Title: Autonomic Indicators of Self-Transcendence: Insights from the Numadelic VR Paradigm

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Abstract

Self-transcendent experiences (STEs) offer profound and beneficial shifts in perspective, yet remain largely inaccessible outside elite contemplative or pharmacological contexts. Neural measures have deepened our understanding of these states, but their cost and limited ecological validity constrain broader application. This study evaluates heart rate variability (HRV) amplitude, a measure reflecting dynamic sympathovagal balance, as a cost-effective and sustainable physiological marker of STE during numadelic virtual reality (VR) experiences—multi-person, immersive journeys that can induce STE through dissolving self-boundaries and fostering embodied presence.

Building on previous work linking non-ordinary states of consciousness with autonomic nervous system activity during psychedelic drug administration, we tested the hypothesis that HRV amplitude may reflect STE depth and predict affective and prosocial outcomes during non-drug numadelic VR experiences. Specifically, ninety-six participants engaged in guided meditation within either a numadelic VR setting or a non-VR audio-guided group format. Physiological data (cardiac activity and respiration) were recorded during the meditation, alongside psychological assessments pre- and post-session.

Findings confirm that HRV amplitude measured during numadelic VR correlates with subjective STE ratings, compassion traits, and emotional improvement following VR practice. Additional analysis of data from a prior psychedelic drug study further validated the relevance of this measure across consciousness expanding modalities.

These results advance the psychophysiological mapping of STEs and highlight HRV amplitude as a potential real-time biomarker which may help to guide participants toward self-transcendent states within adaptive environments. By integrating contemplative science with immersive design, this work supports the development of scalable tools that enhance both access to and understanding of STEs.

Introduction

The value of self-transcendence

Experiences like witnessing breathtaking natural phenomena—standing before a vast mountain range or under a star-filled sky—being profoundly moved by music, art, or literature, or feeling deep love and care for others, are moments when our usual sense of self transcends its boundaries. Such experiences often lead to transformative shifts in perspective, broadening our understanding of our place in the world, while fostering hope, peace, unity, and enhanced compassion (Koltko-Rivera, 2006; Stellar et al., 2017).

According to Reed, self-transcendence can be defined as an "*expansion of self-conceptual boundaries multidimensionally: inwardly (e.g., through introspective experiences), outwardly (e.g., by reaching out to others), and temporally (whereby past and future are integrated into the present)*", that also includes a transpersonal expansion component, which involves connecting with a higher power or a larger reality (Reed, 1991, p 64). Self-transcendent experiences (STEs) have been a cornerstone of human history, deeply embedded in philosophical, spiritual, and psychological traditions (Wong, 2016). They constitute central element of traditional practices such as meditation, rituals, and communal ceremonies sought to dissolve ego boundaries, connecting individuals to a higher purpose or collective identity (Frey and Vogler, 2018). In contemporary Western contexts, however, such practices have become less accessible and often marginalised, possibly contributing to a growing sense of disconnection and existential distress (Turkle, 2011; Osler, 2022).

Amid global challenges and the erosion of communal bonds, there is renewed interest in contemplative modalities and non-ordinary states of consciousness (NOSC) as potential pathways to meaning, resilience, prosociality, and psychological wellbeing (Franco Corso et al., 2023; Grof and Grof, 2023; Ko et al., 2022). The psychedelic 'renaissance' that has unfolded in the past decade, alongside the emergence of mindfulness and compassion based programs, reflect this trend toward a framework that re-introduces STEs in our approach to medical care and personal growth (Hadar et al., 2023). However, the accessibility and broader adoption of these practices remain limited. The democratisation of psychedelics requires careful navigation due to the challenges associated with ensuring their safe, ethical, and supervised use (Pilecki et al., 2021). As for meditation practices, while increasingly popular, they often require sustained dedication to cultivate the depth and maturity necessary for the emergence of STEs.

The present study explores novel tools for eliciting and monitoring STEs through the integration of immersive virtual reality (VR) and physiological monitoring. If successful, this approach may not only advance research into these transformative states, but also provide scalable, embodied access to these experiences in secular contexts.

VR-elicited STEs and the numadelic framework

VR enables the creation of immersive, interactive environments that can profoundly reshape users' perception, agency - the user's felt ability to act, influence, and make meaningful choices in VR, and embodied presence (Slater and Sanchez-Vives, 2016; Suzuki et al., 2023). These altered experiential states have been shown to facilitate STEs, offering pathways to expanded awareness and emotional insight (Quesnel and Riecke, 2018). As such, VR holds promise as a catalyst for personal transformation with potential for therapeutic applications (Riva et al., 2016). VR offers the tantalizing possibility for constructing immersive sensory environments that can represent a vast range of phenomena, limited

by little more than imagination. Nevertheless, the vast majority of VR content utilized in research contexts is relatively limited – i.e., it tends to follow the dominant aesthetics of the metaverse and maintain fidelity to the sorts of visual scenes which people can encounter during their day-to-day experience (Glowacki, 2024). Among existing VR experiences, those designed within the 'numadelic' aesthetic take a dramatically different design approach, representing human bodies as unbounded essences composed of light and energy. Within VR, the numadelic aesthetic has been shown to elicit STEs of comparable phenomenological intensity to those induced by moderate doses of psychedelics (Glowacki et al., 2022, 2020). In multi-person numadelic VR environments, participants experience themselves as luminous, energetically diffuse beings. This blurring of self/nonself distinctions can foster profound interconnectedness and self-transcendence (Glowacki, 2024; Parola et al. (in prep); Vidal et al., 2024).

Maximizing the depth of STEs during a numadelic journey depends on optimizing embodiment and presence, which heavily relies on emotional engagement in the experience (Riva et al., 2016; Yaden et al., 2017). Designing effective VR experiences often relies on participants' subjective accounts of their experiences, which can be limited in accuracy and temporal resolution (Napa Scollon et al., 2009; Vlahovic et al., 2022; Winkler and Appel, 2024), as well as demand characteristics and behavioural compliance, that is the tendency for participants to be influenced by what they think experimenters are looking for (Suzuki et al., 2023). To address this, this article proposes to test the extent to which STEs that emerge during numadelic experiences are reflected in participants' physiological state. Such measure(s) would offer a real-time, objective way to monitor STEs as they unfold, and could ultimately be integrated as real-time biofeedback which modifies the VR environment, helping guide participants toward optimal states conducive to STEs.

The involvement of the autonomic nervous system in emotional processing

Can STEs be reflected in physiological state? The idea that mental states are mirrored in the body is deeply rooted in numerous contemplative traditions, where body awareness is integral to spiritual and psychological practices. Sezer and Sacchet recently reviewed evidence indicating that advanced meditation practice may be associated with a specific profile of autonomic nervous system (ANS) activity, suggesting the potential for sustained modulation of autonomic function through intentional practices (Sezer and Sacchet, 2025).

The ANS, a subdivision of the peripheral nervous system, consists of two branches: the sympathetic and parasympathetic systems, which work in harmony to regulate physiological responses to internal and external stimuli. The sympathetic branch activates the 'fight or flight' response, releasing adrenaline and noradrenaline to increase arousal by elevating heart rate (HR), blood pressure, and respiration rate (Jänig, 2003). These changes prime the body for heightened sensory awareness and physical readiness for action by directing energy to muscles, lungs, and bottom-up attentional processing brain centres, while reducing activity in less urgent systems like digestion and default mode network (Beissner et al., 2013). This high arousal state is also a crucial component of emotional processing, ensuring an adaptative response, particularly in situations involving intense emotions such as stress, fear, or excitement, where the body mobilizes resources to address perceived challenges, threats, or opportunities.

The parasympathetic branch, on the other hand, facilitates the 'rest and digest' response by releasing acetylcholine, which lowers HR, decreases blood pressure, and promotes relaxation (Jänig, 2003). It supports the conservation of energy, digestion, and the restoration of bodily tissues. This branch plays a key role in calming or regulating emotional states, helping the body recover from arousal caused by the sympathetic system, and fostering feelings of safety and wellbeing that form the basis of healthy

humans' interactions (Duarte and Pinto-Gouveia, 2017; McCorry, 2007; Pinna and Edwards, 2020; Porges, 2022).

Both branches are integrally involved in emotional regulation and processing, and their dynamic interplay, known as sympathovagal balance, is essential not only for maintaining homeostasis but also for adapting to the emotional and social demands of daily life (Kreibig, 2010; Siegel et al., 2018; Stifter et al., 2011). This balance is foundational for emotional resilience and flexibility, enabling individuals to respond appropriately to both positive and negative experiences (An et al., 2020; Stifter et al., 2011; Strigo and Craig, 2016).

