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Non-dual awareness and sensory processing in meditators: Insights from startle reflex modulation

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ABSTRACT

Startle modulation paradigms, namely habituation and prepulse inhibition (PPI), can offer insight into the brain's early information processing mechanisms that might be impacted by regular meditation practice. Habituation refers to decreasing response to a repeatedly-presented startle stimulus, reflecting its redundancy. PPI refers to response reduction when a startling stimulus "pulse" is preceded by a weaker sensory stimulus "prepulse" and provides an operational measure of sensorimotor gating. Here, we examined habituation and PPI of the acoustic startle response in regular meditators ($n = 32$), relative to meditation-naïve individuals ($n = 36$). Overall, there was no significant difference between meditators and non-meditators in habituation or PPI, but there was significantly greater PPI in meditators who self-reported being able to enter and sustain non-dual awareness during their meditation practice ($n = 18$) relative to those who could not ($n = 14$). Together, these findings suggest that subjective differences in meditation experience may be associated with differential sensory processing characteristics in meditators.

1. Introduction

Meditation, a form of mental training using a range of practices and techniques, has been gaining popularity across countries and cultures to promote a heightened state of awareness, efficient emotion regulation and psychological well-being (reviews, Álvarez-Pérez et al., 2022; Goyal et al., 2014; Gu, Strauss, Bond, & Cavanagh, 2015; Keng, Smoski, & Robins, 2011), especially in the context of adverse short and long-term mental health impacts of the recent Coronavirus Disease 2019 (COVID-19) pandemic (Antonova, Schlosser, Pandey, & Kumari, 2021; Behan, 2020). The meditation approach most researched in recent years is 'mindfulness' which has been defined as the ability to bring awareness to the present moment and experience it with a sense of openness and lack of judgement (Kabat-Zinn, 2013). The operational definitions of mindfulness meditation, as secularly defined, emphasise two components: i) the self-regulation of attention on the present-moment experience; and ii) an orientation or attitude towards an experience which is that of openness, acceptance, non-judgement and curiosity (e.g., Bishop et al., 2004; Shapiro, Carlson, Astin, & Freedman, 2006). Some

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researchers have also emphasised intention as the part of the first component, i.e., *purposefully* paying attention to the present moment (e.g., Shapiro et al., 2006; Holas & Jankowski, 2012). Mindfulness practice as secularised from Eastern traditions, particularly Buddhism and other spiritual practices (Singla, 2011), typically progresses from directing the present-moment non-judgemental awareness towards the breath and bodily sensations to the awareness of feelings and thoughts before becoming present without an explicit focus. At more advanced stages of mindfulness practice development, practitioners may achieve the ability to enter a state in which their awareness of the self and other/surroundings are perceived as one, without separation (Josipovic, 2010, 2014; Lutz, Dunne, & Davidson, 2007), referred to as 'non-dual mindfulness' (Dunne, 2011).

There are numerous confirmations of a positive association between different meditation practices (e.g., mantra meditation, mindfulness) and psychological health, including increased self-awareness, emotion regulation (e.g., noticing negative experiences earlier and overcoming the negative reactions), and improved mood (reviews, Álvarez-Pérez et al., 2022; Behan, 2020; Dunning et al., 2019; Goyal et al., 2014; Gu et al., 2015; Keng et al., 2011). The exact mechanisms underlying these effects or associations (both across and within different meditation practices) remain to be fully established and may vary according to particular style/s of practice (Lutz, Jha, Dunne, & Saron, 2015). The two main cognitive mechanisms thought to underlie the beneficial effects of mindfulness meditation on mental health and well-being are 'meta-awareness' and 'decentring' (an individual's ability to observe their experience, thoughts, and emotions as passing events in the mind), as these are found to increase following mindfulness training (e.g., Bieling et al., 2012; Hargus, Crane, Barnhofer, & Williams, 2010; Orzech, Shapiro, Brown, & McKay, 2009; Teasdale et al., 2002). According to a theoretical model (Dahl, Lutz, & Davidson, 2015) which classified meditation practices into three families (attentional, constructive, and deconstructive), the attentional meditative practices focus on the cultivation of attentional control and meta-awareness in order to reduce experiential fusion; constructive meditative practices highlight reappraisal and perspective-taking to alter the contents of thoughts and emotions; and the deconstructive meditative practices use self-inquiry to examine the dynamics of one's perception and emotion, questioning validity of beliefs which serve as a basis for maladaptive self-related processing. The model emphasises the multifaceted nature of meditation and is supported by recent neuroimaging findings (Guidotti et al., 2023). Further research using precise markers of early information processing can help to further advance this field.

Startle modulation paradigms have been utilised to index brain's automatic and early sensory information processing mechanisms in a wide variety of contexts (reviews, Dawson, Schell, Swerdlow, & Filion, 1997; Filion, Dawson, & Schell, 1998; Santos-Carrasco & De la Casa, 2023). The startle response, a defensive reflex in reaction to an abrupt, strong sensory stimulus, is easily measurable in a human laboratory setting and shows several forms of plasticity, including habituation and prepulse inhibition (PPI). Habituation occurs following repeated presentation of the same startling stimulus (Geyer & Braff, 1982), reflecting its redundancy in absence of any behavioural consequences. PPI refers to a reliable reduction in startle response amplitude to a strong sensory stimulus, the pulse (e.g. a loud noise), if this is preceded by 30–150 ms by a weak near-threshold stimulus, the prepulse (e.g. weak noise) (Graham, 1975). PPI is considered to provide an operational index of sensorimotor gating: while information processing resources are directed to the prepulse, any incoming information (i.e. the pulse) is attended to at a reduced level, thereby protecting the processing of the prepulse. This explanation is further supported by the finding showing relatively less PPI when two prepulses in close proximity (60–120 ms) precede the pulse relative to when there is only one prepulse closely preceding the pulse (Kumari et al., 2003), conceivably because the second prepulse is attended to at a reduced level while the first prepulse is being processed and thus it becomes less effective in inhibiting the startle response to the pulse. Less-than-normal PPI has been linked to sensory over-stimulation, distractibility and thought disorder in clinical populations (Geyer, Swerdlow, Mansbach, & Braff, 1990; Karper et al., 1996; Kumari et al., 2008).

In line with the potential utility of startle paradigms to advance the neuroscience of mindfulness, a study by Antonova, Chadwick, and Kumari (2015) yielded tentative evidence of reduced startle habituation in mindfulness meditators with intense practice routine ($n = 12$) relative to meditation-naïve individuals ($n = 12$ per group), consistent with the notion that their sustained and receptive awareness fosters openness to incoming stimulus, even if repetitive or aversive. However, in the same study (Antonova et al., 2015), meditators with moderate intensity practice showed stronger habituation than both non-meditators and intensely-practiced meditators, introducing the idea that the relationship between mindfulness practice intensity and startle habituation may be non-linear. Kumari et al. (2023) extended this line of enquiry to self-reported dispositional mindfulness (DM), trait mindfulness as an innate personality characteristic as opposed to mindfulness trained through mindfulness practice (Rau & Williams, 2016), and reported a medium size association between (stronger) habituation and DM in meditation-naïve adults ($n = 26$). This finding is seemingly consistent with relatively stronger habituation in the moderate-practice meditator subgroup in Antonova et al. (2015) study. Furthermore, Kumari et al. (2023) observed that self-reported alexithymia (indexing difficulties in describing and identifying feeling, and externally-oriented thinking), which correlated negatively with DM, was also associated with a weaker habituation, though it did not make a unique contribution after DM had been accounted for. Further work incorporating both trained and dispositional trait mindfulness is needed to establish the replicability of these findings. Concerning PPI in the context of mindfulness, Kumari, Hamid, Brand, and Antonova (2015) observed similar level of PPI in meditators and non-meditators. The meditators, however, did perform better on attention tasks which all participants were required to complete while undergoing PPI assessment (Kumari et al., 2015), indirectly suggesting more efficient attentional processing or resource allocation in this group. A later study (Åsli, Johansen, & Solhaug, 2021) found no effect of a brief single-session mindfulness training on PPI. It is possible that, similar to habituation, the effects of meditation practice on PPI also vary depending on the PPI paradigm as well as specific characteristics of the meditation practice/s or meditators.

The present study aimed to further characterise sensory information processing profiles of regularly meditating individuals, relative to meditation-naïve individuals, as assessed by habituation and PPI of the acoustic startle response. For startle habituation, we used the same paradigm as used by Kumari et al. (2023) and tentatively hypothesised, based on Antonova et al. (2015) findings, that experienced meditators would exhibit less habituation in comparison to meditation-naïve individuals. We, however, expected a

Table 1
Sample characteristics classified by meditation status and sex.

