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Closed-Loop Systems and Real-Time Neurofeedback in Mindfulness Meditation Research

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Abstract

Mindfulness meditation has numerous purported benefits for psychological well-being; however, problems such as adherence to mindfulness tasks, quality of mindfulness sessions, or dosage of mindfulness interventions may hinder individuals from accessing the purported benefits of mindfulness. Methodologies including closed-loop systems and real-time neurofeedback may provide tools to help bolster success in mindfulness task performance, titrate the exposure to mindfulness interventions, or improve engagement with mindfulness sessions. In this review, we explore the use of closed-loop systems and real-time neurofeedback to influence, augment, or promote mindfulness interventions. Various closed-loop neurofeedback signals from functional magnetic resonance imaging and electroencephalography have been used to provide subjective correlates of mindfulness states including functional magnetic resonance imaging region-of-interest–based signals (e.g., posterior cingulate cortex), functional magnetic resonance imaging network-based signals (e.g., default mode network, central executive network, salience network), and electroencephalography spectral-based signals (e.g., alpha, theta, and gamma bands). Past research has focused on how successful interventions have aligned with the subjective mindfulness meditation experience. Future research may pivot toward using appropriate control conditions (e.g., mindfulness only or sham neurofeedback) to quantify the effects of closed-loop systems and neurofeedback-guided mindfulness meditation in improving cognition and well-being.

Mindfulness has numerous reported benefits for psychological well-being (1). However, adherence to mindfulness tasks (2), the quality of a mindfulness session (3), or the dosage of mindfulness interventions (4) may hinder individuals from accessing the purported benefits of mindfulness. As such, methodologies including closed-loop systems and neurofeedback may provide tools to help ensure success in mindfulness task performance and to titrate the exposure to mindfulness interventions. However, the use of closed-loop systems and neurofeedback in mindfulness meditation has been limited, with many studies focused on feasibility and implementation. In the current review, we aim to summarize all studies we are aware of that involved closed-loop systems and neurofeedback in mindfulness meditation.

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CLOSED-LOOP SYSTEMS

Closed-loop systems are a cornerstone of neurofeedback, and we propose a key element of its success in promoting mindfulness (5). Based largely on a decades-long literature on signal detection theory and Bayesian algorithms used in psychophysics research (6), closed-loop systems can be used to optimize interventions, including mindfulness, to maintain a person's engagement with a task by personalizing the experience to the individual in real time. Closed-loop systems take measurements of a person's current state as the input arm of the loop (e.g., calmness, arousal, mood, or neural activity data) to guide real-time adjustments of the intervention to close the loop (Figure 1). As a person's performance improves over time, the task becomes more difficult, but if performance falters, the task becomes easier. The key is to find the "sweet spot" for maintaining engagement for each individual, and this will differ from person to person. Thus, closed loops personalize interventions to individuals in real time, a factor that is critical for optimizing outcomes (7).

Closed-Loop Digital Meditation

We recently set out to develop a closed-loop form of digital meditation that we call MediTrain (8). This digital intervention was designed with the goal of improving focused, sustained attention and is meant to merge the basic elements of focused-attention meditation with key principles of neuroplasticity. We accomplished this goal by providing a brief lesson in mindfulness breathing and then created an environment where the goals were attainable and quantifiable, there was both continuous and punctuated feedback on progress, the intervention was repetitive so participants learn the task, and used adaptivity in the form of a closed-loop system to increase the level of challenge as the user improves and decrease the challenge when they are not doing well. This closed-loop approach to meditation personalizes the experience to the abilities of each individual in real time.

We have now completed several studies that have demonstrated a positive impact of MediTrain on attention in younger populations (8–10). In healthy younger adults, these gains in sustained attention were accompanied by increases in midfrontal theta intertrial coherence measured with electroencephalography (EEG) (8). In adolescents from the foster care system in India, all of whom experienced adverse childhood experiences, we also saw improvements in measures of hyperactivity, improved school performance, and a strengthening of connectivity in the fronto-opercular network as measured by resting-state functional magnetic resonance imaging (fMRI) (10). We are now beginning a large-scale, fully remote trial of this intervention in older adults from across the nation using a mobile randomized controlled trial platform (5). The digital nature of the intervention and the fact that it can be used on any smartphone or tablet means that we have the potential to reach a far more diverse population of participants than would typically be seen in a traditional brick-and-mortar clinical trial. We aimed to reach older adults in rural areas and inner cities and to reach out to underrepresented populations who otherwise might be reluctant to come into a university or hospital for a research study—a factor that is key to achieving equity in translational research (11).