The involvement of the ANS in meditation and other types of STEs

As well as being involved in emotional processing, the state of the ANS has also been found to affect and to be affected by contemplative practices. Meditation, for instance, has long been recognized for its relaxing effects (Davidson, 1976; Kushner and Marnocha, 2008), suggesting a parasympathetic influence. However, meditation encompasses a wide range of practices, each producing distinct outcomes (e.g., Singer and Engert, 2019). Notably, some meditation techniques, particularly those associated with enhanced affective and prosocial processing, such as compassion-based practices (Dahl et al., 2015), have been linked to increased arousal through sympathetic activation, often in tandem with parasympathetic processes (Léonard et al., 2019; Lutz et al., 2009; Sezer and Sacchet, 2025).

In traditional Buddhist frameworks, meditation is understood as a state of calm yet vigilant awareness—one that requires careful balancing to avoid the extremes of hyperarousal (manifesting as restlessness) and hypoarousal (such as drowsiness or sleep) (Britton et al., 2014). This state, described as 'relaxed alertness', corresponds to a unique combination of a still, relaxed body and an active, focused mind. A possibly over-simplified view would be that while early stages of meditation practice mostly promote relaxation through parasympathetic activation, more advanced practice may involve mastering a balanced state between parasympathetic and sympathetic activity (Sezer and Sacchet, 2025).

Beyond meditation, research into the physiological correlates of STEs remains in its early stages. However, several studies suggest that certain types of NOSC can be induced through hyperarousal. This phenomenon has been intuitively understood for millennia, as evidenced by the widespread use of various high arousal trance-inducing practices in ancient traditions (e.g. hyperventilation, fasting, sweat-lodge, dance, drumming) (Gosseries et al., 2024; Oswald et al., 2023; Walter and Altorfer, 2023).

How can hyperarousal lead to spiritual experiences? Bonnelle et al. (2024) have proposed that it may be related to the so-call vagal rebound that follows an intense stress response (Mezzacappa et al., 2001). A well-documented example of this phenomena is HR recovery following aerobic exercise, where parasympathetic reactivation drives rapid heart rate deceleration while sympathetic activity remains elevated, resulting in the transient coactivation of the two branches of the ANS (Perini and Veicsteinas, 2003; Weissman and Mendes, 2021). This unusual physiological state could induce adequate physiological conditions for STEs, characterized by their paradoxical 'peaceful arousal'. Consistent with this hypothesis, previous work has shown that individuals who reported the most profound spiritual and insightful experiences following the administration of the psychedelic drug N,N-Dimethyltryptamine (DMT) - which is associated with a pronounced increase in sympathetic activity post-administration - demonstrated a higher state of co-activation of the sympathetic and parasympathetic nervous systems during their experience (Bonnelle et al., 2024).

Another potential example of this state of sympathovagal interplay may be found in aesthetic chills. This psychophysiological response, often associated with the experience of awe and self-transcendence (Christov-Moore et al., 2024), seem to reflect a state of high sympathetic arousal experienced in a context of awe-induced parasympathetic activation (Gordon et al., 2017; Jain et al., 2023).

Measuring sympathovagal engagement

Although further validation across diverse modalities is needed, multiple forms of STEs may involve dynamic co-engagement of the sympathetic and parasympathetic nervous systems. Accurately capturing this dynamic interplay remains a methodological challenge, particularly when relying on conventional measures (Billman, 2013; Eckberg, 1997). The relationship between the two ANS branches is complex and non-linear, with evidence showing that sympathetic activity can either suppress or enhance parasympathetic reactivity (Shaffer and Ginsberg, 2017).

Here, we propose that this state of sympathovagal engagement may be captured through the amplitude of heart rate fluctuations over time, also known as heart rate variability (HRV). We reason that under reduced constraints imposed by either inhibitory (parasympathetic) or excitatory (sympathetic) dominance, the heart is freer to explore a broader range of physiological states—resulting in a wider HRV amplitude. Our proposed measure, which we refer to as *HRV amplitude* (Figure 1), is designed to reflect this cardiac flexibility, which may manifest behaviourally as the capacity to actively engage with the external environment while simultaneously regulating internal emotional responses. Given the possible relationship between sympathovagal engagement and STEs outlined above, we propose the measure of HRV amplitude as a bridge between subjective experiences and objective physiology in STEs.

Unlike the related metric known as Local Power, which captures rapid, phasic vagal modulation by computing differences between local minima and maxima within each cardiac cycle (Bornemann et al., 2016), our envelope-based approach provides a smoothed upper and lower bound of the HR signal over time. This smoothing attenuates fast vagal dynamics, allowing the measure to reflect broader autonomic modulation depth that incorporates both parasympathetic and sympathetic contributions.

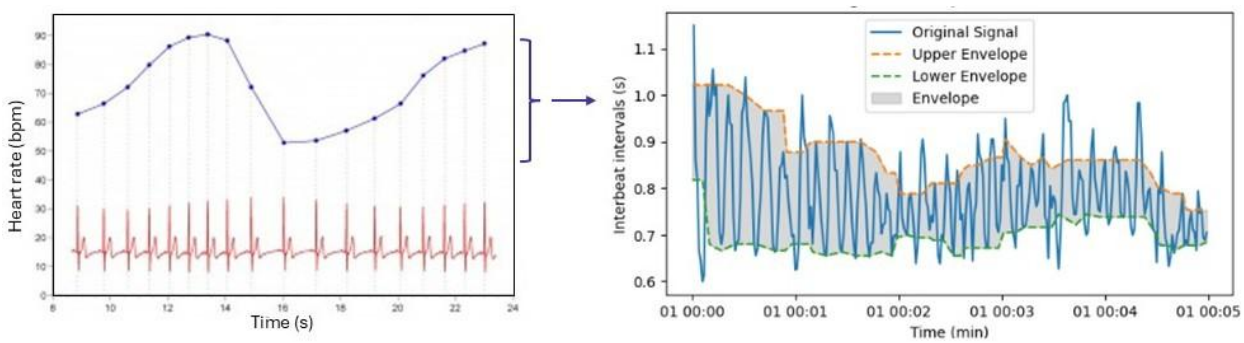


Figure 1: Left panel: ECG signal in red, each heartbeat corresponding to a peak (R-peak). Based on this signal, heart rate variability (HRV) over time can be estimated (blue plot on top). HRV refers to the variation in time intervals between heartbeats. Right panel: Example of HRV signal showing the fluctuations of interbeat intervals over a 5 min period. The upper and lower envelopes of the HRV plot can be derived (as described in Method) in order to estimate local HRV amplitude. In this study, we propose that this measure may reflect sympathovagal co-activation.

Study objectives

After confirming that numadelic VR can reliably elicit deeper STEs than a non-VR meditation, we tested separately in the two conditions our primary hypothesis that HRV amplitude, reflecting autonomic balance and engagement, would correlate with STE ratings. Next, given that STEs are often associated with lasting improvements in mood and relationality (Kitson et al., 2020; Yaden et al., 2017), we assessed whether HRV amplitude predicted post-practice changes in these dimensions. Additionally, given the interconnection between compassion and self-transcendence, one promoting the other (Crockett and Lockwood, 2018; Kang, 2019), we evaluated whether compassion traits may predict STE and HRV amplitude during the experience. Finally, as an *a posteriori* analysis to assess the robustness and generalizability of our findings, we revisited data from a previously published study involving DMT-induced NOSC. This additional step served as a conceptual cross-check, testing whether the same autonomic signature observed during numadelic VR experiences also emerges in a pharmacologically induced context. By extending the analysis across distinct modalities, we aimed to strengthen the case for HRV amplitude as a scalable, cross-context biomarker of STE depth—one that may help unify diverse approaches to eliciting transformative experience.

Methods

Study design

The main study from which this work stems (Validation of the efficacy of Numadelic VR inducing STE, currently under preparation) was preregistered on the Open Science Framework prior to data collection (https://doi.org/10.17605/OSF.IO/YNPCK), and employed a randomized controlled design with two groups, an experimental group participating in a group numadelic VR experience as implemented within the AnumaXR app (available on the Meta Quest App Lab) on Meta Quest 3 wireless head mounted displays (HMDs), and the control group in a traditional group setting (e.g., recorded meditation), both practicing a guided meditation in sub-groups of four. Within the AnumaXR app, group VR experiences (wherein each participant occupies the same virtual space) are possible by connecting each headset to the same cloud-mounted server. The present study constitutes an exploratory analysis addressing secondary objectives outlined in the pre-registration.

Each participant underwent assessments before the practice and immediately after the practice. Data collection involved administering a battery of questionnaires at baseline and post experience, and recording physiological measures (ECG and Respiration) during the practice session, and during two rest periods before and after the session.

Participants

This study was approved by the Ethics Committee of the University of Valencia, Spain (registration number: 2024-PSILOG-3349305). All activities conducted in studies involving human participants adhered to the principles outlined in the 1964 Helsinki Declaration and its subsequent revisions or adhered to equivalent ethical standards.