	Meditators						Non-meditators					
	Males (n = 18)		Females (n = 14)		Total (n = 32)		Males (n = 20)		Females (n = 16)		Total (n = 36)	
	Mean (SD)	Range	Mean (SD)	Range	Mean (SD)	Range	Mean (SD)	Range	Mean (SD)	Range	Mean (SD)	Range
Age (years)	40.56 (13.43)	24–67	47.93 (11.53)	23–62	43.78 (12.98)	23–67	41.80 (13.00)	28–70	39.63 (12.83)	23–68	40.83 (12.79)	23–70
Five Facet Mindfulness Questionnaire (FFMQ)												
Observing	31.50 (4.83)	22–40	33.29 (3.49)	29–40	32.28 (4.33)	22–40	25.50 (6.54)	8–36	25.19 (8.32)	13–40	25.36 (7.27)	8–40
Describing	32.44 (6.07)	18–40	32.43 (4.38)	27–40	32.44 (5.31)	18–40	28.50 (6.39)	19–40	29.44 (5.88)	19–40	28.92 (6.10)	19–40
Act Aware	31.00 (5.95)	21–40	30.93 (4.78)	23–40	30.97 (5.38)	21–40	27.95 (4.38)	20–34	26.06 (8.35)	14–40	27.11 (6.42)	14–40
Non-Judging	30.33 (8.11)	14–40	31.36 (5.73)	21–40	30.78 (7.08)	14–40	25.30 (7.33)	11–40	25.56 (7.68)	16–39	25.86 (7.40)	11–40
Non-React	26.28 (4.76)	16–35	25.71 (3.15)	21–30	26.03 (4.08)	16–35	23.15 (4.80)	15–34	21.50 (5.10)	12–30	22.42 (4.9406)	12–34
Total without Observing*	120.06 (18.90)	89–152	120.43 (13.40)	98–144	**120.22 (16.47) ↑**	89–152	104.90 (11.48)	75–133	103.56 (17.83)	70–127	104.31 (14.43)	70–133
Toronto Alexithymia Scale-20 items (TAS-20)												
DDF	9.33 (3.74)	5–18	9.64 (2.79)	5–15	9.47 (3.31)	5–18	11.35 (4.69)	5–22	11.75 (4.12)	6–23	11.53 (4.39)	5–23
DIF	11.67 (4.68)	7–20	11.21 (3.94)	7–17	11.47 (4.31)	7–20	12.50 (4.25)	7–19	14.06 (6.86)	7–34	13.19 (5.53)	7–34
EOT	14.61 (4.16)	8–23	16.00 (3.82)	10–23	15.24 (3.95)	8–23	18.55 (4.58)	12–28	19.19 (3.76)	13–27	18.83 (4.19)	12–28
Total*	35.61 (10.13)	23–58	36.85 (7.49)	25–49	**36.16 (8.95) ↓**	23–58	42.40 (8.57)	26–57	45.00 (11.79)	32–79	43.55 (10.06)	26–79
Difficulties in Emotion Regulation Scale (DERS)												
Non-Accept	9.78 (4.85)	6–23	9.43 (4.74)	6–23	9.62 (4.73)	6–23	14.30 (6.18)	6–26	14.00 (6.31)	6–26	14.17 (6.15)	6–26
Goals	10.83 (4.35)	5–19	11.29 (3.77)	6–18	11.03 (4.05)	5–19	13.85 (4.94)	5–22	14.37 (4.86)	9–23	14.08 (4.84)	5–23
Impulse	8.83 (3.15)	6–18	9.57 (3.32)	6–16	9.16 (3.19)	6–18	12.60 (4.88)	6–25	13.81 (7.00)	6–28	13.14 (5.86)	6–28
Lack_Aware	12.89 (4.08)	6–18	11.57 (3.00)	6–16	12.31 (3.66)	6–18	14.25 (5.08)	8–27	16.00 (4.84)	6–24	15.03 (4.98)	6–27
Strategies	12.11 (3.48)	8–22	12.64 (4.41)	8–24	12.34 (3.86)	8–24	17.80 (8.02)	8–35	20.50 (8.85)	10–38	19.00 (8.39)	8–38
Clarity	8.67 (3.74)	5–19	7.79 (2.26)	5–12	8.28 (3.16)	5–19	10.30 (3.11)	6–18	11.62 (3.46)	5–15	10.44 (3.23)	5–18
Total*	63.11 (17.76)	39–98	62.29 (12.98)	46–87	**62.75 (15.61) ↓**	39–98	83.10 (20.58)	50–125	89.31 (22.13)	61–135	86.86 (21.21)	50–135

Note. *Significantly ($p < 0.05$) higher ↑ or lower ↓ in meditators, compared to non-meditators. Subscale Means and SDs presented only for information.
Abbreviations: Act Aware = Acting with Awareness; Non-react: Non-reactivity; DDF = Difficulty Describing Feelings; DIF = Difficulty Identifying Feelings; EOT = Externally-Oriented Thinking; Non-Accept = Non-acceptance of Emotion; Goals = Difficulties Engaging in Goal-directed Behaviour; Impulse = Impulse Control Difficulties; Lack_Aware = Lack of Emotional Awareness; Strategies = Limited Access to Emotion Regulation Strategies; Clarity = Lack of Emotional Clarity.

stronger habituation in association with a higher level of DM in meditation-naïve individuals following Kumari et al. (2023). For PPI, we used a variation of the paradigm (Kumari et al., 2003), where a pulse is preceded by one or two prepulses in close proximity. We hypothesised that there will be less PPI when the pulse is preceded by two prepulses in close proximity, relative to when it is preceded by only one prepulse, in non-meditators (Kumari et al., 2003), and tentatively hypothesized that this effect may be reduced or absent, assuming a 'quicker early processing' and 'degrading' of sensory information (and thus less disruptive impact of the first prepulse on processing of the second prepulse) in meditators. Following the same argument, we hypothesised relatively lower PPI in meditators also on single prepulse trials (with 'less' impact of the prepulse on the pulse processing). If found, this pattern of effects would demonstrate a quick(er) processing of incoming information without causing sensory overload in meditators. However, we also considered an alternative hypothesis that meditators may show stronger PPI, regardless of one or two prepulses preceding the pulse, given previous observations of poor PPI in association with a range of psychopathologies (reviews, Santos-Carrasco & De la Casa, 2023; Swerdlow, Braff, & Geyer, 2016) and generally a positive association between mindfulness (trained or dispositional) or other types of meditation practice and psychological well-being (Keng et al., 2011; Tomlinson, Yousaf, Vittersø, & Jones, 2018). If the findings support our alternate hypothesis, it would perhaps indicate a 'deeper' rather than 'faster processing and degradation' of near-threshold environmental stimuli (prepulses, 14 dB above background) in meditators. Furthermore, we explored possible differences amongst the subgroups of meditators using (primarily) attentional, constructive or deconstructive meditative practices (Dahl et al., 2015) and the influence of self-reported ability to enter and sustain non-dual awareness during meditation practice, given its unique neural signature (Josipovic, 2010, 2014; Josipovic, Dinstein, Weber, & Heeger, 2012), in startle habituation and PPI of the meditators.

In addition, this study examined alexithymia (reflecting difficulties in recognising, expressing and describing one's emotions; Sifneos, 1973) and difficulties in emotion regulation in meditators, compared to non-meditators. There is previous evidence of a negative association between alexithymia and DM (e.g., Kumari et al., 2023) and meditation-induced improvements in emotion regulation (e.g., Basso, McHale, Ende, Oberlin, & Suzuki, 2019). We thus hypothesised lower alexithymia scores and fewer difficulties in emotion regulation, on average, in meditators relative to non-meditators. Lastly, we explored possible associations of habituation and PPI measures with alexithymia and difficulties in emotion regulation, across and within the meditator and non-meditator groups.

2. Methods

2.1. Participants and design

The study involved two groups of healthy adults (aged 22–70 years): Group 1: regularly meditating individuals (meditators, n = 32), Group 2: meditation-naïve individuals (non-meditators, n = 36) (see Table 1). Initially, the sample consisted of 73 participants (35 meditators, 38 non-meditators) but three meditators with incomplete or unclear meditation history and two non-meditators with noisy psychophysiological data had to be excluded. Based on our previous studies which showed significant differences between the meditator and non-meditator groups with medium-to-large effect sizes (Kumari et al., 2015, visual attention task during PPI; Antonova et al., 2015; startle habituation), we required 29 participants per group (assuming Cohen's $d \geq 0.75$) to detect the hypothesised between-group differences ($p < 0.05$) with 80 % power, as determined using G*power3 (Faul, Erdfelder, Lang, & Buchner, 2007). We slightly overrecruited in each group to ensure a minimum of 29 participants per group with usable data. All participants were assessed on a single occasion.

Participants were recruited via distribution of research posters through online platforms, in the local area, and also to the National Mindfulness centres in order to recruit individuals who meditate regularly using secular mindfulness or other practices (e.g., secular mindfulness, Vipassana, Tibetan Vajrayana, Mahayana, Theravada, Transcendental Meditation, Raj Yoga Meditation, Zen) with likely effects ranging from 'simple relaxation' to a 'higher sense of well-being' (Dahl et al., 2015; Lutz et al., 2015).