Neurofeedback and Its Relation to Closed-Loop Systems

Fundamentally, neurofeedback involves recording some facet of brain activity and presenting it back to the individual, typically through audiovisual cues. The most common neural signals used for neurofeedback are EEG and fMRI, which will be the focus of this review.

However, closed-loop systems and neurofeedback are both highly interlinked protocols that emphasize the use of real-time metric acquisition. Closed-loop systems can use real-time metrics such as task performance to adjust the task difficulty but can also use real-time metrics derived from neurofeedback signals. In contrast, neurofeedback paradigms are defined by the presentation of a neural signal back to the participant. While neurofeedback paradigms may not include an adjustment step to task difficulty, participant success in positively controlling their neurofeedbck signal is commonly a marker of success in the neurofeedback paradigm (12). Participants typically undergo training sessions during which they apply different strategies to control their neurofeedback signal and can perceive the degree of their success (or failure) in their volitional control of their signal. Therefore, neurofeedback paradigms that simply present neural signals back to participants can be considered closed-loop interventions. Consequently, many of the neurofeedback studies that we review below are inherently closed-loop paradigms as well.

fMRI NEUROFEEDBACK IN MINDFULNESS

fMRI blood oxygenation–level dependent (BOLD) neurofeedback has been used in various contexts to affect participant behavior. Typically, the BOLD neurofeedback signal is extracted from a predesignated region or network of interest, compared with a resting-state baseline, and presented back to the participant. Numerous regions (e.g., the motor cortex, insula, amygdala) have been used in various neurofeedback studies (13). However, neurofeedback for guiding or influencing mindfulness meditation has focused on signals derived from the posterior cingulate cortex (PCC) or brain networks, particularly the default mode network (DMN), salience network (SN), and central executive network (CEN).

Mindfulness meditation typically involves conscious direction of attention toward one's breath with underlying cognitive processes such as reduced mind wandering (reflecting DMN deactivation) (14,15), identifying any lapses of attention (reflecting SN activity) (16,17), and selectively attending to the task (reflecting executive network connectivity) (18–20). The interaction of these 3 networks (and their constituent brain regions) contributes to mindfulness meditative states that have been explored more in recent reviews (21,22). Therefore, signals from these networks (or regions) form the basis of neurofeedback signals attempting to reflect mindfulness meditation.

PCC Neurofeedback

The PCC was the earliest neurofeedback target for mindfulness meditation. A study displayed the percent BOLD signal change (relative to resting baseline) in the PCC during a meditation task to both experienced ($n = 22$) and novice ($n = 22$) meditators (23). Participants reported tight coupling between their subjective experiences and the neurofeedback signal. In further qualitative analyses of participant interviews, PCC deactivations were linked to undistracted awareness, concentration, effortless doing, and content (24). A further investigation found fMRI neurofeedback of the PCC's BOLD signal change to be well-tolerated and feasible to implement in healthy adolescents (25,26). The neurofeedback was presented visually, with participants attempting to reach −0.5% to −1% PCC signal changes relative to the resting baseline block (25). Reduced PCC activation correlated with deactivations of the broader DMN and SN (25), activated anterior insula (26), and deactivated posterior insula (26). These 3 correlations may correspond to self-referential or interoceptive processing, cognitive-affective states, and somatosensory processes, respectively (25,26).