In total, 96 participants (12 sub-groups of 4 for each condition) over 18 years old and proficient in Spanish were recruited through flyers and social media. Exclusion criteria were as follow: (a) current diagnosis of a psychological disorder (e.g., depression, anxiety), (b) use of substances altering the nervous system, (c) cardiac conditions, and (d) current or past diagnosis of post-traumatic stress

disorder (PTSD), psychosis and personality disorders. Upon enrolling to the study, participants were randomly assigned to one of the conditions using https://www.randomizer.org/ software.

Three participants in the VR group were excluded from further analysis; one did not complete the experimental session, one reported that they felt confused by the questionnaires after the experience, and one experienced intense emotional release halfway through the experience and significant discomfort with the headset (Final VR group: n= 45, mean age =27 ± 11 years, 28 males). Two people did not show up on their session day in the control group, and had to be replaced with research team members, whose physiological data were collected but not included in the analysis (Final Control group: n=46, mean age = 23 ± 7 years, 34 males). The control group was significantly younger (Mann-Whitney U test, p=0.046), but there was otherwise no significant difference in gender, Body-Mass Index (BMI) or meditation experience between the two groups.

Experimental Procedure

Participants completed baseline questionnaires and attended experimental sessions (blinded for group assignment until the beginning of the session) in sub-groups of four. The experimental sessions were carried out by a facilitator and a person in charge of physiological data collection (both not blind for participants group assignments). The practices, in both VR and control groups, included three distinct phases during which participants remained seated: preparation, meditation, and integration/discussion. Preparation involved facilitator introduction, explanation of the meditation, intention-setting, and guided breathing practices. Following this initial phase, the facilitator started a pre-recorded guided meditation lasting approximately 25 minutes, composed of seven distinct chapters described in Table 1. Last, participants were invited to share their experiences with the group. Practices were preceded and ended with five minutes of rest periods, with eyes closed in order to collect physiological data (without the VR headset for the VR group).

Description of the VR numadelic experience

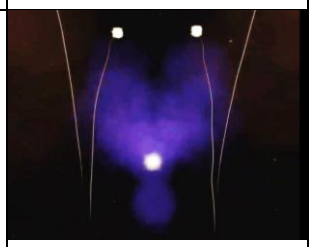
The numadelic VR experience, called 'Ripple' was developed by two of the authors, David Glowacki and Justin Wall, who is a teacher in the Vajrayana Tibetan Buddhist tradition. This guided VR journey takes participants through successive practices (referred to below as 'chapters') involving breathing practices and playful exploration that invites participants to visualize their bodies as diffuse energetic essences (illustrated in Table 1). The audio file of the pre-recorded section of Ripple discussed in this article is available in the data repository (see Data Availability).

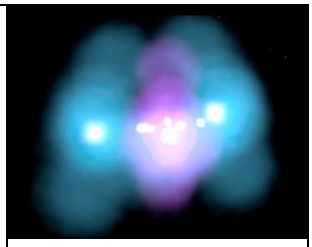
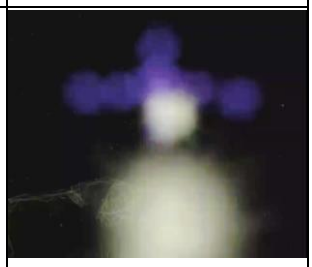
Guided contemplative journeys within numadelic VR environments can support STEs by engaging several fundamental mechanisms underlying such states (Vidal et al., 2024; Parola et al. (under prep.). First, the aesthetics of the numadelic VR environment can enhance absorption, presence, and flow (Hooper et al., 2025; Magon and Cupchik, 2023; Suzuki et al., 2023). Second, embodying an ethereal 'energy body' within the VR space can foster greater permeability of self-boundaries, diminishing the rigidity of the embodied self and opening pathways to experiencing the properties of the VR avatar as one's own - feeling more spacious, fluid and open, an effect which has been referred to as the 'Proteus effect' (Beaufils and Berland, 2022; Dupraz et al., 2024). Third, the multi-person aspect of the VR environment evokes a ceremonial space, priming participants for the emergence of uncommon emotional and cognitive states, and facilitating the dissolution of individual boundaries (Johnson et al., 1995; Rappaport, 1999; Whitehouse, 2002). Fourth, the group cohesion effect cultivated within this space can promote authentic dynamics of 'interbeing' and intimacy, nurturing a sense of group-directed transcendence. By creating a powerful sense of unity and shared experience, it dissolves the perception of self as an isolated entity, deepening the experience of interconnectedness (Dein, 2020).

Lastly, bringing awareness to the breath is at the base of most meditation practices, and in numadelic VR, this process is facilitated by rendering the flow of breath visible through the mediation of the hand controllers. By gently moving their arms in what we refer to as the 'tonglen motion', expanding them outward (away from their chest) during exhalation and inward (toward their chest) during inhalation, in pace with their breathing, participants are enabled to visualize their breath in VR as a kind of proxy for live biofeedback using respiratory monitoring devices. This breathing motion also plays a crucial role in strengthening the connection between the user and their virtual avatar, enhancing the sense of immersion and presence. The breathing practices in pairs or in group also contribute to building group connection through physiological synchrony and a sense of cohesion between participants.

Table 1: VR meditation chapters

Table 1 provides a short description of each chapter in Ripple. The last column shows snapshots of each chapter, as seen from the point of view of a participant's HMD. The control meditation attempted to replicate each of these chapters outside VR, with participants being invited to close their eyes and visualise their body as the VR avatar – a cloud of energy, like a mist, without substance or solidity - and to imagine the other participants in a similar way. They were then guided through the same chapters as the VR session and invited to visualise with closed eyes what participants in the VR session see. * indicates chapters that could be used for the physiological analysis (limited motion and natural breathing).

Pre-recorded Ripple meditation chapters	VR meditation description	Snapshots
1. Mirror breathing	Pair practice involving arm motion (upward and downward) synchronized with slow box breathing, attuning to the breath and movement of partner. *Snapshot description:* Partner's avatar with arms up. The 2 upper orbs represent hands, and the lower one represents the 'heart light'.	
2. Breathing in space	Individual practice of bringing awareness to the breath, represented as a luminous orb coming out of the chest during exhale ('heart light'), and back into the chest during inhale. Heart light motion is guided by the motion of the arms opening and closing (visible as faint trails on the picture).	
3. Breathing in group	Group practice with the tonglen motion, with heart lights shared at the centre of the group. *Snapshot description: Heart lights* are guided by arm motion, and synchronized with breath, flowing from the chest toward the centre of the group on exhalation. NB: only two participants can be seen in this image, but the practice was undertaken with the whole group of four.	

4. Coalescence*	The four participants' avatars progressively move closer to one other until they merge seamlessly, forming one continuous energy cloud, as previously described by Glowacki (2022, 2024). NB: no active motion from participants who remain seated.	
5. Breathing in pairs	Pair practice with the tonglen motion, breathing out one's heart light into the partner avatar's chest, and then breathing in partner's light toward oneself. *Snapshot description:* Although the same snapshot as chapter 3 was used to represent this scene, the 2 practices differ in that participants practice in pair, and the heart light travels all the way to partner's chest on exhalation.	
6. Partner fading	Pair practice in which partners appear represented only as their heart light, which undergoes successive cycles of expansion and contraction at a rate 5.5 per min. Participants are invited to adapt their breathing to this pace, inhaling as the light expands and exhaling as it contracts. The amplitude envelope of the light gradually decreases until it vanishes, leaving participants in complete darkness for about a minute. In the control meditation, the pulsating heart light is replaced by a bell.	
7. Partner reemerging*	The pulsing light re-appears, but participants are not specifically instructed to breathe at the same pace as the light, just to witness it.	

Questionnaires

Trait questionnaires (baseline only):

- Sussex-Oxford Compassion for Others Scale (SOCS-O; Gu et al., 2020). It is a 20-item scale that measures the level of compassion toward others. It comprises five dimensions: 1) *Recognizing suffering* (e.g., "I notice when others are feeling distressed"), 2) *Understanding the universality of suffering* (e.g., "I understand that everyone experiences suffering at some point in their lives"), 3) *Empathizing with the person who is suffering* (e.g., "When someone is going through a difficult time, I feel kindly towards them"), 4) *Tolerating uncomfortable feelings* (e.g., "I stay with and listen to other people when they're upset even if it's hard to bear"), and 5) *Motivation to act* in order to relieve the other person's suffering (e.g., "When others are struggling, I try to do things that would be helpful"). It uses a Likert-type scale ranging from 1 (never true) to 5 (always true).

