state effects would carry over to the control condition if the meditation condition occurred first. I tested the role of condition order in the first-time meditation effect by reversing conditions so that the meditation condition occurred first, followed by the control condition. In contrast to the previous experiments, N1 was attenuated during the control condition. I therefore conclude that the attenuated N1 during first-time meditation cannot be called a meditation effect.

Rather, the effect is dependent on the order of conditions.

7.1 Repetition Suppression

The nature of the condition order effect on N1 amplitude might be best understood through previous studies of N1 attenuation. Studies that may explain an N1 order effect address repetition suppression, an ingrained process which automatically occurs under repeated stimulation, or mental factors such as attention and anxiety, which may in some cases correlate with condition order. I discuss findings from these studies and their impact on the interpretation of the condition order effect below.

Chapter 3 introduced the refractoriness theory of N1 suppression. Refractoriness theory states that the N1 is subject to a recovery period, which results in a reduced N1 to repeated stimulation across short sequences of stimuli when those stimuli are presented close together (Budd et al., 1998). Refractoriness studies demonstrate that N1 elicited by repeating stimuli attenuates from the first to the second stimulus in a sequence. The N1 to the third stimulus may attenuate further; however, beyond this point, the decrement in N1 plateaus. These findings are primarily relevant to short-term changes in N1—across adjacent stimuli, rather than the blocks of 666 stimuli presented in each condition in the experiments reported in this dissertation. Experiment 2 (Chapter 3) addressed the possibility of condition differences in refractoriness, and found no evidence that refractoriness explains N1 attenuation from the first to the second condition.

Chapter 3 also introduced the habituation theory of N1 repetition suppression. Habituation theory, for N1 repetition suppression and for other phenomena of repeated stimulation, states that repeated stimulation elicits a graded decrease in response. Two other criteria differentiate habituation from other forms of repetition suppression: response recovery for non-habituated stimuli, and dishabituation to previously habituated stimuli. These two criteria are not always included in habituation studies, leading to some confusion between habituation in the formal sense and an informal use of the term habituation for all graded decreases in response under repeated stimulation (i.e. repetition suppression) or for repetition suppression which partially satisfies these criteria. Brattico et al. (2003) addressed one of these criteria, response recovery, by demonstrating that repetition suppression is stronger for stimuli that are more perceptually similar to each other than for stimuli that are perceptually dissimilar (i.e., further apart in pitch). Rosburg et al. (2004) further demonstrated response recovery of N1 for non-habituated stimuli in a paradigm similar to that used to demonstrate refractory effects. They presented participants with sequences of six click stimuli at ISIs of 500 ms and inter-trial intervals of 8 s. The first five clicks in each sequence were identical in pitch and duration (1500 Hz, 6.6 ms); the sixth was higher in pitch (2000 Hz) and longer in duration (12.8 ms). There was no active task to focus or distract attention from the clicks. The N1 attenuated from the first click to the subsequent four repeated clicks in the sequence, as predicted by both refractoriness and habituation theories. The N1 to the sixth (non-habituated) click was greater than the N1 to the fifth click, and not reliably different to the first click. These findings offer evidence that N1 repetition suppression is sensitive to stimulus features, even in short sequences. Habituation, in the sense of a graded decrement over repeated stimulation which is stronger for similar than dissimilar stimuli, may be at work in the longer sequences of tones used in the experiments in this dissertation.

Active inhibition theory states that N1 repetition suppression is driven by a mechanism that compares incoming and previous stimuli, then actively suppresses activation for repeating stimuli. Primary support for the active inhibition theory comes from findings of N1 facilitation, rather than attenuation, at very short ISIs (below 300 ms; Budd & Michie, 1994). Repeated stimuli presented at intervals of less than 300 ms elicit a stable N1. This gives rise to the argument that N1 repetition suppression at 400-500 ms ISIs is driven by an active mechanism that is not able to implement a suppressed response within 300-400 ms post-stimulus-onset. Further evidence comes from neuroimaging data that shows a dissociation between regions with the strongest N1 initial response and the strongest N1 repetition suppression (Boutros, Gjini, Urbach, & Pflieger, 2011).

Studies of repetition suppression—whether taken as evidence for active inhibition or habituation—suggest that graded decrease under short-term and long-term repeated stimulation is typical of the N1 response. One study measured the N1 elicited by 32 blocks of 500 pure-tone oddball stimuli (20% pitch-deviants), presented over five hours, and segmented into four sessions by 10 minute breaks (May, Tiltinen, Sinkkonen, & Naatanen, 1994). This experiment is similar to the experiments in this dissertation in the use of extended blocks of passive oddball stimuli. The N1 elicited by standards attenuated across the four sessions. The same long-term repetition suppression mechanism may be at work in the decrease in N1 across blocks of stimuli observed in the experiments in this dissertation.