The inclusion criteria required all participants to (i) be fluent in English, (ii) be aged 18–70 years, (iii) not suffer (as self-reported) from any ear disorder or hearing impairment and have normal (or corrected-to-normal) vision, (iv) have no current or previous history of psychiatric or neurological problems, drug abuse or known cognitive impairment, and (v) not be on any regular psychoactive medication, and not be consuming more than 28 units of alcohol per week or more than 6 units of caffeinated beverages a day. In addition, the criteria for the meditator group required them to have been practicing meditation for at least 20 min a day, 5 days a week, for at least 1 year.

The study was approved by the college of Health, Medicine and Life Sciences ethics committee, Brunel University London (Reference: 12411-LR-Nov/2018-15029-2). All participants gave written informed consent after the study's aim and procedures had been explained to them, and were compensated for their time (£30 Amazon voucher) and travel.

2.2. Sample characterisation: Self-report scales

Detailed meditation history, including the length and style of practice, was obtained for meditators using a self-report questionnaire used in our previous studies (Antonova et al., 2015; Kumari et al., 2017). Their ability for dual awareness was determined based on the response to "Can you enter a non-dual state easily during practice?" and (if answering affirmatively) "For how long?" In addition, all participants completed self-report measures of DM, alexithymia and emotional regulation.

DM was assessed using the 39-item Five Facet Mindfulness Questionnaire (FFMQ, Baer, Smith, Hopkins, Krietemeyer, & Toney, 2006). The five facets are: (1) *Observing* (e.g., "I pay attention to sensations, such as the wind in my hair or sun on my face."), (2) *Describing* (e.g., "I have trouble thinking of the right words to express how I feel about things." with reverse scoring), (3) *Acting with Awareness* (e.g., "I find it difficult to stay focused on what's happening in the present." with reverse scoring), (4) *Non-judging* (e.g., "I make judgments about whether my thoughts are good or bad." with reverse scoring), and (5) *Non-reactivity* (e.g., "In difficult situations, I can pause without immediately reacting."). All facets have 8 items, except the *Non-reactivity* facet which has 7 items. Each item is rated on a 5-point Likert scale from 1 to 5 ('never or very rarely true', 'rarely true', 'sometimes true', 'often true' or 'very often or always true'; some items reverse-scored). Higher scores demonstrate higher levels of DM. The FFMQ is one of the most frequently used measure of DM, and has good-to-excellent psychometric properties [Cronbach's alpha coefficients = 0.75 to 0.93 (Baer et al., 2008; Shallcross, Lu, & Hays, 2020). In the current sample, Cronbach's alpha coefficients were 0.87, 0.88, 0.88, 0.91 and 0.81 for *Observing, Describing, Acting with Awareness*, *Non-judging,* and *Non-reactivity* subscales, respectively. As the *Observing* facet is reported to exist only in experienced meditators (Williams, Dalgleish, Karl, & Kuyken, 2014), we calculated total DM for the purpose of this study (which also included non-meditators) as the sum of the scores on the remaining four facets (*Describing*, *Acting with Awareness*, *Non-judging* and *Non-reactivity*) as advised by Baer et al. (2006, 2008).

Alexithymia was assessed using the 20-item Toronto Alexithymia Scale (TAS-20, Bagby, Taylor, & Parker, 1994). This scale has three subscales: *Difficulty Describing Feelings* (e.g., "I am able to describe my feelings easily."), *Difficulty Identifying Feelings* (e.g., "I am often puzzled by sensations in my body."), and *Externally-Oriented Thinking* (e.g., "Being in touch with emotions is essential."). Each item is rated on a 5-point Likert scale from 1 to 5 ('strongly disagree', 'moderately disagree', 'neither agree nor disagree', 'moderately agree' and 'strongly agree'; some items reverse-scored). A total score of 61 or above indicates alexithymia, score 52–60 possible alexithymia, and score 51 or below non-alexithymia. The TAS-20 is the most frequently used measure of alexithymia though the internal consistency reliability for its *Externally-Oriented Thinking* subscale has been reported to be rather low in some studies (e.g., Cronbach's alpha coefficient = 0.45 in Kooiman, Spinhoven, & Trijsburg, 2002). In the current sample, Cronbach's alpha coefficients were 0.67, 0.79 and 0.52 for *Difficulty Describing Feelings, Difficulty Identifying Feelings and Externally-Oriented Thinking,* respectively.

Emotion regulation was assessed using the 36-item Difficulties in Emotion Regulation Scale (DERS, Gratz & Roemer, 2004). This questionnaires has six subscales (6 items per subscale): (1) *Non-acceptance of Emotion* (e.g. "When I'm upset, I become angry as with myself for feeling that way."), (2) *Difficulties in Engaging in Goal-directed Behaviour* (e.g. "When I'm upset, I have difficulty getting work done."), (3) *Impulse Control Difficulties* (e.g. "When I'm upset, I feel out of control."), (4) *Lack of Emotional Awareness* (e.g. "When I'm upset, I acknowledge my emotions." with reverse scoring), (5) *Limited Access to Emotion Regulation Strategies* (e.g. "When I'm upset, I believe that I'll end up feeling very depressed.") and (6) *Lack of Emotional Clarity* (e.g. "I am confused about how I feel.". A 5-point Likert scale is used to rate each item from 1 to 5 ('almost never', 'sometimes', 'about half the time', 'almost always' or 'most of the time'). Higher scores indicate more emotional regulation difficulties. All subscales are reported to have good-to-excellent internal consistency (Cronbach's alpha coefficients >0.80; Gratz & Roemer, 2004); and this was also true for the current sample (Cronbach's alpha coefficients*, Non-acceptance of Emotion,* 0.89*; Difficulties in Engaging in Goal-directed Behaviour*, 0.89; *Impulse Control Difficulties*, 0.88; *Lack of Emotional Awareness*, 0.76; *Limited Access to Emotion Regulation Strategies,* 0.91*; Lack of Emotional Clarity*, 0.70).

2.3. Startle habituation and PPI experiments: Data collection and scoring

All participants were tested first on startle habituation, followed by PPI, in two separate experiments. In both experiments, all startle-eliciting stimuli were presented binaurally via headphones which the participants were wearing.

The startle habituation experiment was identical to the experiment reported by Kumari et al. (2023). It involved presentation of 20 acoustic probe stimuli in total. Of these, 10 stimuli consisted of a 50-ms presentation of 90-dB (A) white noise, and 10 stimuli consisted of a 50-ms presentation of 100-dB (A) white noise. After two initial probe stimuli (one 90-dB, one 100-dB), the remaining 18 stimuli (9 90-dB, 9 100-dB) were ordered pseudo-randomly (to avoid more than one repetition of 90-dB or 100-dB probes in a row) in three blocks, with each block containing three 90-dB and three 100-dB trials. Inter-trial intervals ranged from 15 to 25 s (average = 20 s). The experiment began with a 2-min acclimatisation period consisting of 70-dB (A) continuous white noise which was used as the background noise throughout the experiment. This experiment lasted approximately 9 min.

For the PPI experiment, the pulse-alone stimulus was a 40-ms presentation of 114-dB (A) white noise, and the prepulse stimulus was a 20-ms presentation of 84-dB (A) white noise, both over 70-dB (A) continuous background noise. In total, there were 36 trials, in addition to an initial pulse-alone trial (not included in any analysis). The 36 trials were arranged into three blocks of 12 trials each. Each block had three pulse-alone trials, three trials with a single discrete prepulse with a 120-ms prepulse-to-pulse (onset-to-onset) interval (PPI-120), and six trials where a second discrete prepulse preceded the first prepulse with 30 ms (PRP-30) or 120-ms prepulse-to-prepulse interval (PRP-120) (three trials/interval). The mean inter-trial-interval ranged from 9 to 23 s (average = 15 s). The session started with a 2-min acclimatisation period during which the participants, as in startle habituation experiment, were exposed to 70-dB (A) continuous white noise. This experiment took about 11 min to complete.

In general, the EMG data collection and scoring procedures replicated those described by Kumari et al. (2023). The eye blink component of the startle response was indexed by recording electromyographic (EMG) activity of the orbicularis oculi muscle directly beneath the right eye by positioning two miniature silver/silver chloride electrodes filled with Dracard electrolyte paste (SLE, Croydon, UK). The ground electrode was attached behind the right ear on the mastoid. A commercial computerised human startle response monitoring system (SR-Lab, San Diego, California) was used to deliver acoustic startle stimuli, and record and score the EMG activity for eye blinks to the pulse stimuli. The amplification gain control for EMG signal was kept constant throughout the entire study. Recorded EMG activity was band-filtered, as per the recommendations of the SR-Lab. Analogue bandpass filtering occurred before digitising. The low-pass and high-pass cut-off frequencies were at 1000 Hz and 100 Hz, respectively. A 50-Hz notch filter was used to eliminate the 50-Hz interference. EMG data were scored off-line, blind to group membership, using the analytic programme of this system for startle response amplitude (in arbitrary Analog-to-Digit units) to pulse-alone trials. Prior to scoring, EMG data were reviewed trial-by-trial for each participant and any trials with noisy data (i.e., no clear eye blink within 20–120 ms of the pulse; <10 %

in total) were excluded. Any participant with noisy data or no clear eye blinks visible on more than 50 % of trials was excluded (in total, 2 participants excluded; see 2.1 *Participants and design*).