State questionnaires (baseline and post session):

- The Hedonic and Arousal Affect Scale (HAAS; Roca et al., 2023) is a 24-item questionnaire designed to assess self-reported affective experiences, specifically focusing on the dimensions of valence (pleasantness/unpleasantness) and arousal (activation level). It employs a Likert-type scale ranging from 1 (not at all) to 4 (extremely).
- A Visual Analog Scale (VAS) to measure compassion and judgement towards others ad-hoc was developed from the Self-Compassion and Self-Criticism Scales (SCCS, Falconer et al., 2015). It uses a Likert-type scale ranging from 1 (not at all) to 7 (very much).
- A VAS was also used to measure connection to the session group ('Connection to group'). It employs a Likert-type scale ranging from 1 (I feel completely disconnected) to 10 (I feel completely connected).
- Meditation pictographic scale (D'elia et al., Under review): a novel self-report tool designed to assess distinct meditative experiences through pictographic representations. The scale was initially developed with 20 items and later expanded to 23 items. Altogether, findings suggest the MPS offers a fair representation of meditation experiences, and that pictographic items help to provide more precise and unbiased measurement of these experiences. Items included in this study are those relevant to mood, relationality and self-transcendence: Positive affect, Negative affect, Compassion, Connection to others, perceived self-expansion and perceived porosity of body boundaries.

Additional questionnaire about the meditation experience (post session only):

- The Mystical Experience Questionnaire (MEQ-30; Maclean et al., 2012) is comprised of 30 items asking participants to reflect on their experiences of unity with the ultimate reality (Unity), feelings of ecstasy and peace (Positive Mood), perceptions of timelessness and loss of the sense of time (Transcendence of Time and Space), and the indescribable nature of their experience (Ineffability). It uses a Likert-type scale ranging from 1 (not at all) to 5 (extremely).
- The Awe Scale (Carrasco et al., 2018) is an instrument originally developed in Spanish for measuring state awe. It has 16 items classified in five factors: appraisals, affective response, physiological response, cognitive-subjective response and action tendency. It employs a Likert-type scale ranging from 1 (nothing) to 7 (a lot).

Subjective experience measures:

After their session, participants rated the quality of their experience along six different dimensions of interest: *Engagement*, *Valence*, *Intensity*, *Boundarilessness, Connection* and *Ego reduction* (Supplementary Table 1), focusing on each chapter separately. Before rating their experience on each chapter, they visualized a short video clip of the chapter to facilitate their recollection of the chapters (Table 1).

Physiological data collection

Data collection

Cardiac and respiratory activity were recorded with the Shimmer 3 ECG module (Shimmer Sensing, Dublin, Ireland) with a sampling frequency of 180Hz. This wireless medical-grade chest electrocardiogram (ECG) monitor can simultaneously record ECG and impedance pneumography -

which varies with each inhalation and exhalation - via four adhesive electrodes placed on the upper side of the chest and lower side of the abdomen. Electrodes were connected via four leads to the shimmer devices, which were strapped on a belt around participants' abdomen. The four shimmer devices were wirelessly connected to the recording PC via Bluetooth, enabling data streaming and real-time monitoring, as well as pre-processing and extraction using the Consensys Pro software (v1.2.0, Shimmer).

Data preprocessing

ECG signal was first band pass filtered in Consensys (120 taps, cut off frequency of 0.5-30Hz) and saved for further pre-processing and analyses in Python using the Neurokit2 toolbox (Makowski et al., 2021). The function ecg_process was used for cleaning the data, detecting R peaks and calculating heart rate and RR intervals (time difference between two consecutive R peaks). To improve R peak detection, we applied the 'kubios' method using the function 'signal_fixpeaks' which helps identify ectopic peaks. Data was visually inspected, and segments with poor R peak detection exceeding 10% of the analysis's windows were excluded from analysis. One ECG dataset had to be excluded in the VR group, and three in the control group.

ECG-derived Measures of interest were computed as timeseries, and then averaged across the chapters of interest. These were:

Root Mean Square of Successive Differences (RMSSD): RMSSD, a well-established measure of parasympathetic activity that can be computed based on short data segments (minimun 10s) was calculated from RR intervals timeseries using 30s sliding windows, with 1s steps (Shaffer and Ginsberg, 2017).

Sympathetic and Parasympathetic indexes (SAI and PAI) : SAI and PAI calculation was performed following the methodology described in Valenza et al.(2018a), by uploading the timing of R events to the URL http://www.saipai-hrv.com/. These output series are derived from a Kalman-based estimation (Valenza et al., 2018b).

HRV amplitude: The amplitude of the RR interval signal envelope was computed at each time point by taking the difference between the moving median of local maxima and the moving median of local minima (Figure 1). This method, which uses a window of five data points, is robust to outliers, preserves local trends, and provides a stable estimate without excessive fluctuations. We used this approach rather than a Hilbert Transform because visual inspection revealed superior performance for highly entropic RR interval time series.

Since conditions varied throughout the meditation session, and given our focus on a measure that may reflect real-time subjective experience, we did not compute HRV parameters requiring longer data windows for reliable estimation—such as frequency-based and non-linear metrics. The rational for using this measure is described in Supplementary Information.

Respiratory Rate & Amplitude: Respiratory signal was low pass filtered in Consensys (120 taps, cut-off frequency of 3Hz) before being exported for further pre-processing in Python using the rsp_process function from the Neurokit2 toolbox (Makowski et al., 2021). The raw signal, sampled at 180 Hz, was then further preprocessed using a second order 0.05-3 Hz bandpass Butterworth filter (Khodadad et al., 2018). The peak detection was carried out using the method described in Khoadadad et al. (2018). To ensure data quality, visual inspection was performed using the same approach as for ECG signals.

Datasets were excluded if artifacts or detection issues exceeded acceptable thresholds, leading to the removal of 2 respiratory datasets in the VR group and 5 in the Control group. Finally, respiratory rate and amplitude were extracted from the cleaned respiratory signal for further analysis.

Statistical analysis

Data normality was assessed using the Shapiro-Wilk test. When comparing VR and Control groups, normally distributed variables were analyzed using an independent t-test, while non-normally distributed variables were assessed using the Mann-Whitney U test.

Physiological data analysis focused exclusively on Chapters 4 and 7, the only segments where participants experienced unconstrained motion and breathing. To reduce the number of measures and tests, data from these two chapters were averaged.

To examine the relationship between physiological and psychological variables within groups, all variables were normalized using a min-max scaler, and Spearman correlations were performed, controlling for Age, Gender, and BMI as covariates.

Given our hypothesis-driven approach with a primary focus on HRV amplitude in relation to STEs, we did not perform multiple comparison corrections on the corresponding correlation. Other correlations—reported for comparative purposes—were likewise not corrected, serving as reference points for HRV amplitude performance relative to other measures.

To explore whether HRV amplitude's relationship with psychological measures was mediated by other physiological metrics (notably respiratory amplitude), we employed partial correlations and mediation analysis, using Pingouin's toolbox in Python (Vallat, 2018).

Participants' psycho-emotional state was assessed before and after the session through multiple measures, grouped into three domains to streamline analysis: 1) Positive Affect – Pictographic scale (Positive affect), HAAS (Positive valence emotions), 2) Negative Affect – Pictographic scale (Negative affect), HAAS (Negative valence emotions), and 3) Relationality – Pictographic scales (Compassion, Connection group, Connection others). Since these measures were already used in primary validation of the Numadelic VR effectives (Parola et al., under prep.), in this study we use them for correlational purposes only.

Analysis of Psychedelic Data

For this analysis, we revisited data from a previously published study examining the impact of DMT on ANS activity (Bonnelle et al., 2024). Instead of pre-processing and analyzing ECG data with Kubios software, as in the original study, we applied the same ECG processing protocol used for Shimmer recordings, utilizing Python's Neurokit2 toolbox.

While working in Python provides greater flexibility for advanced analysis, one limitation compared to Kubios is the lack of manual correction for R peak detection via a graphical interface. In the original DMT study, manual inspection enabled corrections, resulting in 17 usable ECG datasets out of 19 ECG data. However, in this reanalysis, four additional datasets were excluded due to noisy signals that could not be adequately corrected using our automated processing pipeline.

For each participant, ECG data consisted of 8 minutes of baseline recording, followed by 20 minutes of post-injection data. HRV amplitude was computed as a time series across the entire session and

then averaged after the initial physiological stress response induced by DMT injection—starting at minute 4 post-injection and continuing until the end of data collection.

These averaged HRV amplitude measures were then correlated using Spearman correlations with subscales from two questionnaires assessing the quality of peak experiences: the Mystical Experience Questionnaire (MEQ-30) and the 11 Dimensions Altered States of Consciousness Questionnaire (11D-ASC). The 11D-ASC features the following subscales: Experience of Unity, Spiritual Experience, Blissful State, and Insightfulness Impaired Control and Cognition, Anxiety Disembodiment, Complex Imagery, Elementary imagery, Synesthesia and Meaning (Studerus et al., 2010).