Network-Based Neurofeedback

Network-based signals for mindfulness neurofeedback protocols are typically calculated from the DMN, CEN, and SN. For example, the positive diametric activity (PDA) metric—described as CEN minus DMN activation—has been shown to increase during meditation (27) and has been used in several neurofeedback studies (28–30). One study recruited 11 individuals with schizophrenia to participate in a neurofeedback fMRI trial while performing mental noting meditation (30). The neurofeedback signal was displayed as a moving white dot moving toward either a fixed red (increased PDA) or fixed blue (decreased PDA) circle. Participants reported significant reductions in auditory hallucinations, exhibited reduced intra-DMN hub connectivity, and exhibited increased DMN-CEN anticorrelation (30). Building on this finding, adolescents with a lifetime history of major depressive disorder also performed mental noting with PDA neurofeedback displayed in a similar manner (28). Participants exhibited reduced intra-DMN connectivity and increased total state mindfulness (28). The authors have since prospectively published a trial protocol to recruit 90 adolescents with depression to identify dosing, efficacy, and connectivity effects of this protocol (29). In another study, mediation analysis was performed using the past 30 BOLD values of voxels belonging to the triple network regions (i.e., DMN, CEN, and SN) (31). Mediation analysis involved regressing DMN signals against SN and CEN signals. This signal was displayed as a red–blue-green thermometer bar, and participants were informed that the height of the bar would correspond to the depth of mindfulness (31). The neurofeedback regression feature correlated positively with both mindfulness scores and self-rated performance scores in controlling the neurofeedback (31). Lastly, another study used normalized BOLD changes from the sustained attention network and the DMN with intermittent feedback every 70 seconds (instead of real-time feedback) to participants undergoing sustained attention tasks (32). All 30 young, healthy participants could control their sustained attention network and DMN signals, and their self-reported ratings correlated with participants' levels of concentration during neurofeedback runs (32). Participants exhibited increases in sustained attention network activity, decreases in DMN activity, and slight improvements in psychomotor vigilance test reaction times after neurofeedback training (32).

Other Regions for fMRI Neurofeedback

Other mindfulness-adjacent neurofeedback research has explored or is exploring additional regions including the ventral striatum and auditory cortex to affect mindfulness tasks. One study performed neurofeedback from the primary auditory cortex on 27 healthy volunteers who simultaneously received binaural auditory stimulation and performed mindfulness tasks (33). The average signal in the regions of interest from the past 4 volumes was compared with the baseline resting state to derive percent signal change, which was presented as a thermometer-style plot. Participants could downregulate primary auditory cortex activity during binaural stimulation, with the most successful control strategy being focusing on breathing. Lastly, a prepublished study protocol was used to calculate the relative signal change from the last 3 voxels from the ventral striatum (in the intervention group) and the auditory cortex (in the sham group) (34). The signal change was displayed as a thermometer to patients with alcohol use disorder in an attempt to regulate cue reactivity. The authors hypothesized that ventral striatum neurofeedback during a mindfulness-based task (i.e., presenting images of alcoholic beverages) would reduce the number of relapses (34).

Considerations in fMRI Neurofeedback

Neurofeedback using fMRI poses several problems including accessibility and incorporating the hemodynamic delay (35). Barriers to MRI accessibility include health risks due to contraindications involving metals, high expense, and relative geographical sparsity because MRI scanners are typically available only at tertiary care centers. This inherently limits fMRI neurofeedback studies strictly to mechanistic, hypothesis-driven explorations into mindfulness meditation. Furthermore, fMRI neurofeedback studies must also consider the hemodynamic delay that is inherent to the BOLD signal. Past studies typically refreshed the fMRI neurofeedback at every volume (usually 1–2 seconds) while incorporating a moving average of the last few voxels in time such that the weighted BOLD changes would take a few seconds to manifest (23,25,30,31). To address these delays, in one study, participants were explicitly told to expect a 2- to 4-second delay between brain activity and the neurofeedback signal (23).

EEG SPECTRAL POWER NEUROFEEDBACK

In contrast to fMRI, EEG neurofeedback is seen as far more accessible, potentially being performed in the comfort of people’s homes. EEG neurofeedback has been used in mindfulness meditation tasks particularly with alpha (8–13 Hz), theta (4–8 Hz), and gamma (40–57 Hz) oscillations. Elevated alpha and theta wave coexistence has consistently been linked to mindfulness meditation and may indicate a state of relaxed alertness (36). In the subsequent sections, we summarize the studies that have used alpha, theta, and gamma power as neurofeedback signals together with consumer EEG devices to augment or influence participant behavior during mindfulness meditation.