EMG recordings were taken with participants sitting comfortably in a chair in psychophysiology laboratory. They were instructed to stay relaxed but to keep their eyes open and look straight ahead at a large black screen during both experiments. There were no specific instructions aimed at manipulating their attention.

2.4. General procedure

Participants were told that the study aimed to investigate how we perceive and respond to environmental stimuli and how regular meditation might affect these processes. Between the two startle experiments, they were asked to complete the self-report questionnaires (with breaks as needed) with a researcher present in the laboratory.

2.5. Statistical analyses

All analyses were performed using the Statistical Package for Social Sciences (version 28; IBM, New York, USA). Alpha level for testing the significance of effects was maintained at $p \leq 0.05$.

2.5.1. Sample characteristics

Group differences in age and various self-report measures were examined using a 2 (Group: Meditators, Non-meditators) × 2 (Sex: Males, Females) analysis of variance (ANOVA), and followed up with post-hoc mean comparisons as relevant. We compared the subgroup of meditators who reported being able to enter and sustain non-dual awareness during formal meditation practice ('Non-dual', n = 18) with the subgroup of meditators who could not ('Dual', n = 14) on age, total estimated hours of meditation practice, and various self-report measures using independent sample t-tests. Similarly, we compared the subgroups of meditators who were engaged in attentional, constructive or deconstructive family of meditation practice (as per classification of meditation practices proposed by Dahl et al., 2015) using univariate ANOVAs; and the subgroup of meditators who practiced secular mindfulness and similar Buddhist traditions ('mindfulness', n = 21) versus those who used any approaches/traditions to meditate ('other meditation practices', n = 11) using independent sample t-tests. In addition, correlational analyses (Pearson's *r*) were run to confirm expected inter-relationships of the FFMQ, TAS-20 and DERS scales in the entire sample, and also separately in the meditator and non-meditators groups.

2.5.2. Startle habituation experiment

Startle habituation was quantified as slopes over 90-dB and 100-dB intensity trials (separately) across the entire session (9 trials per intensity; the first 90-dB and 100-dB probes excluded to avoid exaggerated initial startle reactivity) using the formula "$Y = a + bx$" where X refers to the log-transformed startle stimulus number (trial number), Y refers to the square root of the response amplitude for that stimulus, a is an intercept referring to the level of initial reactivity (i.e. the response amplitude to the first startle stimulus), and b is the slope representing the individual rate of startle habituation. Negative slope values indicate a decreased response over time, with greater negative values demonstrating a faster and steeper habituation. We have used this method to quantify startle habituation in our previous studies (Antonova et al., 2015; Kumari et al., 2023).

Response amplitude data were first analysed using a 2 (Group: Meditators, Non-meditators) × 2 (Sex: Males, Females) × 2 (Probe Intensity: 90-dB and 100-dB) × 3 (Block: Blocks 1–3, with each block representing the average of valid responses to three probes) analysis of variance (ANOVA) with Group and Sex as the between-subjects factors, and Probe Intensity and Block as the within-subjects factors. Next, we analysed habituation slopes using a 2 (Group) × 2 (Sex) × 2 (Probe Intensity) ANOVA with Group and Sex as the between-subjects factors, and Probe Intensity as the within-subjects factor. A 2 (Non-dual Awareness: Yes, No) × 2 (Probe Intensity) × 3 (Block) ANOVA was run on startle amplitude, and a 2 (Non-dual Awareness) × 2 (Probe Intensity) ANOVA was run on habituation slopes to explore possible differences between the groups of meditators that could or could not go into and sustain non-dual awareness within their practice (small n, and no Sex effect in habituation in earlier analyses, so Sex not included as a factor). We also ran a 3 (Meditation Family: Attentional, Constructive, Deconstructive) × 2 (Probe Intensity) × 3 (Block) ANOVA on startle amplitude, and a 3 (Meditation Family: Attentional, Constructive, Deconstructive) × 2 (Probe Intensity) ANOVA on habituation slopes, to explore whether there was a marked difference between the subgroups of meditators using different practice/s. For all factors involving a repeated-measure, the assumption of sphericity was assessed using Mauchly's test and, where the assumption of sphericity was violated (i.e., Mauchly's test was significant), the Greenhouse-Geisser correction was applied to adjust for potential violations of sphericity. Effect sizes for ANOVA/ANCOVA results, where reported, are partial eta squared (ηp2; the proportion of variance associated with a factor). Lastly, a similar approach was used to explore possible differences between the subgroups of meditators who practiced secular mindfulness and Buddhist meditation practices similar to secular mindfulness ('mindfulness') versus other meditation approaches/styles ('other meditation practices').

Correlational analyses (Pearson's *r*) were conducted to examine the relationship of habituation slopes at 90-dB and 100-dB stimuli with DM (FFMQ total), alexithymia (TAS-20 total) and difficulties in emotion regulation (DERS total) scores. Correlation coefficients found to be significant ($p < 0.05$) were re-evaluated, unless hypothesised *a priori* or expected based on previous literature (i.e., negative correlations between FFMQ total and TAS-20 total; and stronger startle habituation in people with FFMQ total and/or lower TAS-20 scores) after applying Bonferroni correction to control for family-wise Type-I error.

2.5.3. PPI experiment

PPI (% reduction) was computed as [(amplitude on pulse-alone trials *minus* amplitude on PPI trials)/amplitude on pulse-alone trials] × 100.

PPI scores were first subjected to a 2 (Group: Meditators, Non-meditators) × 2 (Sex: Males, Females) × 3 (Trial Type: PPI-120, PRP-30, PRP-120) ANOVA, with Group and Sex as between-subjects factors and Trial Type as a within-subjects factor. Further 2 (Non-dual Awareness) × 3 (Trial Type) ANOVA was run to examine possible differences in PPI between the groups of meditators that could or could not go into and sustain non-dual awareness (Sex not included due to a small n, and no Sex effect in PPI of meditators in earlier analyses). A 3 (Meditation Family: Attentional, Deconstructive, Combination) × 3 (Trial Type) ANOVA was then used to explore any differences in PPI related to the family of meditation practice (Attentional, Constructive, Deconstructive); and a 2 (Mindfulness Practice: Mindfulness, Other Approaches) × 3 (Trial Type) ANOVA was used to explore any differences between meditators practicing mindfulness and those practicing other meditation approaches. Significant main effects and interactions in all ANOVAs were followed up with lower-order ANOVAs and post-hoc t-tests as appropriate. Prior to running ANOVAs on PPI scores, startle amplitude to pulse-alone trials (i.e., mean amplitude over 114-dB pulse-alone trials) were subjected to a 2 (Group: Meditators, Non-meditators) × 2 (Sex: Male, Female) ANOVA, with Group and Sex as between subjects-factors. This was followed by further ANOVAs to explore any differences that might exist in pulse-alone amplitude in relation to Non-dual Awareness, Meditation Family or Mindfulness factors. As noted earlier for the habituation experiment, we assessed the assumption of sphericity using Mauchly's test and found no significant violations (thus, Greenhouse-Geisser correction not applied). Effect sizes for ANOVA/ANCOVA results, where reported, are again partial eta squared (ηp2).

Lastly, correlational analyses (Pearson's *r*) were conducted to examine possible relationship of PPI (on different trial types) with DM, alexithymia and difficulties in emotion regulation, first across the entire sample then separately in meditators and non-meditators. As for habituation, for all non-hypothesised correlations, correlation coefficients found to be significant at $p \leq 0.05$ were re-evaluated after applying a Bonferroni correction.

3. Results

3.1. Sample characteristics

3.1.1. Meditators versus non-meditators

Meditators and non-meditators did not differ in age, and there was no effect of Sex or any interaction between Group and Sex (see Table 1). The main effect of Group was significant in the FFMQ scores (total without *Observing*), $F(1,64) = 17.47$, $p < 0.001$, $\eta_p^2 = 0.214$, showing a significantly higher level of DM in meditators, relative to non-meditators; in the TAS-20 (total) score, $F(1,64) = 10.00$, $p = 0.002$, $\eta_p^2 = 0.135$, indicating a significantly lower (alexithymia) scores in meditators, relative to non-meditators; and in the DERS (total) score, $F(1,64) = 25.74$, $p < 0.001$, $\eta_p^2 = 0.287$, showing a lower level of difficulties in emotion regulation in meditators, relative to non-meditators (Table 1). There was no effect of Sex, or a Sex × Group interaction in the FFMQ, TAS-20 or DERS scores. The FFMQ (DM) scores correlated negatively with the TAS-20 (alexithymia) and DERS (emotion regulation difficulties) scores, and the TAS-20 and DERS scores correlated positively with each other, with a similar pattern of interrelationships present in the meditator and non-meditator groups (Table 2).