Results

Subjective experience during Numadelic VR meditation compared to control meditation

Figure 2 illustrates the differences observed between the VR and Control groups across the six different Subjective experience measures, and throughout each of the seven chapters. *Engagement*, *Valence* and *Intensity* of emotions were significantly higher during VR on most chapters, apart from the first and last one ($p<0.05$). *Connection* and *Ego-reduction*, two measures reflecting self-transcendence (Yaden et al., 2017), were also significantly higher in the VR group on chapters 1, 4, 5 6 and 7, and also chapter 3 for connection ($p<0.05$), consistent with previous findings that numadelic experiences can achieve a significant degree of self-transcendence (Glowacki et al., 2022; Vidal et al., 2024). Surprisingly, however, the perceived *Boundaries* scores did not statistically significantly differ between groups, possibly the result of participants in the Control group having their eyes closed and being explicitly invited to visualise their body as a cloud without substance or solidity.

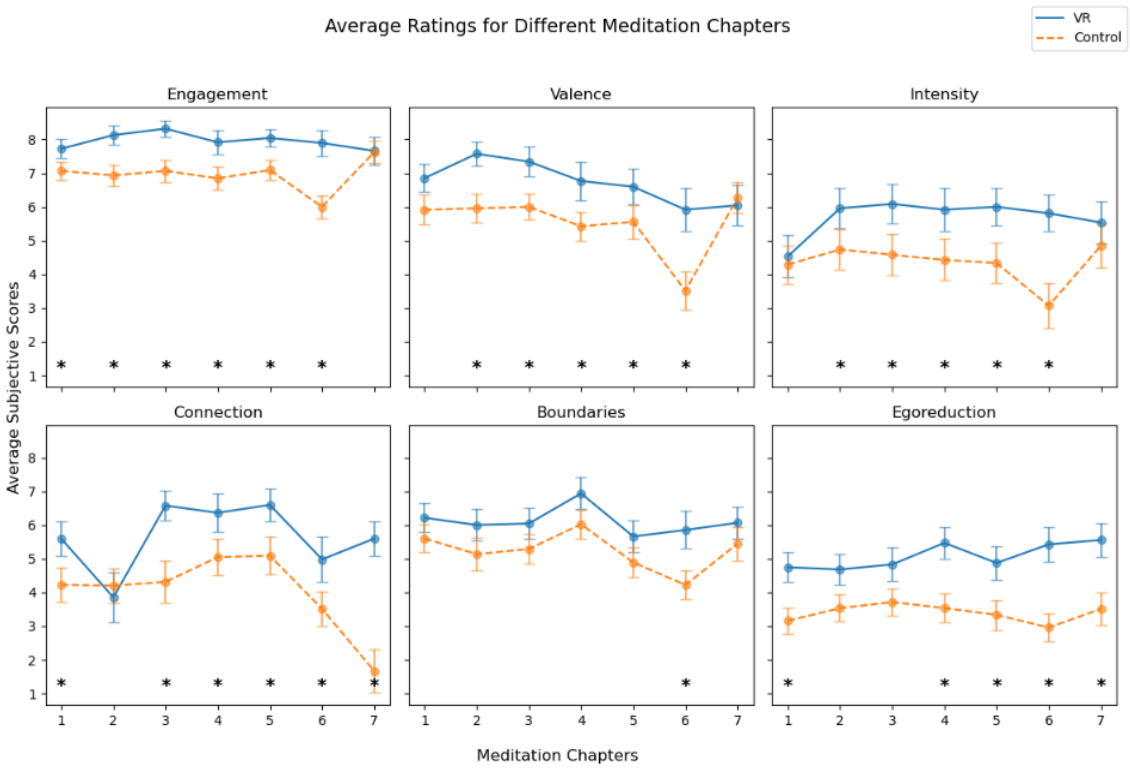


Figure 2: Averaged subjective ratings for each of the 7 chapters of the VR (continuous blue line) and control (dotted orange line) guided meditations. * indicates significant ($p<0.05$) differences between groups (Mann-Whitney U test).

Relation between STE ratings and HRV amplitude during the numadelic experience

Both motion and breathing can significantly influence ANS activity, reducing the extent to which emotional state accounts for ANS variance. To minimize these confounding effects, we focused our analysis on Chapters 4 (Coalescence) and 7 (Re-emergence), during which participants experienced neither imposed breathing nor arm motion. Incidentally, these two chapters also correspond to the peak phases of the experience, characterized by high Ego reduction ratings (Fig. 2).

As hypothesized, HRV amplitude, averaged across these chapters, showed a positive correlation with *Ego reduction* ratings (n = 44, ρ = 0.47, CI95% = [0.19, 0.68], p = 0.001). Closer inspection of the data suggests a potential nonlinear relationship between *HRV amplitude* and *Ego reduction* (Figure 3). The asymmetrical U shape of the distribution hints at a possible quadratic relationship. A quadratic fit demonstrated a higher R^2 than a linear fit (R^2 linear = 0.14; R^2 quadratic = 0.22), with a vertex estimated at *Ego reduction* = 0.3 (i.e below this value, the positive relation between ego reduction ratings and HRV amplitude disappears). The shape of the distribution suggests that the association between *HRV amplitude* and *Ego reduction* may only become apparent in participants who experience some threshold level of self-transcendence.

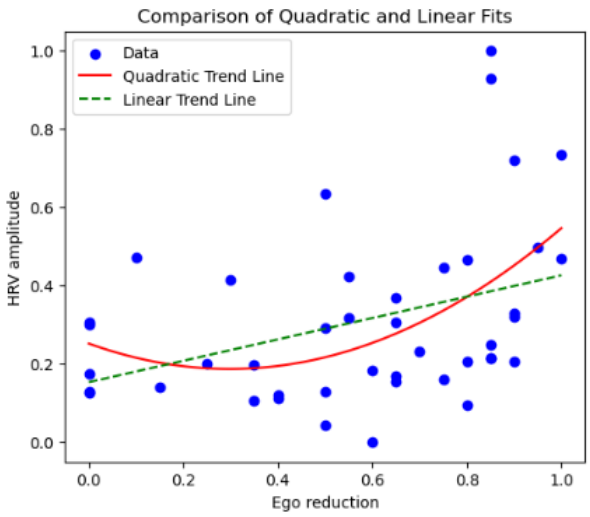


Figure 3: Comparison of a linear (green dotted line) and quadratic (red continuous line) fits to model the distribution of HRV amplitude as a function of *Ego reduction* ratings. Values are normalized between 0 and 1.

To evaluate how HRV amplitude compares to other autonomic activity measures in capturing STEs during the VR session, we report Spearman correlation coefficients between autonomic metrics (HR, RMSSD, PAI, SAI, respiratory amplitude and respiratory rate) and subjective ratings (Figure 4). Since respiratory parameters were included in this analysis, only participants whose respiratory data could be reliably analyzed were considered (n = 40). Within this subset, HRV amplitude remained significantly correlated with *Ego reduction* ratings (ρ = 0.47, CI95% = [0.18, 0.69], p = 0.003). It was also marginally correlated with *Connection* ratings (ρ = 0.30, CI95% = [-0.04, 0.55], p = 0.08). Respiratory amplitude was the only other measure showing a correlation with *Ego reduction* ratings (ρ = 0.40, CI95% = [0.09, 0.64], p = 0.01).

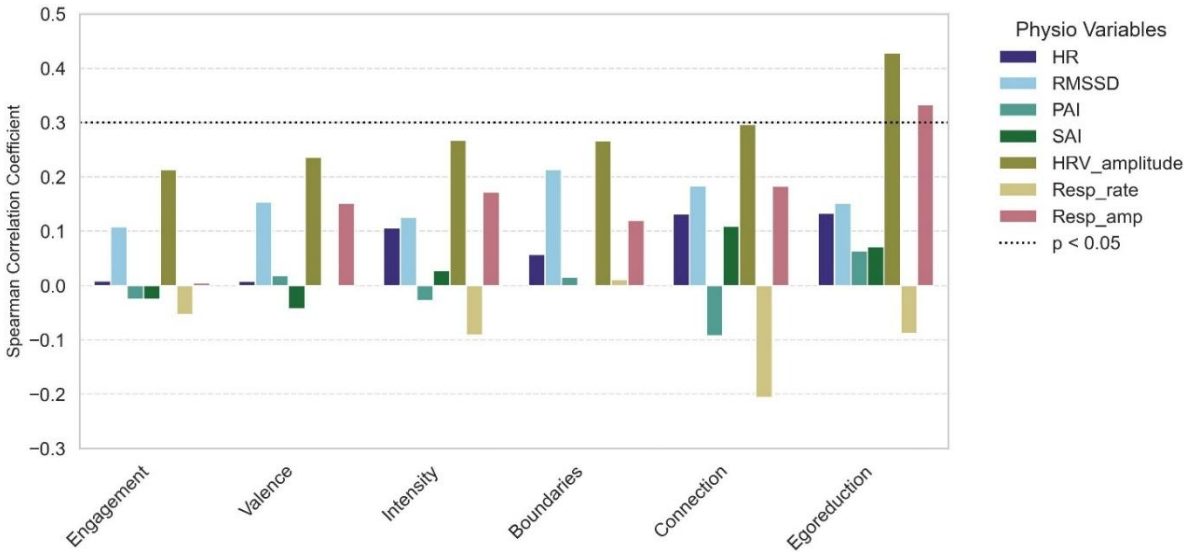


Figure 4: Spearman linear correlation coefficients for each correlation between the six subjective ratings (horizontal axis) and the 8 physiological variables in the VR group, for participants with reliable ECG and respiratory data (n=40). The dotted line indicates the significance threshold, so that coefficients above this threshold correspond to statistically significant correlations.