Alpha Neurofeedback

Alpha oscillations (8–13 Hz) have traditionally been associated with an idle state of the brain, although they are more specifically thought to arise as an inhibitory mechanism to synchronize cortical processing (37). Early alpha upregulation neurofeedback studies conducted in the 1960s and 1970s induced an alpha experience state typified by pleasant feelings, serenity, relaxation, and feelings of egolessness (38,39). This was thought to be similar to a meditative state due to the similarly observed increase in alpha power during meditation (40). Following these early investigations, research into EEG neurofeedback was scarce, with a recent resurgence only in the 2010s (41). In a 2017 study, university students were recruited and randomly allocated to mindfulness meditation tasks, sham alpha neurofeedback, and alpha neurofeedback (42). The alpha neurofeedback signal was the alpha (8–12 Hz) power amplitude from electrode Pz, with low-pitch auditory tones to indicate whether participants were successful in increasing their alpha power. The mindfulness meditation and alpha neurofeedback groups showed similar increases in alpha power postintervention. However, the mindfulness meditation and alpha neurofeedback groups did not exhibit between-group differences in subjective mood states, state mindfulness, or behavioral performance on the Stroop task (i.e., attentional control) (42). Similarly, another study recruited 50 healthy adults and used upper alpha power from parieto-occipital EEG electrodes (P3, Pz, P4, O1, O2) translated into a visual cue of a square with changing saturation colors as neurofeedback (43). The neurofeedback group exhibited enhanced task-related upper alpha power and mindfulness outcomes as measured by the Mindful Attention Awareness Scale (44).

Two studies have used alpha neurofeedback protocols more recently, but during explicit mindfulness meditation tasks. One study recruited 2 groups (healthy control participants and participants with anxiety) displaying left and right frontal alpha power (displayed as bar graphs) as a neurofeedback signal during a mindfulness task (45). Participants were also able to judge the difference in height of the left and right alpha power to gauge the extent of alpha asymmetry. Participants with anxiety exhibited power increases in EEG spectral bands, whereas healthy participants did not exhibit this trend, which was interpreted as a normalization effect or an anxiolytic effect in participants with anxiety. Another study used global alpha power (across 22 electrodes) with auditory feedback (i.e., the volume of running water) as neurofeedback during a focused attention meditation task (46). This study used both increases and decreases in global alpha power as positive reinforcement in separate runs. While participants were unsuccessful in upregulating alpha power with neurofeedback on average, they were successful in downregulating alpha power during neurofeedback runs.

Taken together, these findings suggest that alpha neurofeedback (particularly from parieto-occipital electrodes) may induce states that are comparable to mindfulness meditation as shown by similar changes to alpha power and mindfulness scales (42,43). However, alpha neurofeedback conducted during mindfulness tasks warrants further investigation because the limited number of studies that have been conducted to date utilized either frontal or global alpha power (45,46) instead of the more popular use of parieto-occipital alpha electrodes in past alpha neurofeedback research (42,43).

Theta Neurofeedback

Theta (4–8 Hz) oscillations, which are typically associated with executive function and working memory (47), have also been used as a neurofeedback signal, but in fewer studies. This may be due to theta being more prominent during meditation in experienced meditators than in novice meditators (36). In one study, independent components analyses were performed to obtain frontal theta topographies to obtain weighted averages of the frontal midline theta power (48). This frontal midline theta power signal was used to provide neurofeedback (in the form of a circle of variable size) to 6 healthy adults while they performed a mindfulness task. This intervention increased midline theta power and promoted meditative states. However, the authors noted that only 2 (of 6) participants were able to strongly augment theta (48). In another study, 24 healthy adults were randomized to receive either theta neurofeedback or sham neurofeedback (49). The midline theta power was averaged across 8 channels (Fpz, Fz, F7, F8, Cz, P7, P8, Oz) and displayed visually (in the form of a square with differing shades of blue) while participants underwent focused attention meditation tasks. Participants successfully increased their frontal midline theta power and improved their reaction times during an n-back task. This study reported that all 12 (of 24 total) participants who received neurofeedback were successful in using at least 1 meditation strategy to modulate the theta neurofeedback signal and improved their reaction time on correct trials of an n-back working memory task (49). Taken together, these results suggest that midline theta oscillations represent a promising neurofeedback target for mindfulness meditation.