Another study measured the N1 elicited by standards in sequences of five active oddball tones (20% duration-deviants, button-press response; Roth & Kopell, 1969). Each sequence was presented at an ISI of 500 ms, 1 s, or 2 s, with 11 s between sequences. The N1 attenuated both within and across sequences. N1 attenuation within sequences was consistent with refractoriness theory: N1 elicited by all stimuli except the first in the sequence were reduced compared to the first stimulus, and the difference between first and subsequent stimuli was greater at short ISIs than at long ISIs. N1 attenuation across sequences was consistent with active inhibition or habituation theory: the average N1 elicited by the final sequence was attenuated compared to the initial sequence. Button-press responses to deviants were consistent in accuracy across the experiment, suggesting that N1 decrement was not due to disengagement from the task. This reinforces the theory that graded decrease in the N1 elicited by repeated, unattended stimuli is typical of the N1.

A third study addressed N1 attenuation for adjacent stimuli and across blocks (Woods & Courchesne, 1986). Pure tone stimuli were presented in sequences of six tones, with the fifth replaced 50% of the time by a pitch-deviant probe, and the sixth replaced 20% of the time by a duration-deviant target requiring a button-press response. Stimulus onset asynchrony (the interval from onset of one stimulus to onset of the next) was fixed at 500 ms or 1 s. Sequences were separated by 2 s or 6 s. Refractory effects presented in the form of N1 decrement among the first three stimuli in each sequence. In line with other refractoriness findings, the decrement was greater at stimulus onset asynchronies of 500 ms than at asynchronies of 1 s. Further, N1 attenuated across 5-minute blocks of the same stimuli. As in Roth and Kopell (1969), N1 attenuation across blocks was not associated with changes in the behavioural response to target tones, nor was it associated with subjectively experienced changes in vigilance.

These findings suggest that repetition suppression of the N1 occurs over short-term and a long-term stimulation. Short-term repetition suppression—demonstrated in adjacent stimulus studies—reflect refractoriness, habituation in the form of perceptual similarity effects, and active inhibition of the N1 to repeated stimuli. Long-term repetition suppression—demonstrated across sequences, blocks, and hours of stimulus presentation—may reflect both habituation and active inhibition of the N1. The inherent tendency of the N1 to attenuate under repeated stimulation across hundreds of tones—as opposed to refractory effects on adjacent tones—may explain the N1 attenuation from the first to the second condition in the experiments reported in this dissertation.

7.2 Attention and Anxiety

Factors associated with N1 attenuation independent of stimulus repetition include attention and anxiety. These factors may also be partly responsible for the condition order effect if they changed systematically over the course of the experiment. Attention to tones increases N1 amplitude (Maclean et al., 1975; Muller-Gass & Campbell, 2002; Öhman & Lader, 1972). Attention-related changes in N1 occur through direct effects on the exogenous N1 component (Hillyard, Hink, Schwent, & Picton, 1973; Woldorff & Hillyard, 1991) and through overlap with a processing negativity associated with active attention (Muller-Gass & Campbell, 2002; Näätänen & Michie, 1979) found by subtracting the waveform for unattended stimuli from the waveform for attended stimuli (Teder, Alho, Reinikainen, & Naatanen, 1993; Näätänen & Picton, 1987). For example, Woldorff and Hillyard (1991) simultaneously presented a stream of 5000 Hz tones to the left ear and a stream of 3400 Hz tones to the right ear. Stimuli in both streams were jittered between 120 and 320 ms. Both streams contained low intensity deviant tones, which made up 9% of the stimuli in each stream. However, only deviants in one stream required a button-press response. The N1 was larger when elicited by standards in the attended stream of tones, compared to the unattended stream of tones. Attentional effects on exogenous and endogenous components were demonstrated in the difference ERP between attended and unattended tones in the N1 latency range. The difference ERP was similar to the attended and unattended tone ERPs at central and parietal electrode sites, but not at frontal sites. Specifically, the difference ERP formed an extended negativity in the N1 latency range at frontal sites, which was distinct from the tri-phasic (negative-positive-negative) fluctuations of the individual ERPs for attended and unattended tones. In contrast, the difference ERP at central and parietal sites reflected the tri-phasic nature of individual ERPs for attended and unattended tones in the N1 latency range. The dissimilarity between the difference ERP measured frontally and the ERPs for attended and unattended tones could reflect an endogenous component elicited by attention to one stream, whereas the similarity between the difference ERP measured at central and parietal sites and the ERPs for attended and unattended tones could reflect attention-related enhancement of the exogenous N1 component. Woldorff and Hillyard (1991) found that the Fz site, used in the experiments in this dissertation, reflected findings at both central and frontal sites in its attentional information. Thus, attentional effects on exogenous and endogenous components of the N1 could be included in the measurement of N1 amplitude at the Fz site in the experiments in this dissertation. Although participants were not instructed to attend to stimuli in any condition, they may have initially attended to the stimuli as they adjusted to the novel situation. This would have resulted in the observed order effect through an increased processing negativity, or through attention-related increases in the "true" N1, in the first condition compared to the second condition. Some participants reported consciously attending to the tones, though this was not systematically measured. Recording participants' reports of attention to the tones may elucidate attention differences between conditions.