To explore the possibility that respiratory amplitude may mediate the relation between HRV amplitude and Ego reduction ratings, we performed a mediation analysis. Given the non-normal distribution of the data, we opted for a bootstrapped approach. Results from this analysis indicate that respiratory amplitude does not significantly mediate the relationship between *HRV amplitude* and *Ego reduction*, and that HRV amplitude directly relates to *Ego Reduction* with a large effect size (Indirect effect size = 0.084, Bootstrapped 95% CI: [-0.10, 0.35]; Direct effect size = 0.471).

Relation between HRV amplitude and STE ratings during the control meditation

Based on the observed nonlinear relationship between HRV amplitude and *Ego reduction* in the VR group, and given that *Ego reduction* ratings were significantly lower in the Control group, we anticipated that the association between HRV amplitude and *Ego reduction* in this group would be weaker or potentially absent. This expectation was confirmed by the lack of a significant correlation between ego reduction ratings and HRV amplitude in the Control group (n=42, ρ=-0.07, p= 0.65). Within this group, no significant relationship was detected between physiological and subjective measures.

Relation between HRV amplitude during the VR experience and changes in psycho-emotional state after the experience

Averaged HRV amplitude during Chapters 4 and 7 of the VR session significantly correlated with changes in *Positive affect* (n=44, ρ=0.43, CI95%=[0.14, 0.65], p= 0.005) and *Negative affect* (n=44, ρ=-0.39, CI95%=[-0.63, -0.1], p= 0.01) after the session relative to baseline, but not with changes in *Relationality* (ρ=0.26, p=0.10)

When looking at the impact of other autonomic measures, respiration amplitude during the session also appeared to positively impact *Positive affect* (ρ=0.41, CI95%=[0.11, 0.64], p=0.01), as well as *Relationality* (ρ=0.35, CI95%=[0.04, 0.6], p=0.03), but not *Negative affect* (ρ=-0.21, p=0.18)

Relation between HRV amplitude and STE questionnaires

Two questionnaires assessing participant's STE were used: the MEQ-30 and the Awe Scale. They were administered after the session, with respect to the entire session (rather than specific chapters). None of these scales showed significant correlation with *HRV amplitude* (MEQ-30_Tot: ρ=0.13, p=0.41; Awe_Tot: ρ=0.18, p=0.24), although they were both correlated with subjective ratings, particularly robustly with *Ego reduction* (MEQ: ρ=0.73, Awe: ρ=0.75, p<0.001) and *Boundaries reduction* (MEQ: ρ=0.77, Awe: ρ =0.73, p<0.001). None of the other physiological measures correlated with these questionnaires.

Relation between Compassion traits, quality of the experience and HRV amplitude

Higher levels of compassion trait, as measured by the SOCS-other questionnaire at baseline, were associated with higher ratings on all the subjective ratings dimensions during the VR meditation, particularly *Ego-reduction* (ρ=0.47, p<0.001), and *Connection* (ρ=0.43, p=0.002). Higher compassion trait was also associated with a more pronounced increase in *Relationality* after the experience compared to baseline (ρ=0.33, p=0.025).

Importantly, compassion traits were also associated with significantly higher *HRV amplitude* during the VR experience (SOCS for others (total score) n=44, ρ=0.50, CI95%=[0.23, 0.70], p<0.001). The SOCS subscales with the strongest influence on this relationship were '*Recognizing suffering*' (ρ=0.51), 'Feeling for others' (ρ=0.41), and '*Tolerate suffering*' (ρ=0.39). The subscales '*Understanding the universality of suffering*' (ρ=0.06) and '*Motivation to act*' (ρ=0.27) did not significantly correlate with HRV amplitude.

RMSSD (n=44, ρ=0.44, p=0.004) and *Respiratory amplitude* (n=0.40, ρ=0.43, p=0.006) during the VR experience were also positively correlated with compassion traits at baseline.

Assessing HRV Amplitude as a Physiological Marker of Self-Transcendence in Psychedelic States

To evaluate the effectiveness of HRV amplitude in capturing STEs within other NOSC, we revisited previously published ECG data collected during DMT-induced STEs. First, we averaged across each participant HRV amplitude time course in order to visualise how HRV amplitude fluctuates, on average, throughout the entire DMT experience. As illustrated on Figure 5, HRV amplitude increases approximately 10 minutes post-injection, possibly reflecting the previously described window of sympathovagal co-activation associated with vagal rebound following the initial peak of sympathetic activity induced by DMT, which we refer to as the 'post-acute stress response' phase (Bonnelle et al., 2024).

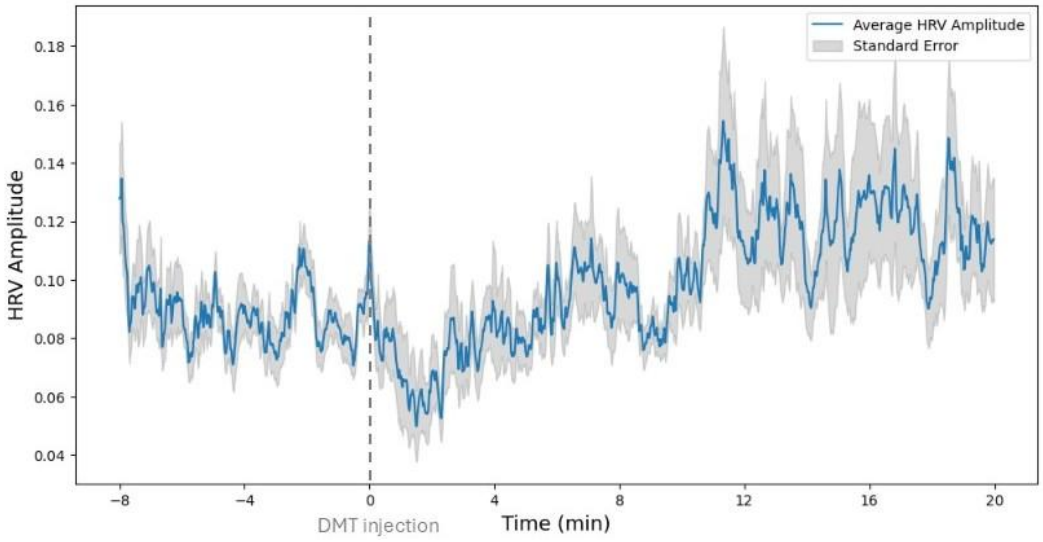


Figure 5: Fluctuations in HRV amplitude averaged across 13 participants. The grey area indicates standard errors. DMT was injected following a 8-min baseline period (grey dotted line).

For each participant, we then averaged HRV amplitude during the post-acute stress response phase, between minutes 4 and 20 post injection, and correlated these measures with subjective ratings of peak experience collected with the Mystical Experience Questionnaire (MEQ30) and the Altered State of Consciousness scale (11D-ASC).

Average scores on the MEQ-30 where robustly correlated with *HRV amplitude* (N=13, spearman ρ =0.82, CI95%=[0.50, 0.93], p<0.001), which was mostly driven by the two subscales '*Mystical experience*' (ρ =0.77, CI95%=[0.43, 0.94], p=0.002), and '*Positive mood*' (ρ =0.73, CI95%=[0.34, 0.93] p=0.004). In addition, HRV amplitude was also highly correlated with the 11D-ASC dimension '*Blissful state*' (ρ =0.80, CI95%=[0.43, 0.94], p<0.001), and more marginally, with the subscale *'Oceanic Boundlessness*' (ρ =0.55, CI95%=[-0.045, 0.84], p=0.05). Correlations can be visualised on Figure 6.