3.1.2. Meditators: quantity, quality and family/styles of meditation practice

On average, meditators had been practicing for 14.68 years (SD = 11.88), with a total of 4114.03 estimated hours of practice (SD = 5541.56). Of 32 meditators in total, 18 meditators (8 males, 10 females; mean age = 43.72 years, SD = 13.66; meditation family: 9 attentional, 4 constructive, 5 deconstructive; 12 of 18 practicing mindfulness) reported being able to enter and sustain non-dual awareness during formal meditation practice while 14 meditators (10 males, 4 females; mean age = 43.8 years, SD = 12.55; meditation family: 8 attentional, 3 constructive, 3 deconstructive; 9 of 14 practicing mindfulness) did not. These two subgroups did not

Table 2
Inter-relationships (Pearson's *r;* all significant) amongst self-report measures.

Questionnaire/Scale	Meditators (n = 32)		Non-meditators (n = 36)		Entire Sample (n = 68)	
	Five Facet Mindfulness Questionnaire (FFMQ)Total without *Observing*	Toronto Alexithymia Scale-20 items (TAS-20) Total	Five Facet Mindfulness Questionnaire (FFMQ) Total without *Observing*	Toronto Alexithymia Scale-20 items (TAS-20) Total	Five Facet Mindfulness Questionnaire (FFMQ) Total	Toronto Alexithymia Scale-20 items (TAS-20) Total
	r (*p*)	*r* (*p*)	*r* (*p*)	*r* (*p*)	*r* (*p*)	*r* (*p*)
Toronto Alexithymia Scale-20 items (TAS-20) Total	**−0.693** (<.001)	–	**−0.692** (<.001)	–	**−0.736** (<.001)	–
Difficulties in Emotion Regulation Scale (DERS) Total	**−0.711** (<.001)	**0.647** (<.001)	**−0.542** (<.001)	**0.624** (<.001)	**−0.696** (<.001)	**0.691** (<.001)

differ in age, the total years and estimated hours of meditation practice, or on any self-report measures except a trend-level difference in the *Observing* facet of the FFMQ, $t(30) = 1.98$, $p = 0.057$, $d = 0.704$, where the subgroup with non-dual awareness ability scored higher (mean = 33.56, SD = 3.57) than those without (mean = 30.64, SD = 4.78).

The subgroups of meditators classified by meditation family (17 attentional, 7 constructive, 8 deconstructive), or those practicing mindfulness (n = 21) relative to those practicing other approaches (n = 11), did not differ significantly in age, the total years and estimated hours of meditation practice, FFMQ (also no difference in *Observing*), TAS-20 or DERS scores.

3.2. Startle habituation experiment

3.2.1. Startle amplitude

There was a significant main effect of Probe Intensity, $F\,(1{,}64) = 55.75$, $p < 0.001$, $\eta_p^2 = 0.466$, indicating a higher amplitude on 100-dB probes compared to 90-dB probes. There was also a significant main effect of Block, $F(1.65, 105.90) = 25.75$, $p < 0.001$; Greenhouse-Geisser corrected $p < 0.001$; $\eta_p^2 = 0.287$, with a linear trend, $F(1{,}64) = 34.84$, $p < 0.001$, $\eta_p^2 = 0.353$, as well as a significant Probe Intensity × Block interaction, $F(2{,}128) = 3.93$, $p = 0.022p = 0.023$, $\eta_p^2 = 0.058$.

Further analysis of Probe Intensity × Block interaction indicated that, for the low intensity (90-dB) probes, Block 1 had a significantly higher startle amplitude compared to Block 2, $t(67) = 3.61$, $p < 0.001$, $d = 0.437$, and Block 3, $t(67) = 3.74$, $p < 0.001$, $d = 0.453$, but the difference between Blocks 2 and 3 was non-significant, $t(67) = 1.18$, $p = 0.242$ (see Fig. 1). For the higher intensity (100-dB) probes, Block 1 had higher amplitude compared to both Block 2, $t(67) = 3.90$, $p < 0.001$, $d = 0.473$, and Block 3, $t(67) = 6.81$, $p < 0.001$, $d = 0.828$; and Block 2 had higher amplitude compared to Block 3, $t(67) = 4.18$, $p < 0.001$, $d = 0.507$.

There was no significant main effect of Group or Sex, and no significant interaction involving these factors.

Further ANOVAs to explore possible differences between the subgroups of meditators with and without non-dual state ability revealed no significant main effect of Non-dual Awareness and no significant Block × Non-dual Awareness interaction, indicating comparable amplitude on all three blocks of 90-dB and 100-dB trials in these meditator subgroups. The main effects of Probe Intensity, $F(1{,}30) = 24.50$, $p < 0.001$, $\eta_p^2 = 0.450$, as well as Block, $F\,(2{,}60) = 16.73$, $p < 0.001$, $\eta_p^2 = 0.358$, and a Probe Intensity × Block interaction, $F\,(2{,}60) = 5.76$, $p = 0.005$, $\eta_p^2 = 0.161$, were again significant, reflecting the same pattern of effects as described earlier for the whole sample (meditators and non-meditators). Lastly, no main effect of Meditation Family or Mindfulness Practice (versus other meditation approaches), or any interactions involving these factors, were found in further ANOVAs which again showed only the significant main effects of Probe Intensity and Block, and a Probe Intensity × Block interaction (same pattern as noted earlier for the entire sample).

3.2.2. Habituation slopes

There was a non-significant effect of Probe Intensity (steeper response habituation over 100-dB probes, compared to 90-dB probes), $F(1, 64) = 1.94$, $p = 0.169$, $\eta_p^2 = 0.029$, and no significant effect of Group, $F(1{,}66) = 0.00$, $p = 0.993$, $\eta_p^2 = 0.000$, and no Probe Intensity × Group interaction, $F(1{,}64) = 2.15$, $p = 0.148$, $\eta_p^2 = 0.0325$ (Fig. 2). There was no main effect of Sex or any interaction involving Sex.

There was also no difference between the meditator subgroups with and without non-dual awareness ability, as indicated by no main effect of Non-dual Awareness, $F(1{,}30) = 0.94$, $p = 0.339$, $\eta_p^2 = 0.030$, and no Probe Intensity × Non-dual Awareness interaction, $F(1{,}30) = 0.28$, $p = 0.598$, $\eta_p^2 = 0.009$. The main effect of Probe Intensity, however, was significant, $F(1{,}30) = 6.03$, $p = 0.02$, $\eta_p^2 = 0.167$,

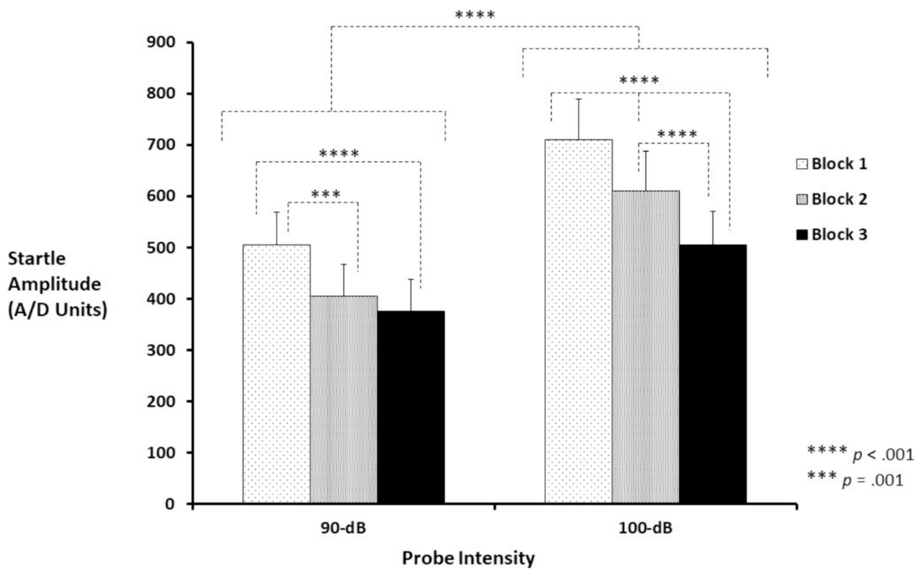

Fig. 1. Mean startle amplitudes over the three blocks of 90-dB and 100-dB acoustic probes (n = 68). Error bars represent +1 SEM.