Increased anxiety is also associated with increased N1 amplitude (Al-Abduljawad, Baqui, Langley, Bradshaw, & Szabadi, 2008; Bastien, Turcotte, St-Jean, Morin, & Carrier, 2013). For example, expectation of a small electric shock increases auditory N1 amplitude (Al-Abduljawad et al., 2008). In the experiments reported in this dissertation, anxiety during the first condition may have increased N1 amplitude, as participants were unfamiliar with the task demands and the testing environment. Decreased anxiety over the testing session may have driven part of the N1 attenuation observed in the second condition. However, we do not have a measure of anxiety or tone-directed attention change throughout the testing session; we cannot gauge what role these factors played in N1 attenuation across conditions. Condition differences in anxiety could be assessed through participants' reports of their experience. Possible effects of anxiety during the first condition could be reduced by introducing an ice-breaker task at the start of the session to allow participants to adjust to the environment.

7.3 Implications and Future Directions

This series of experiments finding no true meditation effect in the condition difference in N1 validates the inclusion of non-meditators as a control group. First-time meditation effects could be problematic for interpreting novice and expert differences. Thus, finding no evidence of meditation effects on low-level attention in people meditating for the first-time is a useful sanity check for meditation and ERP research.

While the finding of no true meditation effects during first-time meditation is reassuring, the observed condition order effect on the N1 in this paradigm calls for further thought and investigation. First, it raises the question of whether the same order effects are present among meditators in the reviewed studies which did not counterbalance conditions. The role of N1 long-term habituation in meditation studies may be complicated by differential order effects among meditators and non-meditators. Long-term meditators in Biedermann et al. (2016) did not show order effects in N1 and P2 amplitudes (i.e., their N1 and P2 ERPs did not change between a mind-wandering control condition and subsequent meditation condition). In contrast, Corby et al. (1978) found evidence of N1 repetition suppression among expert and first-time meditators, with no differences between groups. It is therefore possible that expert meditators are affected by N1 habituation, but then compensate for N1 attenuation in later trials by maintaining an increased awareness of the tones during meditation, compared to non-meditators. Evidence in favour of this theory comes from Telles et al. (2015), who found decreased P1, P2, and N2 amplitudes to repeated clicks during a control condition compared to baseline rest, and no evidence of a decrease during meditation conditions. Thus, it is possible that a robust N1 amplitude in Biedermann et al. (2016) and P1, P2, and N2 amplitude in Telles et al. (2015) may demonstrate a meditation state effect in expert meditators that obscures a repetition suppression effect. Alternately, the robust N1 in Biedermann et al. (2016) may indicate less susceptibility to order effects in their expert meditator group. Meditators could produce N1 attenuation which is more consistent across blocks of stimuli, be more consistently relaxed across time, or be more consistently attentive to their primary task than non-meditators. Interesting questions arise from this possible meditator versus non-meditator difference in susceptibility to order effects. How long would a testing session have to be for an expert meditator's N1 to attenuate? Would N1 suppression among meditators be induced more effectively by extended session time or the number of stimuli presented? How far does this insusceptibility to order effects, if it is a real effect, generalise to other tasks? Addressing these questions may help interpret studies that have not counterbalanced condition order, and may inform theory of the mechanisms by which meditation changes low-level attention. These two possibilities of masked order effects vs insusceptibility to order effects could be tested empirically by asking meditators to complete a meditation task prior to a control task. If there is consistently no difference in N1 and P2 amplitude between conditions, we may conclude that meditators are not susceptible to order effects within that time-frame. If the N1 and P2 measured during meditation increases compared to the control condition, we may conclude that order effects were masking a meditation-state effect of increased sensory awareness among expert meditators.