Gamma Neurofeedback

Gamma oscillations (typically >40 Hz) are ubiquitous and support many cognitive functions (50). In one study, gamma was suppressed in DMN areas during a visual search task (51), and participants undergoing focused attention tasks also showed decreases to centroparietal gamma power (52). Consequently, reduced gamma in the DMN (such as the PCC) represents a putative target for mindfulness neurofeedback. This was explored in one study that recruited 16 novice and 16 experienced meditators (53). The neurofeedback signal was based off the 40- to 57-Hz gamma power source localized from the PCC and presented as a bar graph. Participants were able to reduce their gamma power and exhibited high moment-to-moment correlations between PCC gamma power and their subjective experiences of effortless awareness (53).

Portable EEG Neurofeedback Algorithms

Consumer EEG headbands, e.g., Muse (InteraXon), OMNIFIT Brain (OMNI C&S Inc.), and Emotive have also been used for neurofeedback during mindfulness tasks. Several studies (54–57) have used Muse EEG headbands, which have 5 electrodes (AF7, AF8, FPz reference, TP9, TP10) and output proprietary signals representing “calm”-ness that were used to provide auditory feedback ranging from gentle rain to thundery, heavy rain sounds. Another study recruited 26 healthy adults and found that 6 weeks of daily neurofeedback-assisted mindfulness training (compared with a daily math training control) improved attentional reaction time and subjective wellbeing (55). Another study used this neurofeedback protocol during breathing awareness focused attention meditation sessions in sportspeople for 14 consecutive days (57). Participants in the neurofeedback group exhibited improvements in behavioral measures (e.g., response times and false alarms during the Stroop task) and neurophysiological measures (e.g., increased N2 event-related potential negativity during the Stroop task). In another study, 68 adult participants were instructed to complete 14 days of consecutive mindfulness meditation practice, with the auditory feedback arm of participants reporting greater state mindfulness, reduced mind wandering, and improved meditation performance (56). Lastly, a study involved 140 young adults split into 4 groups (control, running, Muse-neurofeedback, and combined running with Muse-neurofeedback) with 16 interventions across 8 weeks (54). This study aimed to observe the interventions' effects on intrinsic connectivity network dynamics of the triple networks (DMN, CEN, SN) as measured by 128-channel EEG-based network analysis. Participants who benefited the most from the interventions (i.e., improved VO_2 max or increased calm from the Muse recordings) exhibited increased synchronicity between their CEN and SN. This synchronicity may reduce persistent DMN activation, which has been associated with dysregulated mood, rumination, and difficulty staying on task (54).

Another study used the OMNIFIT headband, which has 2 EEG and 1 photoplethysmography sensor for pulse detection (58). The neurofeedback signal was the ratio of alpha power (8–12 Hz) to beta power (20–30 Hz) calculated at 2-second intervals, with participants receiving a positive auditory sound through headphones if the ratio exceeded 2.775. The healthy adult participants in the neurofeedback group underwent 4 weeks of neurofeedback-augmented sessions including breathing, awareness, and body scan meditation tasks. The participants receiving neurofeedback exhibited the greatest improvements, particularly in resilience (58). Lastly, one study used the Emotive headset to develop a MeditAid system where recorded EEG signals were translated into monaural or binaural beats as feedback (59). The authors found that experienced meditators were able to achieve deeper meditation states with low-alpha aural entrainment (59).

Taken together, these findings show that portable take-home EEG devices have also demonstrated feasibility in affecting mindfulness meditation tasks.

Considerations in EEG Neurofeedback

Several considerations must be made when performing EEG spectral neurofeedback such as the degree of artifact rejection and limiting the magnitude of change in the neurofeedback signal. Blink artifacts, muscle artifacts, and electrode spikes are generally removed when calculating the online neurofeedback signal. Blink artifacts may be removed online using independent component analysis to filter out eye-blink artifacts (43). Muscle artifacts typically manifest at frequencies above 20 Hz (i.e., beta and gamma frequencies) (60,61), and the impact of these artifacts may be attenuated using strategies such as removing points exceeding 100 μV (46) or limiting the maximum feedback value change to 2.5% (48) or 5% (49). The importance of artifact removal was highlighted in one study in which such artifacts were not removed and significant associations between artifacts (particularly the temporalis muscle) and the neurofeedback signal were reported in 40% of participants (53). Taken together, the degree of artifact rejection and the wide variability in the neurofeedback signal may limit the ability of participants to control their EEG neurofeedback signal, as has been reported in a few studies (46,48). Therefore, careful selection of online preprocessing methods is needed to maximize the signal-to-noise ratio for a successful neurofeedback experiment.