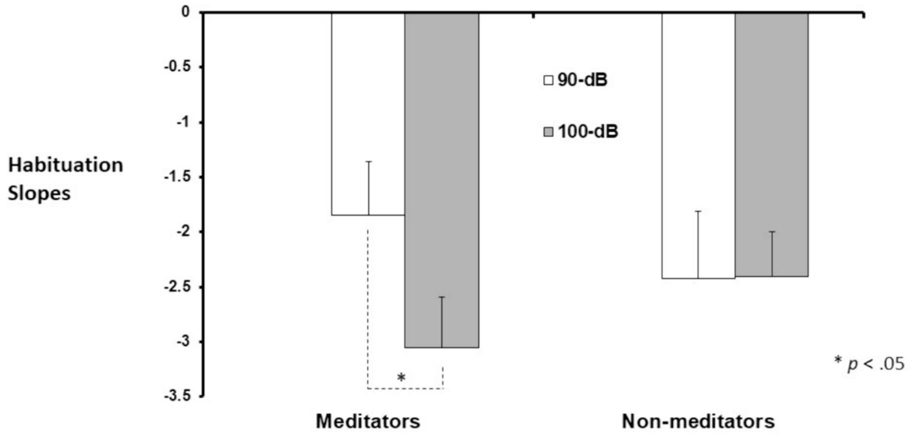

Fig. 2. Mean habituation slopes in meditators (n = 32) and non-meditators (n = 36). Error bars represent +1 SEM.

indicating more habituation on 100-dB than 90-dB probes in meditators as a group (Fig. 2). The ANOVA with Meditation Family as a factor again confirmed the main effect of Probe Intensity, $F(1,29) = 9.50$, $p = 0.004$, $\eta_p^2 = 0.247$, but showed no effect of Meditation Family, $F(2,29) = 0.08$, $p = 0.925$, $\eta_p^2 = 0.005$, and no Probe Intensity × Meditation Family interaction, $F(2,29) = 1.55$, $p = 0.230$, $\eta_p^2 = 0.096$. Similarly, the ANOVA to examine mindfulness versus other meditation approaches again showed only the significant main effects of Intensity in habituation slopes, $F(1,30) = 6.57$, $p = 0.016$, $\eta_p^2 = 0.18$, and no main effects or any interaction involving Mindfulness Practice.

3.2.3. Correlations between habituation slopes and self-report measures

As shown in Table 3, startle habituation slopes did not correlate, even at the uncorrected level, with the FFMQ, TAS-20 and DERS scores. The total number of estimated hours of practice also did not correlate with habituation slopes at 90-dB ($r = 0.042$) or 100 dB probes ($r = -0.007$).

3.3. PPI experiment

3.3.1. Amplitude on pulse-alone trials

The main effects of Group, $F(1,64) = 1.21$, $p = 0.276$, $\eta_p^2 = 0.019$, and Sex, $F(1,64) = 0.52$, $p = 0.462$, $\eta_p^2 = 0.008$, and the Group × Sex interaction, $F(1,64) = 1.09$, $p = 0.301$, $\eta_p^2 = 0.017$, were all non-significant. There was also no significant effect of Non-dual Awareness, $F(1,30) = 0.23$, $p = 0.638$, $\eta_p^2 = 0.007$, Meditation Family, $F(1,29) = 0.82$, $p = 0.451$, $\eta_p^2 = 0.054$, or Mindfulness Practice, $F(1,30) = 0.26$, $p = 0.612$, $\eta_p^2 = 0.009$, in pulse-alone amplitude over the entire session.

3.3.2. PPI

3.3.2.1. Meditators versus non-meditators. There was a significant main effect of PPI Trial Type, $F(2,128) = 5.20$, $p = 0.007$, $\eta_p^2 = 0.075$, showing as expected, lower PPI on PRP120 trials (where two prepulses were separated by 120 ms) than on single prepulse PPI120 trials, $t(67) = 2.34$, $p = 0.022$, $d = 0.284$, and also on PRP30 trials (two prepulses separated by only 30 ms), $t(67) = 3.011$, $p = 0.002$, $d = 0.365$. PPI on PPI120 and PRP30 trials did not differ significantly from each other, $t(69) = 0.77$, $p = 0.223$, $d = 0.093$.

Table 3
Correlations (Pearson's *r*; none significant, for all $p > 0.05$ uncorrected) between startle habituation slopes and self-report measures.

	Meditators (n = 32)		Non-meditators (n = 36)		Entire Sample (n = 68)	
	90-dB	100-dB	90-dB	100-dB	90-dB	100-dB
Measure	*r*	*r*	*r*	*r*	*r*	*r*
Five Facet Mindfulness Questionnaire (FFMQ)						
Observing	0.221	0.121	−0.320	0.011	−0.099	0.022
FFMQ Total without *Observing*	0.01	0.041	0.030	0.190	0.060	0.040
Toronto Alexithymia Scale-20 items (TAS-20)						
TAS-20 Total	−0.179	−0.090	−0.063	−0.261	−0.130	−0.121
Difficulties in Emotion Regulation Scale (DERS)						
DERS Total	0.046	0.201	−0.275	−0.183	−0.190	0.047

The main effects of Group, $F(1,64) = 0.02$, $p = 0.891$, $\eta_p^2 = 0.00$] and Sex, $F(1,64) = 0.45$, $p = 0.504$, $\eta_p^2 = 0.007$] were non-significant, but there was a significant Group × Sex interaction, $F(1,64) = 4.36$, $p = 0.041$, $\eta_p^2 = 0.064$. Lower-order ANOVAs (Sex × Trial Type in each group) showed a significant Sex effect in non-meditators, $F(1,34) = 4.73$, $p = 0.037$, $\eta_p^2 = 0.122$, with more PPI in non-mediating males compared to non-meditating females (Fig. 3). In meditators, there was no effect of Sex, $F(1,30) = 0.81$, $p = 0.375$; $\eta_p^2 = 0.026$, and no Sex × Trial Type interaction, $F(2,60) = 0.32$, $p = 0.725$, $\eta_p^2 = 0.011$ (Fig. 3). Further follow-up ANOVAs (Group × Trial Type separately in males and females) did not show a significant effect of Group, or a Group × Trial Type interaction in either sex.

3.3.2.2. Meditation quantity, quality and style influence in meditators. The total number of estimated hours of practice did not correlate significantly with PPI at any trial type (r values from 0.032 to −0.024).

There was a significant main effect of Non-dual Awareness, $F(1,30) = 4.24$, $p = 0.048$, $\eta_p^2 = 0.124$, indicating more PPI in the subgroup who could enter and maintain a non-dual awareness during formal meditation practice, compared to those who could not (Fig. 4). In the same ANOVA, there was a trend-level main effect of Trial Type, $F(2,60) = 2.77$, $p = 0.071$, $\eta_p^2 = 0.084$ (reflecting the same pattern as already described for the entire sample) but no significant Non-dual Awareness × Trial Type interaction, $F(2,60) = 0.46$, $p = 0.632$, $\eta_p^2 = 0.015$. Supplementary analyses involving these two meditator subgroups along with the non-meditator group showed that PPI in neither of these sub-groups differed significantly from PPI in the non-meditator group (Fig. 5).

Further ANOVAs to explore PPI in relation to Meditation Family or Mindfulness Practice did not show any significant influence of these factors on their own, or in interaction with Trial Type.

3.3.2.3. Correlation between PPI and self-report measures. PPI had no significant relationships with the FFMQ, DERS or TAS-20 scores in non-meditators or when examined across the entire sample (Table 4). In meditators, PPI on the PRP120 trial type had a negative correlation with the total TAS-20 score but only at the uncorrected significance level (Table 4).

4. Discussion

The main aim of the present study was to investigate the effect of regular meditation practice on startle habituation and PPI, by comparing the groups of meditators and meditation-naïve individuals. The findings showed significantly greater response amplitude and slightly (non-significantly) more habituation on 100-dB, relative to 90-dB, probe trials, but no difference between the meditator and non-meditator groups and no influence of DM in startle habituation. Regarding PPI, we observed (i) more PPI on prepulse trials with a single, compared to those with two prepulses (with 120-ms prepulse-to-prepulse interval), and a sex difference in PPI of the non-meditator group but not the meditator group, and (ii) no significant difference between the meditator and non-meditators groups, but greater PPI in the subgroup of meditators who could enter and sustain a non-dual awareness state easily during meditation practice (regardless of the meditation style or approach) than those who could not. As expected, the meditator group, compared to the non-meditator group, scored higher on DM and lower on the measures of alexithymia and difficulties in emotion regulation. DM had a negative association with alexithymia and difficulties in emotion regulation, and there was a positive association between alexithymia and difficulties in emotion regulation across the entire sample. We now discuss each of these findings in turn.