Investigating the role of repeated stimulation and other order effects may inform interpretation of the difference between meditators' and non-meditators' N1. However, based on findings reported in this dissertation, and the current lack of research explaining meditation trait interactions with condition order, I suggest that order effects should be controlled for in future meditation experiment designs. Order of conditions may differentially affect non-meditators and meditators. Overlooking this may confound the comparison between meditators and non-meditators. Comparisons among meditators between conditions may also be influenced by condition order. We cannot confidently rule out the role of order in group or condition comparisons. Thus, counterbalancing order is essential for ensuring "meditation" effects reported are truly meditation effects.

The findings reported here also underline the reliance of meditation state effects on experience. Biedermann et al. (2016) investigated meditation trait and state effects through a two-by-two comparison of meditators and non-meditators, during meditation and non-meditation. They found evidence of a trait effect distinguishing meditators from non-meditators regardless of condition. They found an interaction between state and trait, with no difference between conditions among meditators, but an attenuated N1 during meditation among non-meditators. The findings of this dissertation suggest that there is no true meditation state effect on non-meditators in terms of N1 amplitude.

The role of experience, demonstrated by group comparisons between meditators and non-meditators (Atchley et al., 2016; Biedermann et al., 2016), suggests that meditation effects are not limited to meditative tasks. Meditation effects in non-meditative tasks, such as increased MMN across conditions (Biedermann et al., 2016), as well as increased ERP amplitudes to attended tones among meditators (Atchley et al., 2016), suggest that meditation trains attentive processes which affect non-meditative tasks. The extent to which meditation experience carries over to non-meditative tasks is not clear. Future research should investigate carry-over of meditation effects on low-level auditory attention to non-meditative tasks.

7.4 Conclusion

The findings reported here demonstrate the role that order of conditions can play in meditation research. First-time meditators, which have been used as a control group in meditation studies, are susceptible to order effects. These order effects can present as meditation state effects in studies with no control condition, or when conditions are not counterbalanced. Current research does not rule out the possibility of similar order effects among expert meditators. Research into the relationship between meditation and low-level attention may be best served by counterbalancing condition order to control for interactions between meditation and order effects that we do not yet understand.

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A Excluded Articles

Did not report meditation effects

Cosme and Wiens (2015)

McFadden et al. (2011)

van den Heuvel, Donkers, Winkler, Otte, and Van den Bergh (2015)

Did not report auditory ERPs

Abukonna, Yu, Zhang, and Zhang (2013)

Alderman, Olson, Brush, and Shors (2016)

Antonova, Chadwick, and Kumari (2015)

Beauregard, Courtemanche, and Paquette (2009)

Beng et al. (2015)

Bostanov et al. (2012)

C. A. Brown and Jones (2010)

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K. W. Brown, Goodman, and Inzlicht (2013)

Bumgartner and Epstein (1982)

Cahn, Delorme, and Polich (2013)

Chen et al. (2015)

Cole, Martyanova, and Palmiter (2001)

Crespo, Recuero, Galvez, and Begona (2013)

Dorjee, Lally, Darrall-Rew, and Thierry (2015)

Eddy, Brunye, Tower-Richardi, Mahoney, and Taylor (2015)

Faber et al. (2015)

Garland, Froeliger, and Howard (2015)

Goodrich, Wahbeh, Mooney, Miller, and Oken (2015)

Gootjes, Franken, and Van Strien (2011)

Grant and Rainville (2009)

Guglietti, Daskalakis, Radhu, Fitzgerald, and Ritvo (2013)

Ho, Sun, Ting, Chan, and Lee (2015)

Holzel et al. (2008)

Howells, Ives-Deliperi, Horn, and Stein (2012)

Jo, Hinterberger, Wittmann, and Schmidt (2015)

Jo, Schmidt, Inacker, Markowiak, and Hinterberger (2016)

Jo, Wittmann, Borghardt, Hinterberger, and Schmidt (2014)

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Kumar, Nagendra, Naveen, Manjunath, and Telles (2010)

Lakey, Berry, and Sellers (2011)

Larson, Steffen, and Primosch (2013)

Lee et al. (1997)

Lu and Lo (2008)

Luders, Cherbuin, and Kurth (2015)

Lutz, Greischar, Perlman, and Davidson (2009)

Lutz, Slagter, et al. (2009)

Mackenzie et al. (2014)

Malinowski, Moore, Mead, and Gruber (2015)

Mason, O'Sullivan, Blackburn, Bentall, and El-Deredy (2012)

McEvoy, Frumkin, and Harkins (1980)

McHugh and Wood (2013)

Moore, Gruber, Derose, and Malinowski (2012)

Ode, Robinson, and Hanson (2011)

Panjwani et al. (2000)

Quaglia, Goodman, and Brown (2015)