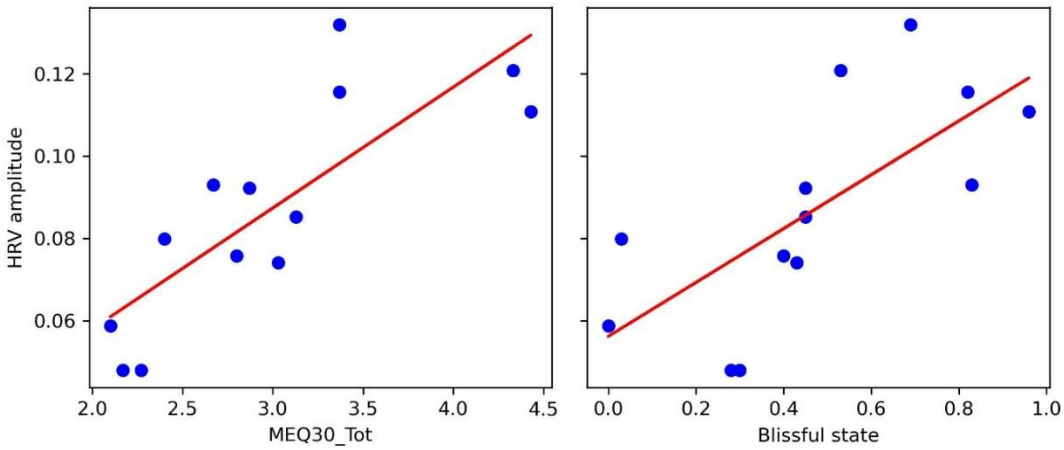


Figure 6: Correlations between HRV amplitude during the post-acute stress response phase following DMT injection, and ratings of STEs collected with the MEQ-30 and the 11d-ASC (Blissful state).

Discussion

The central question driving this study was if STEs experienced during numadelic VR may be captured at the physiological level using a measure reflecting sympathovagal co-activation. Addressing this is essential for advancing research into these NOSC, without solely relying on participants' subjective reports, which are limited in time resolution, labor-intensive to collect, and dependent on accurate recollection and interpretation of experiences along specific questionnaire dimensions. Building on prior research into the role of the ANS in psychedelic peak experiences, we introduce a novel measure, referred to as HRV amplitude, to capture sympathovagal influence on cardiac activity. Consistent with our hypothesis, findings indicate that HRV amplitude significantly correlates with STE ratings across both numadelic and psychedelic-induced STEs. In addition, this measure is also related to compassion traits, and can robustly predict the positive after-effects of numadelic sessions on participants' emotional state.

Numadelic VR as a promising tool to study STEs

Research on STEs has been constrained by their inherently non-ordinary nature, as these states typically require years of advanced contemplative practice or the use of mind-altering substances like psychedelics. The potential of numadelic experiences to induce STEs in individuals is remarkable and holds significant value not only for research, but also for therapeutic applications and personal development. Amid the psychedelic research renaissance, one of the most consistent themes emerging over the past decade is the central role of STEs in the long-term benefits of psychedelic-assisted therapy (Ko et al., 2022). As modern psychiatry increasingly acknowledges the therapeutic potential of these states for mental health, there is growing interest in developing novel, safe, and reliable methods to induce such experiences, alongside tools to monitor their occurrence and intensity.

Our results indicate that numadelic VR is not only more engaging than an audio-guided meditation, but also more effective at lowering the sense of ego, enhancing the perceived porosity of self-boundaries, while fostering connection between participants. As outlined in the Methods section, several core features of numadelic experiences contribute to their potential for STEs: 1) Greater absorption, fostering deep immersion and altered attentional states; 2) Aesthetic qualities characterized by low representational imagery, evoking the essential traits of STEs—non-rigidity, openness, and shifts in self-perspective; 3) Ceremonial space, reinforcing meaning and engagement and 4) Social connection, enhancing intersubjective experiences. Together, these features reduce cognitive rigidity, enhance openness, and encourage altered self-perception, making them potent facilitators of STEs.

Another potentially relevant component underlying the impact of numadelic VR may be summarized as 'safe exposure'. VR has the potential to create a structured yet fluid environment where individuals may feel safe enough to lower their defences and explore altered states of consciousness. Much like exposure therapy, where a controlled space allows patients to gradually confront their fears without overwhelming anxiety (Boeldt et al., 2019), a numadelic-guided experience may act as a container that enables individuals to let go of rigid identity structures—allowing for ego dissolution, self-transcendence, or profound shifts in awareness.

Physiological marker of STEs

Previous research on the physiological basis of STEs has largely focused on their neurophysiological correlate. While neural activity provides valuable insights into the phenomenology of these experiences, its measurement is often costly, computationally demanding, and impractical outside laboratory settings. In contrast, moment-to-moment cardiac metrics offer a more ecologically valid and accessible approach. Drawing from prior research on psychedelics (Bonnelle et al., 2024), where shifts in ANS function have been implicated in altered states, we hypothesized that ANS activity could serve as a physiological marker of STEs. More specifically, we hypothesized that STEs manifest as a paradoxical state of 'relaxed alertness', in which both sympathetic and parasympathetic branches of the ANS may be co-activated.

Since HR oscillation amplitude reflects the dynamic interplay between these systems, it presents a promising moment-to-moment indicator of sympathovagal activation. To assess its effectiveness, we compared this measure with other short-segment estimations of autonomic function. Although HRV amplitude partially correlated with other parasympathetic markers, it was the only cardiac-derived measure to significantly correlate with ego-reduction ratings, suggesting that this relation was not mostly driven by the parasympathetic component of HRV amplitude.

The relation between HRV amplitude and ego-reduction ratings was non-linear, so that the two variables were more related with each other when participants' STE ratings were above a certain threshold. Possible interpretations of this observation are discussed below.

ANS and emotions

Research on the relationship between emotional states and ANS activity suggests that the connection is complex, influenced by multiple modulating factors (Friedman, 2010; Kop et al., 2011; Kreibig, 2010). We propose that specific conditions must be met for individuals' subjective experiences to reliably map onto their ANS activity.

Firstly, given that a large portion of ANS activity is involved in the regulation of involuntary functions essential for survival, only a subset of autonomic fluctuations directly reflect emotional states. This relationship may strengthen with intense emotional experiences but can become less distinguishable within autonomic signals for subtle or secondary emotions (Levenson, 2014). Additionally, body motion and imposed breathing introduce variability, diminishing the portion of ANS variance relevant to emotional state (Bernardi et al., 2001; Laborde et al., 2017; Norman et al., 2014). To minimize these confounding influences, our analysis focused on periods when participants remained relatively still and breathed naturally.

Secondly, the accuracy of subjective experience reports likely correlates with presence and absorption levels. At the neural level, high-absorption states—where individuals are deeply immersed without deliberate effort—are linked to bottom-up (stimulus-driven) attention, characterized by enhanced sensory and interoceptive processing (Barrett et al., 2004). This contrasts with, on the one hand, default mode network activity, which prioritizes energy-saving low sensory engagement (Raichle, 2015), and on the other hand, top-down attentional control, which relies on prior expectations rather than real-time sensory integration (Corbetta and Shulman, 2002). When individuals experience heightened presence, they are therefore more likely to accurately report their internal state than those engaged in abstract cognition or mind-wandering.

Taken together, optimal conditions for aligning subjective experience with ANS activity may involve physical stillness, natural breathing, and heightened present-moment absorption—the foundation of most meditation practices, which aim to harmonize physiological and psychological states (Lutz et al., 2008; Tang et al., 2015). Consistent with this, our results indicate that STE ratings correlated with ANS activity during numadelic and psychedelic experiences, but not during a control meditation performed by non-advanced meditators. This difference may reflect a greater body-mind disconnect in ordinary states of consciousness. Additionally, the non-linear relationship between STE ratings and HRV amplitude suggests that physiological markers become more reflective of self-transcendent states as experience depth increases.

Respiratory measures

Our results indicate that respiratory amplitude plays a favorable role in the experience, showing a moderate correlation with ego reduction ratings during the session—though less robustly than HRV amplitude. Additionally, respiratory amplitude predicted beneficial post-session effects on affect and relationality.

While HRV amplitude and respiratory amplitude are not directly linked, they can be modulated by shared physiological mechanisms. One such mechanism, respiratory sinus arrhythmia (RSA), refers to the increase in HR during inhalation and decrease during exhalation, creating rhythmic fluctuations synchronized with the breathing cycle. This alignment between respiration and HRV amplitude is strongest when RSA is high, typically occurring at a low breathing frequency of 5.5-6 breaths per minute—a pattern known as resonant breathing frequency (Shaffer and Meehan, 2020).

Despite both respiratory rate and respiratory amplitude being correlated with HRV amplitude (one negatively, the other positively), only respiratory amplitude was significantly linked to STE ratings during the VR session. A mediation analysis further revealed that the relationship between HRV amplitude and STE ratings was not mediated by respiratory amplitude, suggesting that HRV and respiratory amplitude contribute to STE through distinct pathways.

Breathing practices that engage the abdomen (diaphragmatic breathing) or the entire torso (Dirga pranayama, also known as Three-Part Breath or Complete Breath) are well-documented for their positive effect on emotional regulation (Hamasaki, 2020). At the physiological level, high-amplitude breathing increases carbon dioxide partial pressure in the blood, which enhances cerebral blood flow, optimizes oxygen delivery to the brain, and directly benefits cognitive function and emotional stability (Goheen et al., 2023). In addition, breath amplitude has been shown to entrain brainwave activity, potentially enhancing focus, emotional resilience, and stress regulation (Allen et al., 2023; Brændholt et al., 2023; Heck et al., 2017). Respiratory amplitude may thus serve as another, albeit weaker, physiological marker of STE in numadelic experiences. However, it is important to note that with currently available biosensors, recording high-quality respiratory signals is more challenging than HRV.