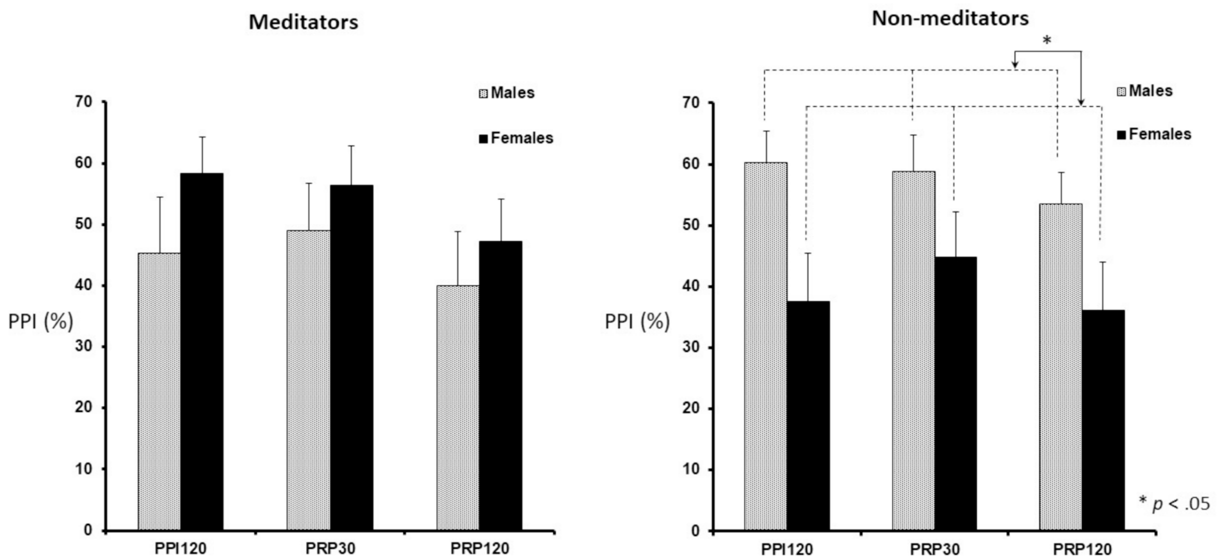

Fig. 3. PPI (% inhibition) in the meditator and non-meditator groups, with a significant sex effect seen only in non-meditators (males > females). Error bars represent +1 SEM.

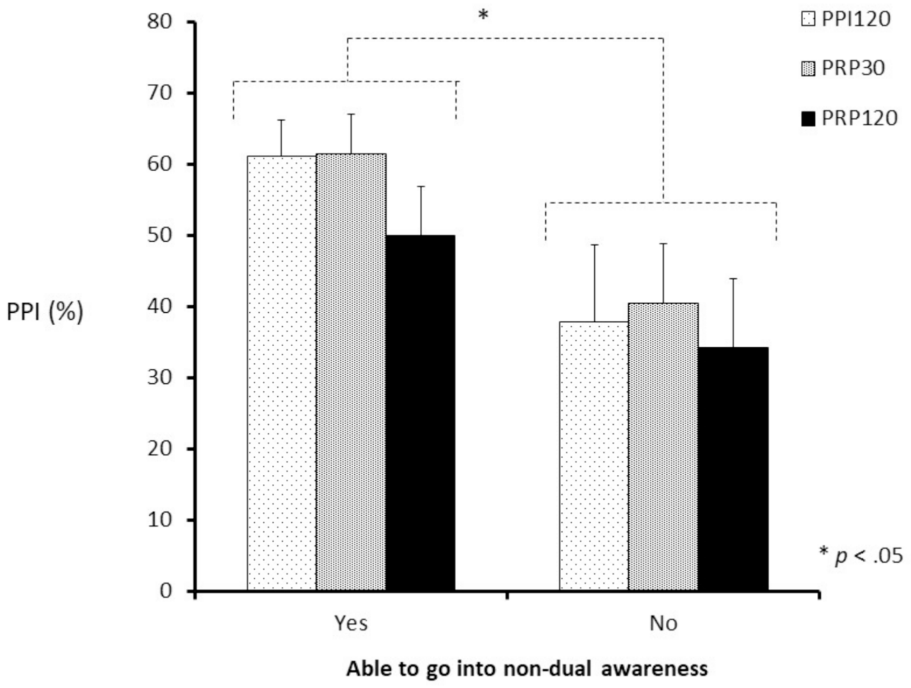

Fig. 4. PPI (%) on different PPI trials (PP120, PRP30, PRP120) in meditators with (n = 18) and without (n = 14) self-reported ability to achieve and sustain a non-dual awareness during practice. Error bars represent +1 SEM.

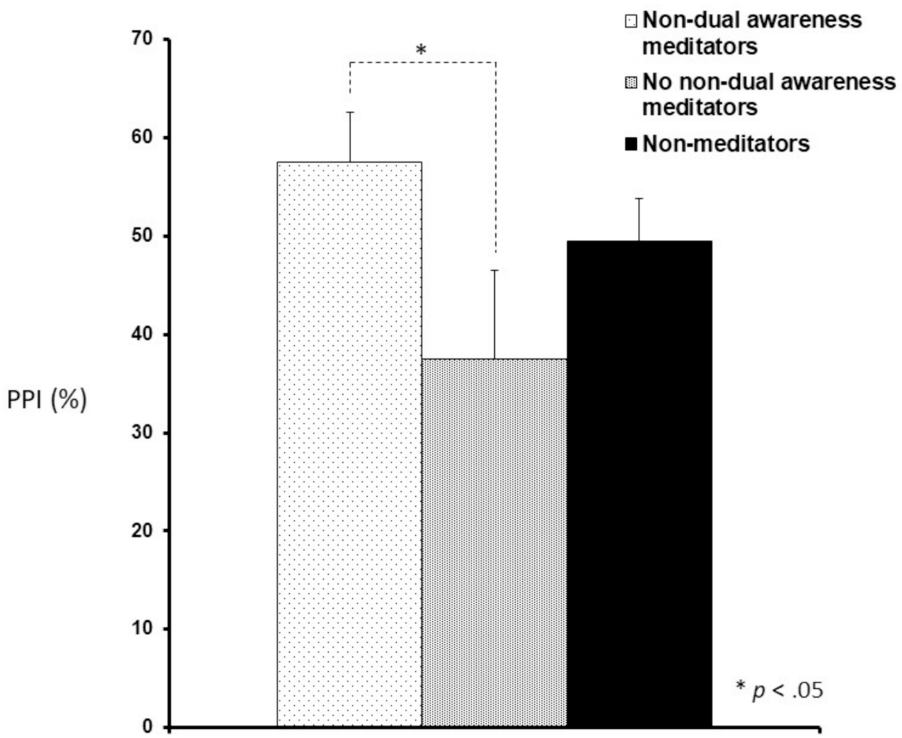

Fig. 5. Average PPI across three trial types in subgroups of meditators with (n = 18) and without (n = 14) self-reported ability to achieve and sustain a non-dual awareness during practice, and in the non-meditator group (n = 36). Error bars represent +1 SEM.

Table 4
Correlation between PPI and self-report measures (FFMQ, DERS, TAS-20).

	Meditators			Non-meditators		
	PPI120	PRP30	PRP120	PPI120	PRP30	PRP120
Five Facet Mindfulness Questionnaire (FFMQ)						
Observing	0.023	0.098	0.234	−0.249	−0.162	−0.169
FFMQ Total without *Observing*	0.001	−0.009	0.135	−0.062	−0.152	−0.055
Toronto Alexithymia Scale-20 items (TAS-20)						
TAS Total	−0.159	−0.183	**−0.360***	0.105	0.281	0.014
Difficulties in Emotion Regulation Scale (DERS)						
DERS Total	0.150	0.055	0.100	−0.089	0.018	−0.182

* $p = 0.043$ (two-tailed, uncorrected). All other correlations are non-significant ($p > 0.05$ uncorrected).

4.1. *Startle habituation*

Higher startle amplitude and more habitation on the 100-dB, relative to 90-dB, probe trials in this study are consistent with the findings of many previous studies (e.g., Blumenthal & Berg, 1986; Blumenthal et al., 2005; Kumari et al., 2023). There was, however, no significant difference between the meditator and non-meditator groups in habituation and no association between DM and habituation, seemingly in contrast with our hypotheses which anticipated attenuated habituation in meditators, relative to non-meditators (based on Antonova et al., 2015), and more habituation in association with a higher level of DM (based on Kumari et al., 2023). There appear to be valid reasons for us not finding a significant association between startle habitation and meditation practice or DM in this study. First, our meditator sample was heterogenous in terms of the meditation practices used, compared to the homogeneous sample of mindfulness practitioners tested in Antonova et al. (2015); and our present sample was also not as experienced having practiced, on average, for only 4,114.03 h (11,326.25 and 5,856 h for the intensely- and moderately-practiced meditator groups, respectively, in Antonova et al., 2015). Second, although we used the same startle habituation paradigm as used in Kumari et al. (2023), there was an unavoidable change in laboratory conditions due to the move to a newly furbished building. Specifically, the laboratory used in the current study was much larger, more pleasant, and had natural light, compared to rather dark and confined laboratory space we used in our previous study (Kumari et al., 2023). Given previous evidence of a robust effect of experimental settings, particularly changes in ambient illumination, on startle responding in rats (Schmajuk, Larrauri, De la Casa, & Levin, 2009) as well as humans (Grillon, Pellowski, Merikangas, & Davis, 1997), the laboratory environment of Kumari et al. (2023) most likely caused the startling stimuli to appear more threatening, affecting startle responding and habituation, and had provided better conditions than those of the current study for a DM-habituation association to emerge.