Reva, Pavlov, Loktev, Korenyok, and Aftanas (2014)

Saunders, Rodrigo, and Inzlicht (2016)

Schoenberg et al. (2014)

Sobolewski, Holt, Kublik, and Wrobel (2011)

Song, Schwartz, and Russek (1998)

Subramanya and Telles (2009)

Telles and Desiraju (1993)

Telles, Maharana, Balrana, and Balkrishna (2011)

Telles, Nagarathna, Nagendra, and Desiraju (1994)

Telles and Naveen (2004)

Telles, Raghavendra, Naveen, Manjunath, and Subramanya (2012)

Teper and Inzlicht (2013)

Terhaar, Viola, Baer, and Debener (2012)

Travis et al. (2009)

van Leeuwen, Singer, and Melloni (2012)

Wang, Zhang, Yang, Yang, and Yang (2014)

Wu, Lin, Chu, and Liang (2015)

Did not report meditation effects on auditory ERPs

Murthy, Janakiramaiah, Gangadhar, and Subbakrishna (1998)

B Descriptive and Inferential Statistics for N1, P2, and MMN

The tables below contain descriptive and inferential statistics for N1 (deviants), P2, and MMN for Experiments 1-5. Deviant-elicited N1 extraction was identical to standard-elicited N1 extraction detailed in Chapter 2. P2 and MMN extraction was identical to methods detailed in Biedermann et al. (2016). P2 and MMN mean amplitude was calculated in the range of 150-190 ms post-stimulus onset. All data are were recorded at the frontal midline electrode (Fz). The hypothesis for all experiments is greater N1 amplitude (more negative) during the first condition, compared to the second condition. Bayesian t-tests use a one-tailed Cauchy prior, width 0.71.

Table A.2.1

Descriptive and inferential statistics for N1 (deviants), P2, and MMN for Experiment 1

	Mind-wandering			Meditation			Pairwise Comparison			
Electrode	Mean	SD	Range	Mean	SD	Range	*B*	error (%)	Student's *t* (df: 7)	Cohen's *d*
N1 (deviants)	-6.24	2.49	-9.18, -1.75	-4.62	2.47	-7.99, -0.85	9.34	7.48e-7	-3.20**	-1.13
P2 (standards)	-1.37	1.19	-3.50, 0.35	0.19	0.81	-0.73, 1.44	19.20	5.62e-6	-3.88**	-1.37
P2 (deviants)	-2.10	1.16	-4.17, -0.63	<0.00	1.88	-2.44, 3.47	5.62	5.27e-6	-2.74*	-0.97
MMN	-0.73	1.29	-2.20, 1.02	-0.19	1.98	-1.71, 3.87	0.52	3.48e-6	-0.54	-0.19

Note. * = p<.05; ** = p<.01.

Table A.2.2

Descriptive and inferential statistics for N1 (deviants), P2, and MMN for Experiment 2

	Mind-wandering			Meditation			Pairwise Comparison			
Electrode	Mean	SD	Range	Mean	SD	Range	*B*	error (%)	Student's *t* (df: 10)	Cohen's *d*
N1 (deviants)	-6.65	2.06	-9.40, -3.90	-5.14	3.55	-12.66, -0.71	1.83	3.39e-5	-1.78	-0.54
P2 (standards)	-1.15	1.17	-2.68, 1.19	-0.81	1.29	-2.37, 1.11	0.82	1.54e-4	-1.11	-0.33
P2 (deviants)	-1.62	1.17	-4.27, 0.52	-0.52	1.86	-3.69, 3.35	5.17	8.11e-6	-2.56*	-0.77
MMN	-0.47	1.20	-2.86, 1.56	0.30	1.08	-1.32, 2.25	1.66	3.79e-5	-1.70	-0.51

Note. * = p<.05; ** = p<.01.

Table A.2.3

Descriptive and inferential statistics for N1 (deviants), P2, and MMN for Experiment 3

	Mind-wandering			Meditation			Pairwise Comparison			
Electrode	Mean	SD	Range	Mean	SD	Range	*B*	error (%)	Student's *t* (df: 11)	Cohen's *d*
N1 (deviants)	-6.73	3.33	-13.44, -0.57	-5.77	3.51	-11.74, 0.56	1.63	1.37e-4	-1.70	-0.49
P2 (standards)	-1.72	1.61	--3.82, 0.94	-0.39	1.40	-2.19, 1.99	156.27	1.22e-7	-4.92**	-1.42
P2 (deviants)	-0.94	1.80	-3.96, 1.51	-0.88	1.71	-3.09, 2.47	0.31	2.14e-4	-0.11	-0.03
MMN	0.78	1.46	-1.71, 2.96	-0.48	1.46	-2.53, 1.26	0.11	6.57e-5	2.27	0.66

Note. * = p<.05; ** = p<.01.