CURRENT CHALLENGES IN NEUROFEEDBACK-GUIDED MINDFULNESS MEDITATION

The outlined studies have focused mostly on the feasibility of using neurofeedback-guided mindfulness. Without an appropriate control condition (such as only mindfulness meditation or a sham-neurofeedback session), it is difficult to measure the efficacy of neurofeedback-guided mindfulness (62). Typical challenges in neurofeedback experimental design include the lack of appropriate control (or comparison) conditions, individual differences in learning, the number of training sessions, and intersession intervals (63). Furthermore, the success of neurofeedback protocols may be influenced by psychosocial factors such as the experimenter's gender and trait mindfulness and a person's comfort with technology (termed by some authors as locus of control with technology) (64). Female experimenters, lower trait mindfulness, and reduced locus of control have been associated with reduced learning effects in controlling the neurofeedback signal (64,65). These concerns have been highlighted and published in a consensus on the reporting and experimental design of clinical and cognitive-behavioral neurofeedback studies checklist from 84 authors (66).

FUTURE DIRECTIONS

In this review, we highlighted several studies that have successfully performed both closed-loop and closed-loop neurofeedback mindfulness interventions; however, the question remains whether closed-loop neurofeedback-guided mindfulness interventions are superior to a control condition (such as sham neurofeedback or mindfulness only). Prior investigations have used transfer runs (25,28,30), healthy control comparisons (45), and no-intervention test-retest groups (32,43) as the comparator to observe the effects of neurofeedback-guided mindfulness. In contrast, one study used a sham neurofeedback signal (a recording of a neurofeedback participant's signal) while participants were meditating and found faster reaction times in the active neurofeedback group on an n-back working memory task (49). However, beyond this study, there is little evidence to indicate whether neurofeedback-guided mindfulness exhibits greater effects than mindfulness meditation alone. Given the extent of studies that have reported success in implementing neurofeedback-guided mindfulness, future research may pivot to focusing on identifying the neural, clinical, and behavioral effects of this intervention beyond the effects of mindfulness meditation only. This may involve the use of mindfulness questionnaires or qualitative interviews that link the neurofeedback signal to participant experience. This would more fully capture whether neurofeedback-guided mindfulness is more efficacious in promoting a mindful state and can afford novices greater access to the purported benefits of meditation.

Neurofeedback-augmented mindfulness meditation may also be explored in conjunction with other forms of biofeedback modalities such as heart rate variability (HRV). While HRV itself has often been explored as an outcome for the success of mindfulness meditation in recent reviews (67–69), no known studies have investigated HRV biofeedback simultaneously with mindfulness meditation tasks. However, 2 studies have compared HRV biofeedback to mindfulness meditation and found no differences in outcomes between the 2 groups (70,71).

The most apparent utility of closed-loop neurofeedback-guided mindfulness meditation is to help novice meditators or clinical populations to learn mindfulness meditation so as to access the numerous purported benefits of mindfulness. This could begin with in-laboratory EEG or fMRI neurofeedback sessions and continue at home with portable EEG headbands or closed-loop meditation apps. Neurofeedback is generally better tolerated than other neuromodulation and pharmacological therapies and may prove to be a promising alternative treatment for individuals with few other options.

CONCLUSIONS

Closed-loop systems including neurofeedback may promote or augment the benefits observed from mindfulness meditation. Past research has found many promising closed-loop neurofeedback signals using both EEG and fMRI that reflect mindfulness meditative states. Future research is now moving toward accessible clinical trials that measure the efficacy of closed-loop, neurofeedback-guided mindfulness meditation with adequate control conditions (e.g., mindfulness only or sham neurofeedback). The use of accessible technologies (such as online randomized control trial platforms or portable EEG headbands) may further improve the equitable accessibility of the therapeutic benefits of mindfulness meditation.