HRV amplitude and compassion training

Our results indicate that individuals with higher compassion traits exhibit higher HRV amplitude levels during the numadelic experience. Compassion can be understood as a state of presence and openness to others' challenging emotions combined with an active willingness to engage when the natural tendency may be to withdraw or shield oneself from their suffering (Gilbert and Van Gordon, 2023). In addition to this heightened receptivity, sensitivity, and empathy, compassion also entails the ability

to regulate difficult emotional states, allowing for sustained empathic connection while mitigating empathic distress (Condon and Barrett, 2013; Strauss et al., 2016).

From an autonomic perspective, simultaneously maintaining high emotional awareness alongside effective regulation likely requires the ability to dynamically engage both branches of the ANS. Specifically, sympathetic activity supports enhanced sensory processing, while parasympathetic activity facilitates a return to homeostasis (Critchley, 2005; Laborde et al., 2017; Thayer and Lane, 2009). Previous studies on the physiological markers of compassion have frequently reported associations with increased parasympathetic activity (Di Bello et al., 2020; Stellar et al., 2017), and individual differences in altruistic prosocial behavior have been found to predict the ability to voluntarily upregulate high frequency HRV, a marker of parasympathetic activity (Bornemann et al., 2016). In line with this, we observed significant correlations between compassion traits at baseline and higher levels of parasympathetic activity (reflected via RMSSD) during the VR meditation.

While parasympathetic activation supports compassion through its role in emotional regulation, we propose that excessive vagal dominance may dampen sympathetic responsiveness—blunting emotional arousal and sensory acuity, and in some cases contributing to emotional disengagement or numbness (Di Bello et al., 2021). Consistent with this perspective, research has shown that 1) the empathic component of compassion traits is inversely related to parasympathetic activity (Di Bello et al., 2021) and 2) parasympathetic activity follows a quadratic relationship with prosocial traits, suggesting that both excessively high and low vagal activity may impair prosocial engagement (Kogan et al., 2014).

Are all STEs associated with the same physiological state?

While STEs have only recently gained attention in modern science, they have long been explored in Eastern traditions, particularly through Buddhist jhanas—eight progressively deeper states of mental unification and absorption. Early jhanas are marked by sensory-rich experiences such as joy and energy, but as practice deepens, sensory content diminishes, giving way to equanimity and inner stability (Gunaratana, 1988).

The ANS involvement in these stages remains largely unexplored, though deeper states are hypothesized to correspond with reduced ANS and central nervous system activity. Evidence from 'pure presence' states suggests widespread reductions in brain electrical activity, contrasting with findings of increased gamma activity in earlier meditation phases—indicating distinct high-content vs. minimal-content states (Boly et al., 2024).

Advanced meditation has been reported to induce autonomic quiescence, marked by low HRV despite unchanged or reduced heart rate—suggesting a global reduction in autonomic function (McCraty et al., 2009). Some practitioners can reach a so-called 'breathless state', characterized by marked reductions in both breathing rate and amplitude (Devarshi, 2010; Sparby, 2019). However, research on autonomic changes across meditation depth remains limited.

While deep meditation is often linked to ANS suppression, some techniques actively engage cognitive and emotional processing, influencing autonomic dynamics. Practices like Loving-kindness and Tonglen meditation, which involve high emotional absorption, may sustain HRV amplitude rather than suppressing autonomic function (Andreu et al., 2025; Kok et al., 2013). Ultimately, the ANS involvement may largely rely on the degree of embodiment associated with the practice.

A model emerges in which STEs may unfold along a continuum of information-processing complexity. On the high-embodiment end of the spectrum, STEs are characterized by expanded sensory awareness, increased gamma-band activity and neural entropy, and elevated sympathovagal engagement. These features support a broadening of the sensory field, often accompanied by a felt sense of unity with the environment, enhanced relationality, and positive affect. According to the Jhanas progression framework, such high-content, metabolically demanding states may serve as gateways to deeper meditative absorptions, marked by progressive sensory withdrawal, dissolution of self-referential processing, and reduced physiological activity. Numadelic experiences are designed to facilitate both forms of STEs, integrating immersive, sensory-rich phases alongside progressive sensory reduction. However, achieving object-free pure awareness may require deeper states of absorption and nonegoic self-awareness (Metzinger, 2024), making deeper STEs less accessible to non-meditators—likely explaining the relation between STEs and higher autonomic activity observed in our dataset.

Limitations

Within-subject experience sampling

Although HRV amplitude appears to be a promising marker for STE, its ability to track moment-to-moment fluctuations within individuals remains uncertain. Given that our design included only two chapters during which ANS activity could reliably reflect subjective experience, free from external confounds such as body motion or non-natural breathing, it was not possible to assess whether HRV amplitude dynamically varied with STE ratings over time. It is worth noting that although some measures were adopted to minimize such confounds, motion and breathing practices are inherent to the positive impact of numadelics, by providing embodied practices which enhance presence and connection between participants. Future research efforts for physiological monitoring should therefore not aim to reduce these factors, but instead, incorporate structured rest periods between embodiment practices. This approach would help maximize the number of data points per participant, allowing for more robust assessments of ANS-STE interactions and enabling a deeper understanding of how physiological markers evolve throughout immersive experiences.

Mystical experience questionnaire

The MEQ-30 was used across both datasets in this study to assess the depth of participants' STEs following either numadelic or psychedelic sessions. Notably, MEQ-30 ratings correlated with HRV amplitude in the psychedelic dataset, but not in the numadelic one. Widely considered the most commonly used questionnaire for assessing mystical or spiritual experiences, the MEQ-30 is derived from the earlier MEQ-43, itself grounded in Walter Stace's seminal framework on the core features of spiritual awakening (Stace, 1960). However, the MEQ-30 was developed and psychometrically validated almost exclusively within psychedelic research contexts (Barrett et al., 2015). A recent study (Formoso, 2023) attempted to validate the MEQ-30 in a sample reporting non-psychedelic mystical experiences. The findings indicated that the scale's factor structure did not adequately fit this population, suggesting potential phenomenological differences between psychedelic and non-psychedelic STEs.

Another important consideration is temporal specificity. In the numadelic dataset, our analysis focused on distinct experiential chapters, each accompanied by subjective ratings of ego-reduction. In contrast, the MEQ-30 was administered post-session and captured participants' reflections on the

overall experience, rather than its discrete phases, possibly introducing some noise in the relation between physiological measure and questionnaire scores.

Comparison with traditional meditation

The control meditation used in this study was not an established traditional practice, but rather a self-constructed adaptation of the numadelic experience, designed as an audio-guided meditation where participants internally visualized the scenes seen by the VR group. While it may be tempting to infer from the results that VR enhances meditative depth relative to non-VR meditation, it is important to acknowledge the possibility that a more authentic meditation practice may have been more effective at eliciting some degree of STE (NB: A thorough exploration of differences between numadelic VR and the control meditation is addressed separately – Parola et al., in prep). Given this limitation, our intent is not to claim that numadelic experiences surpass traditional meditatio§n in their ability to induce STEs. Instead, future research should reverse the approach, developing a VR experience based on an existing meditative tradition rather than constructing a meditation adapted from numadelic elements. This shift would allow for a more robust evaluation of whether numadelic meditation can function as a catalyst for contemplative practice—potentially enabling novices to access states of consciousness that would otherwise require years of dedicated practice to achieve.

Conclusion

We introduced a novel measure of autonomic activity—HRV amplitude—that effectively captures inter-individual differences in the depth of STEs during high-absorption states, whether elicited through numadelic VR or psychedelic modalities. As a practical physiological marker, this measure opens new avenues for tracking transformative experiences as they occur.

While research into numadelic experiences remains in its early stages, empirical insights and participant feedback suggest a growing potential for these immersive journeys to evoke profound psychological shifts, offering a non-drug-based path for achieving states usually reserved for advanced contemplative practitioners. Understanding how best to guide individuals into NOSC—through gradual immersion that facilitates the softening of ego boundaries—will be essential. In this context, tools that can objectively reflect the unfolding of such states hold great promise, both for experience design and for biofeedback-enhanced therapeutic interventions. Looking ahead, further research may refine this measure and explore its integration into scalable contemplative and clinical practices, potentially making self-transcendence more accessible to a wider population.

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Data availability

ECG data and audio file of the audio of the pre-recorded meditation 'Ripple' in English are available at https://doi.org/10.5281/zenodo.17061627.

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Code for data-preprocessing, final dataset for statistical analyses (with questionnaires and subjective ratings as well as physiological measures of interest) and VR experience chapters video snapshots are available at https://github.com/vbonnelle/Ripple_Study_Bonnelle2025.

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