Table A.2.4

Descriptive and inferential statistics for N1 (deviants), P2, and MMN for Experiment 4

	Mind-wandering			Meditation			Pairwise Comparison			
Electrode	Mean	SD	Range	Mean	SD	Range	*B*	error (%)	Student's *t* (df: 7)	Cohen's *d*
N1 (deviants)	-6.14	2.20	-9.94, -2.66	-4.63	1.92	-7.66, -1.94	1.88	3.54e-5	-1.78	-0.63
P2 (standards)	-1.17	0.89	-1.91, 0.71	-0.29	1.05	-1.40, 2.08	11.57	1.77e-6	-3.40**	-1.20
P2 (deviants)	-1.62	1.30	-3.53, 0.30	-0.81	1.09	-2.04, 0.61	1.21	2.83e-5	-1.39	-0.49
MMN	-0.45	1.11	-2.18, 1.81	-0.52	1.25	-1.92, 1.47	0.31	3.47e-4	0.11	0.04

Note. * = p<.05; ** = p<.01.

Table A.2.5

Descriptive and inferential statistics for N1 (deviants), P2, and MMN for Experiment 5

	Mind-wandering			Meditation			Pairwise Comparison			
Electrode	Mean	SD	Range	Mean	SD	Range	*B*	error (%)	Student's *t* (df: 7)	Cohen's *d*
N1 (deviants)	-6.62	3.01	-11.45, -2.82	-7.14	2.12	-10.14, -3.86	0.61	6.38e-6	-0.71	-0.25
P2 (standards)	-1.47	1.89	-3.49, 1.31	-2.16	1.89	-4.33, 0.67	19.82	4.96e-6	-3.91**	-1.11
P2 (deviants)	-1.94	1.39	-4.25, 0.08	-2.33	1.55	-4.26, 0.07	0.58	5.57e-6	-0.66	0.09
MMN	-0.47	1.03	-1.28, 1.49	-0.17	1.46	-2.64, 1.86	0.50	2.78e-6	-0.49	-0.17

Note. * = p<.05; ** = p<.01.

C Human Research Ethics Approval

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MACQUARIE
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SYDNEY·AUSTRALIA

31 March 2016

Dear Dr Badcock

Reference No: 5201500921

Title: *Meditation and attention: Effects on behavioural and neurophysiological measures*

Thank you for submitting the above application for ethical and scientific review. Your application was considered by the Macquarie University Human Research Ethics Committee (HREC (Medical Sciences)).

I am pleased to advise that ethical and scientific approval has been granted for this project to be conducted at:

- Macquarie University

This research meets the requirements set out in the *National Statement on Ethical Conduct in Human Research* (2007 – Updated May 2015) (the *National Statement*).

D Instructions for Experimental Conditions

Experiment 1 and Experiment 2

Mind-wandering. Please close your eyes, and keep them closed until I ask you to open them. Throughout this experiment, sit comfortably and relax, with your back straight and both feet flat on the floor. I would like you to think about how to build a tree house. Think about a suitable location. What type of tree might you use? Would it be in Australia, or somewhere else? How might you get to the tree house? What materials would you use? What kinds of things would you fill it with? Think about the steps involved from beginning to end. After some time building your tree house, some tones will start to play through the headphones. Just ignore them, and continue building your tree house. At the end of this task, I am going to ask you to draw or describe your tree house to me. Just keep your eyes closed, and remember: do not open them until I let you know.

Meditation. Please close your eyes again, and keep them closed until I let you know. Concentrate now on your breath: slowly breathing in, and slowly breathing out. With the first exhalation, count "one"; with the second exhalation, count "two"; and so on, until you reach 10. Then, start again at one. If you lose count, just start with the count of "one" on your next exhalation. Focus on your breath. When a thought arises, just notice it, let it go, and come back to your breath. After some time counting your breath, some tones will start to play through the headphones. Just notice them, do not attend to them. Gently let them go, and continue counting your breath. Please do not open your eyes until I come in and let you know, even if the tones stop.

Experiment 3 and Experiment 4

Mind-wandering. Please close your eyes, and keep them closed until I ask you to open them. Throughout this experiment, sit comfortably and relax, with your back straight and both feet flat on the floor. I would like you to think about how to build a tree house. Think about a suitable location. What type of tree might you use? Would it be in Australia, or somewhere else? How might you get to the tree house? What materials would you use? What kinds of things would you fill it with? Think about the steps involved from beginning to end. After some time building your tree house, some tones will start to play through the headphones. Just notice them, do not attend to them. Gently let them go, and continue building your tree house. At the end of this task, I am going to ask you to draw or describe your tree house to me. Just keep your eyes closed, and remember: do not open them until I let you know.