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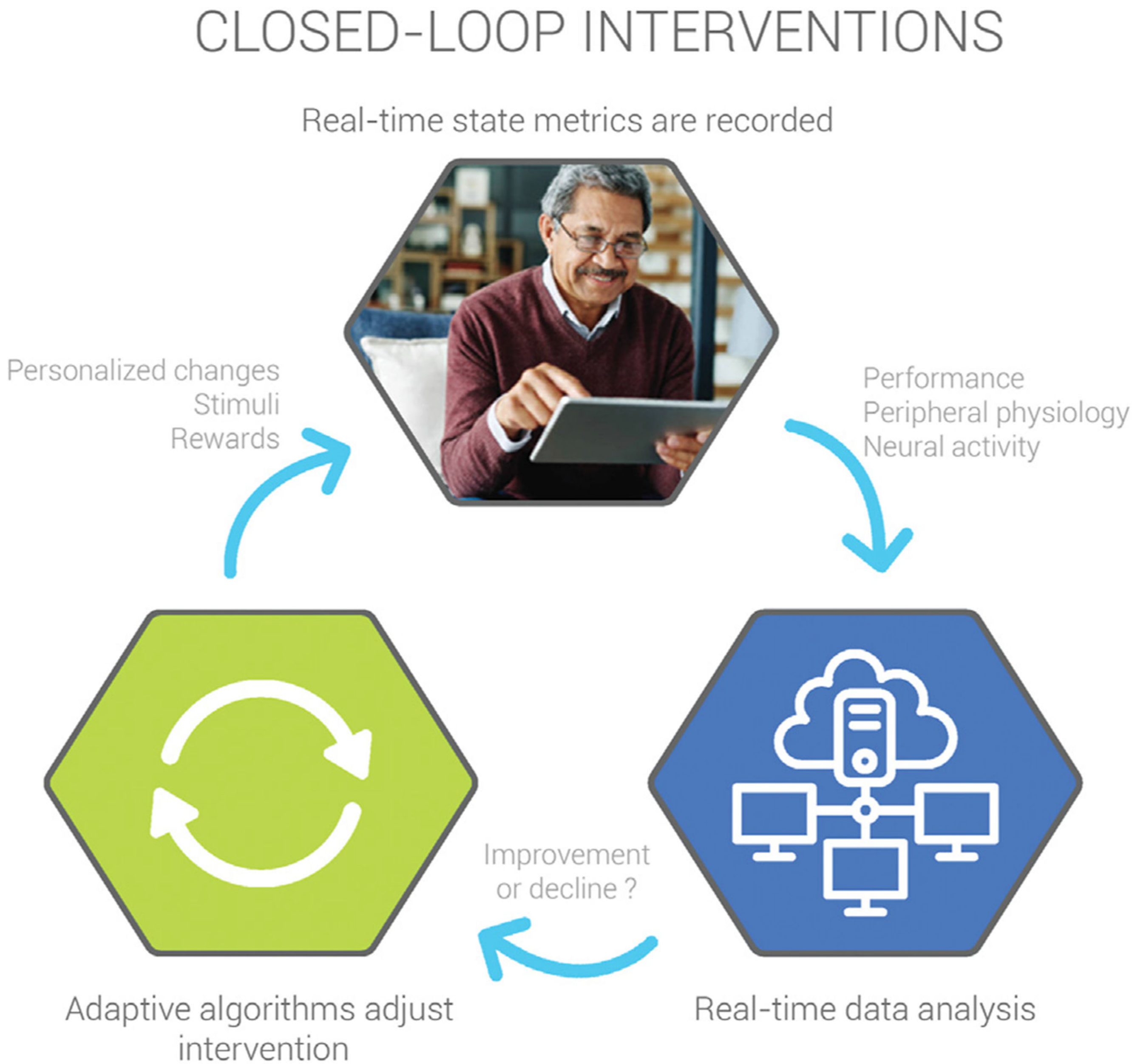

Figure 1.
Elements that define a closed-loop system.