4.2. *PPI*

As expected, and replicating a previous study (Kumari et al., 2003), we observed more PPI on prepulse trials where a single prepulse preceded the pulse (120-ms prepulse-to-pulse interval) relative to where two prepulses with a 120 ms prepulse-to-prepulse interval preceded the pulse (2nd prepulse-to-pulse onset also 120 ms). There was no difference between PPI on single prepulse trials and PPI on trials with two prepulses but with only a 30-ms prepulse-to-prepulse interval. This is not surprising as there is typically a small and non-significant PPI with 30 ms prepulse-to-pulse intervals (Åsli et al., 2021; Kumari et al., 2003, 2015, 2023), and hence only a limited impact of the first prepulse on the second prepulse is expected with a 30-ms prepulse-to-prepulse interval (Kumari et al., 2003). Furthermore, there was greater PPI in males compared to females of the non-meditator group. This is also consistent with the findings of many previous studies in healthy adult samples using PPI paradigms involving a single prepulse (reviews, Kumari, 2011; Hantsoo, Golden, Kornfield, Grillon, & Epperson, 2018; Swerdlow et al., 2016) or two prepulses (Kumari et al., 2003). Interestingly, this sex effect was absent in meditators. Female meditators, if anything, showed more PPI than male meditators (see further for an explanation). In general, our findings showing more PPI on single-prepulse, compared to two-prepulse trials with 120-ms prepulse-to-prepulse interval, and sex effect in PPI (males > females) in the non-meditator group replicate previous literature.

Our finding showing no significant difference between PPI of meditators and non-meditators, on average, is perhaps also not surprising, given previous findings on this topic using cross-sectional (Kumari et al., 2015) or within-subject designs (pre- and post-assessments after a single brief mindfulness session; Åsli et al., 2021). Nonetheless, the present findings partially supported our (alternate) hypothesis in showing significantly more PPI in the subgroup of meditators that could easily enter and sustain a non-dual awareness during their meditation practice, compared to the subgroup of meditators who could not. As there was no difference between these two subgroups in response to pulse-alone trials, this (sub)group difference in PPI suggests a deeper processing of the prepulse (a sub-threshold stimulus) and more effective sensorimotor gating and possibly, as a consequence, reduced sensory load and distractibility in meditators who are able to enter and sustain a non-dual awareness regardless of the style of meditation practice/s or the total estimated hours of practice (since these did not associate with PPI). The only measure to differentiate these two meditator subgroups (at the trend level) was *Observing* facet of the FFMQ which was also the facet correlating with better eye movement performance of meditators in a previous study (Kumari et al., 2017). However, *Observing* showed no direct correlation with PPI in this study so it cannot explain PPI difference between the meditator subgroups. Furthermore, it is hard to decide whether our results indicate 'enhanced PPI' in meditators with the non-dual awareness ability, or 'attenuated PPI' in meditators without this ability, since PPI in neither of these two sub-groups differed significantly from PPI in the non-meditator group (Fig. 5). As a result, our finding can also be interpreted as 'attenuated PPI' in meditators without the nondual awareness ability and, if so, it would be consistent with the notion of 'quicker processing and degrading' of the prepulse/s in this meditator subgroup. Whatever the case might be, it would be prudent for future neuroscientific investigations to incorporate both qualitative and quantitative aspects of meditation practice (Josipovic et al., 2012; Josipovic, 2010, 2014). A simple 'meditator versus non-meditator' study design seems insufficient to meaningfully advance this field.

Another factor deserving some comment is that the majority of females in the meditator group (10 of 14) reported being able to easily enter a non-dual awareness state during practice (i.e. the subgroup with greater PPI), and this perhaps also explains the earlier described finding of no sex effect in PPI of the meditator group. Interestingly, previous studies (e.g., Kang et al., 2018; Rojiani, Santoyo, Rahrig, Roth, & Britton, 2017; Zhang, Zheng, Hu, & Wang, 2024) have reported a more favourable response to mindfulness training in females, compared to males. Our findings suggest that such a benefit may also extend to PPI and that meditation training with a focus on reaching and being able to sustain dual awareness during practice may improve sensory information processing. Further studies with larger samples of male and female meditators are needed to examine whether and how meditation practices which allow achieving non-dual awareness during practice might improve PPI, especially in females who (when tested regardless of their menstrual cycle phase or sexual orientation) typically show less PPI, on average, than males (reviews, Kumari, 2011; Hantsoo et al., 2018; Swerdlow et al., 2016).

Lastly, it is also plausible that the subgroup of meditators who showed the strongest PPI (Figs. 4 and 5) had good PPI or sensorimotor gating (which is typically correlated with lower distractibility; e.g., Karper et al., 1996; Kumari et al., 2008) prior to starting meditation practice, which facilitated their ability to reach and sustain non-dual awareness (i.e., good PPI was the cause, rather than an effect, of non-dual awareness being experienced) during meditation practice. Future studies adopting longitudinal design should investigate the cause-effect relationship of stronger PPI/sensorimotor gating with the ability to enter and sustain non-dual awareness during meditation practice. Furthermore, future studies with pre-and post- design should include other factors known to respond favourably to meditation (Keng et al., 2011; Tomlinson et al., 2018) that have been linked to reduced PPI [for example, demotivation (e.g., Acheson et al., 2022), stress (e.g., Santos-Carrasco & De la Casa, 2024) and insomnia (Milner, Cuthbert, Kertesz, & Cote, 2009)] to disentangle which factors predict or facilitate and which change as a result of meditation practice. Finally, it would be valuable to directly compare the predictors and outcomes of meditative practices (e.g., Dzogchen, Mahāmudrā) that focus on eliciting and sustaining non-dual awareness (Dahl et al., 2015; Meling, 2022) with other types of meditation practices in sufficiently powered studies.

4.3. Self-report measures: Group difference and inter-relationships

Higher DM in the meditator group, relative to the non-meditator group, was expected (e.g., de Bruin, Topper, Muskens, Bogels, & Kamphuis, 2012; Kiken, Garland, Bluth, Palsson, & Gaylord, 2015; Kumari et al., 2015, 2017) and so was the negative association of DM with alexithymia (de Bruin et al., 2012; Kumari et al., 2023) and difficulties in regulating emotions (e.g., Pandey et al., 2023; Prakash, 2021; Tang, Tang, & Posner, 2016). The moderate negative association found between alexithymia and PPI in the meditator group (Table 4), although consistent with reports of lower PPI in association with many psychopathologies (reviews, Santos-Carrasco & De la Casa, 2023; Swerdlow et al., 2016), is hard to interpret. It failed to survive Bonferroni correction and was also not present in the non-meditator group despite them having a good range of alexithymia scores (TAS-20 score range in meditators: 25–49; in non-meditators: 26–79).

4.4. Study limitations

First, although this study incorporated both categorical (meditator versus non-meditator) and dimensional approaches (i.e. DM related influences within and across meditators and non-meditators), the effects of meditation practice on startle habituation and PPI in meditators were examined without any information on their performance prior to them starting meditation practice. Second, the menstrual cycle phase (Jovanovic et al., 2004) or hormonal status (Naysmith, Williams, & Kumari, 2022) which affect PPI in females, as well as sexual orientation which may also influence PPI (Rahman, Kumari & Wilson, 2003), were not assessed. Third, the study with 32 meditators and 36 non-meditators was sufficiently powered to detect group differences, but it lacked power to meaningfully examine any effects associated with specific meditation family/approach and did not have sufficient range of practice experience in the meditator group.

4.5. Conclusions

The present study examined sensory processing profiles of meditators using different practice approaches and meditation-naïve individuals using startle habituation and PPI paradigms. The findings revealed no significant difference, on average, between the meditator and meditation-naïve groups in habituation or PPI. There was, however, more PPI in meditators who self-reported being able to easily enter and sustain non-dual awareness during meditation practice relative to those who could not. Collectively, these findings suggest that qualitative differences in meditation experience may be associated with differential sensory processing characteristics of meditators. Future investigations involving larger samples of male and female meditators (and non-meditators) and incorporating both qualitative and quantitative aspects (Josipovic et al., 2012; Josipovic, 2010, 2014) of different meditation practices

(Dahl et al., 2015; Lutz et al., 2015) are needed to confirm and extend these findings.

CRediT authorship contribution statement

Veena Kumari: Writing – original draft, Visualization, Supervision, Resources, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Umisha Tailor:** Writing – original draft, Project administration, Investigation, Formal analysis, Data curation. **Anam Saifullah:** Writing – review & editing, Project administration, Investigation, Data curation. **Rakesh Pandey:** Writing – review & editing, Methodology, Funding acquisition, Conceptualization. **Elena Antonova:** Writing – review & editing, Methodology, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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