Meditation. Please close your eyes again, and keep them closed until I let you know. Concentrate now on your breath: slowly breathing in, and slowly breathing out. With the first exhalation, count "one"; with the second exhalation, count "two"; and so on, until you reach 10. Then, start again at one. If you lose count, just start with the count of "one" on your next exhalation. Focus on your breath. When a thought arises, just notice it, let it go, and come back to your breath. After some time counting your breath, some tones will start to play through the headphones. Just notice them, do not attend to them. Gently let them go, and continue counting your breath. Please do not open your eyes until I come in and let you know, even if the tones stop.

Experiment 5

Meditation. Please close your eyes, and keep them closed until I ask you to open them. Throughout this experiment, sit comfortably and relax, with your back straight and both feet flat on the floor. Concentrate now on your breath: slowly breathing in, and slowly breathing out. With the first exhalation, count "one"; with the second exhalation, count "two"; and so on, until you reach 10. Then, start again at one. If you lose count, just start with the count of "one" on your next exhalation. Focus on your breath. When a thought arises, just notice it, let it go, and come back to your breath. After some time counting your breath, some tones will start to play through the headphones. Just notice them, do not attend to them. Gently let them go, and continue counting your breath. Please do not open your eyes until I come in and let you know, even if the tones stop.

Mind-wandering. Please close your eyes again, and keep them closed until I let you know. I would like you to think about how to build a tree house. Think about a suitable location. What type of tree might you use? Would it be in Australia, or somewhere else? How might you get to the tree house? What materials would you use? What kinds of things would you fill it with? Think about the steps involved from beginning to end. After some time building your tree house, some tones will start to play through the headphones. Just notice them, do not attend to them. Gently let them go, and continue counting your breath. At the end of this task, I am going to ask you to draw or describe your tree house to me. Just keep your eyes closed, and remember: do not open them until I let you know.

E Post-Test Questionnaire

Subjective Experiences of Task One

Below are some statements about your experience of the first task. Please rate how much you agree with each statement, from 1, 'strongly disagree', to 7, 'strongly agree'. Bear in mind that there is no wrong answer; we are interested in your subjective experience of the task.

Please circle the number that best expresses your experience of the **first task**.

		Strongly Disagree — Strongly Agree
1.	I was fully absorbed by the task.	1 2 3 4 5 6 7
2.	I found my mind constantly wandering away from the task	1 2 3 4 5 6 7
3.	I noticed what was happening around me	1 2 3 4 5 6 7
4.	I was aware of internal sensations like my breath and heart rate	1 2 3 4 5 6 7
5.	I found myself focusing so hard on the task that I did not notice anything else	1 2 3 4 5 6 7

Using the line below as a timeline for the **first task**, try to mark out visually which segments of the time you spent focused on the task.

PLEASE CONTINUE OVER THE PAGE…

Subjective Experiences of Task Two

Below are some statements about your experience of the second task. Please rate how much you agree with each statement, from 1, 'strongly disagree', to 7, 'strongly agree'. Bear in mind that there is no wrong answer; we are interested in your subjective experience of the task.

Please circle the number that best expresses your experience of the **second task**.

		Strongly Disagree … Strongly Agree
1.	I was fully absorbed by the task.	1 2 3 4 5 6 7
2.	I found my mind constantly wandering away from the task	1 2 3 4 5 6 7
3.	I noticed what was happening around me	1 2 3 4 5 6 7
4.	I was aware of internal sensations like my breath and heart rate	1 2 3 4 5 6 7
5.	I found myself focusing so hard on the task that I did not notice anything else	1 2 3 4 5 6 7

Using the line below as a timeline for the **second task**, try to mark out visually which segments of the time you spent focused on the task.

F Bayes Factor Robustness Check

Figures A.4.1 to A.4.5 show the Bayes Factor (B) for each experiment across a range of Cauchy prior widths. Points marked identify the user prior of 0.71 (grey), wide prior of 1.00 (black), and ultrawide prior of 1.41 (white).

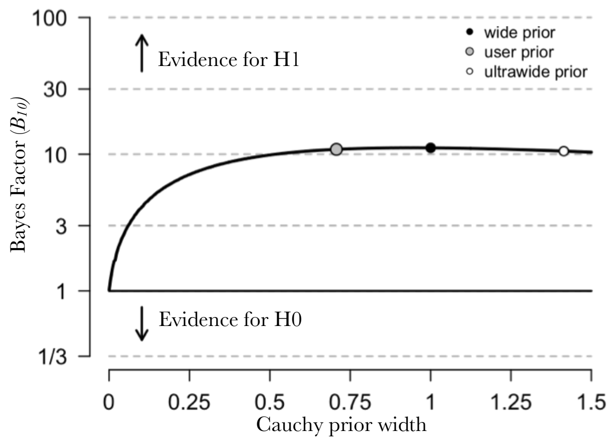

Figure A.4.1. Robustness check for Experiment 1 (Chapter 2)

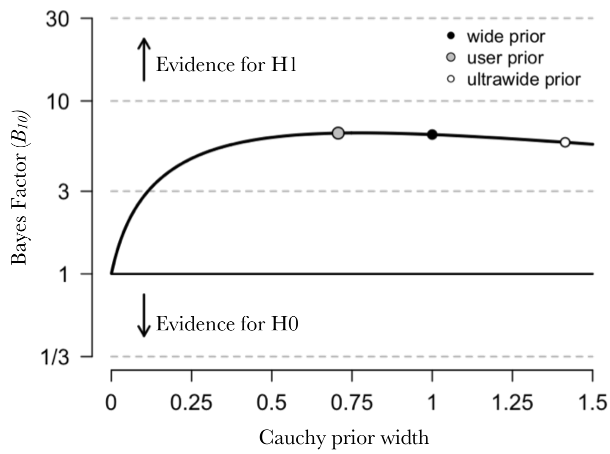

Figure A.4.2. Robustness check for Experiment 2 (Chapter 3)

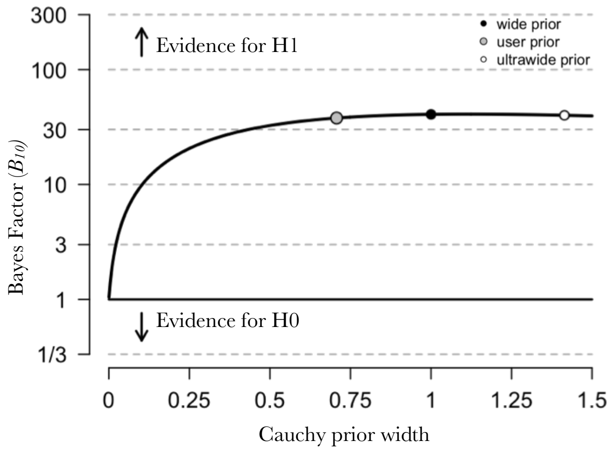

Figure A.4.3. Robustness check for Experiment 3 (Chapter 4)

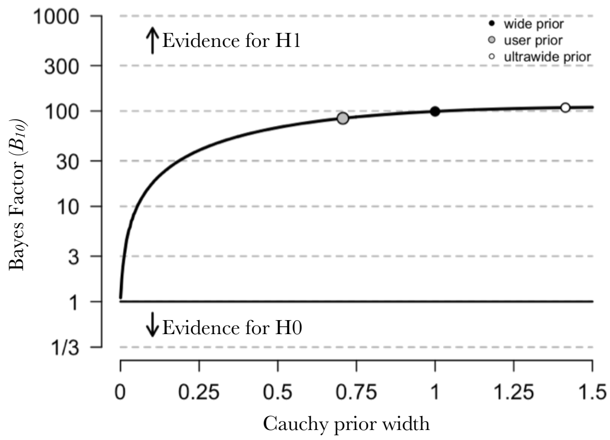

Figure A.4.4. Robustness check for Experiment 4 (Chapter 5)

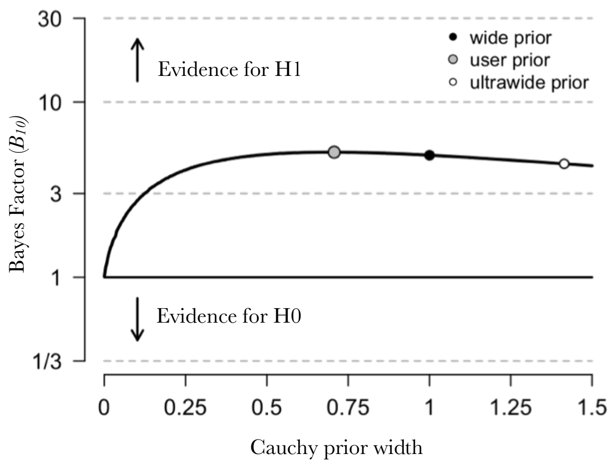

Figure A.4.5. Robustness check for Experiment 5 (Chapter 6)