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Review

Brain mechanisms of mental processing: from evoked and spontaneous brain activities to enactive brain activity

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Abstract

Within the context of the computer metaphor, evoked brain activity acts as a primary carrier for the brain mechanisms of mental processing. However, many studies have found that evoked brain activity is not the major part of brain activity. Instead, spontaneous brain activity exhibits greater intensity and coevolves with evoked brain activity through continuous interaction. Spontaneous and evoked brain activities are similar but not identical. They are not separate parts, but always dynamically interact with each other. Therefore, the enactive cognition theory further states that the brain is characterized by unified and active patterns of activity. The brain adjusts its activity pattern by minimizing the error between expectation and stimulation, adapting to the ever-changing environment. Therefore, the dynamic regulation of brain activity in response to task situations is the core brain mechanism of mental processing. Beyond the evoked brain activity and spontaneous brain activity, the enactive brain activity provides a novel framework to completely describe brain activities during mental processing. It is necessary for upcoming researchers to introduce innovative indicators and paradigms for investigating enactive brain activity during mental processing.

Keywords: brain mechanism; evoked brain activity; spontaneous brain activity; enactive brain activity; mental processing

Introduction

One of the fundamental experimental paradigms for exploring brain mechanisms underlying mental processing is to evoke brain activity through psychological tasks. Typically, non-random brain signals induced by external stimuli are used to denote evoked brain activity [e.g. event-related potential, ERP (Talsma and Woldorff, 2005); steady-state visually evoked potential (Vialatte *et al.*, 2010)], whereas the fluctuations of brain signals that are not caused by external stimuli are employed to denote spontaneous brain activity [e.g. motor imagery (Al-Saegh *et al.*, 2021); spontaneous low-frequency fluctuations (Fransson, 2005)]. The primary indicators for detecting brain activity, including brain activation and ERP, presuppose that there is no or only minimal interaction between evoked and spontaneous brain activity. As a result, the evoked brain activity can be modelled using a general linear model (Friston *et al.*, 1994). This model assumes that the brain undertakes evoked and spontaneous activities in parallel, producing two signals that can be linearly superimposed. In this framework, evoked brain activity remains constant between trials, whereas inter-trial variability is attributed to random fluctuations in spontaneous brain activity and can be eliminated by averaging between trials (Fox *et al.*, 2007). Based on the assumption that evoked and spontaneous brain activities are independent of each other, numerous studies have unveiled brain regions and time courses of mental processing. However, if the assumption is right, how do we explain the effects of learning and experience on spontaneous brain activity (Pezzulo *et al.*, 2021) and the plasticity of brain functions? For example, Dong *et al.* found that expertise can shape the patterns of spontaneous activity in the resting brain (Dong *et al.*, 2014). In addition, visual perceptual learning appears to modify the covariance structure of spontaneous brain activity among task-related networks, with the degree of visual perceptual learning being relevant to this alteration (Lewis *et al.*, 2009). Therefore, the brain is influenced by expectations and prior experiences.

Spontaneous brain activity, on the other hand, has been demonstrated, by numerous resting-state brain imaging studies, to hold a wealth of information about brain functions (Finn, 2021). In a resting state, when individuals do not need to think about specific problems and are not exposed to external stimuli, the spontaneous activity of the human brain consumes 20% of the body's energy intake to maintain normal functions and prepare for upcoming events (Buckner and DiNicola, 2019), far exceeding the energy consumption of 2–4% of cognitive effort (Pezzulo *et al.*, 2021). A simulation study conducted by Chen and Gong showed that only a small fraction, ∼20% of brain signal variations, can be attributed to evoked brain activity, leaving the remaining 80% to be accounted for by changes in spontaneous brain activity (Chen and Gong, 2019). In the same vein, Lynch and colleagues compared the functional connectivities (FCs) of participants when watching films and in resting state (Lynch *et al.*, 2018). Their findings revealed that the difference in FCs was mainly

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caused by changes in spontaneous brain activity, with task-locked FC changes accounting for <2%. Despite variations in the indicators, spontaneous brain activity constitutes the predominant form of brain activity, whether external stimulation is present or not. As a result, a growing number of researchers have been focusing on spontaneous brain activity and its dynamic relationship with evoked brain activity (Avitan *et al.*, 2021; Chen *et al.*, 2020; Ferezou and Deneux, 2017; Huang *et al.*, 2017; Wainio-Theberge *et al.*, 2021).

The perspective that prioritizes spontaneous brain activity as the primary form of brain activity typically views evoked brain activity as a perturbation to the former (Finn, 2021). As research progresses, recent studies have introduced the concept of enactive cognition, which posits that there exists a singular functional activity both prior to and following the presentation of stimuli, that is the trajectory of the brain in the multi-dimensional functional space (He, 2013; Jia-Jia and Gao-Sheng, 2021). The brain constantly monitors both internal and external changes and adapts its activity accordingly, without relying on any evoked activity (Bolt *et al.*, 2018). Researchers are becoming increasingly aware of the limitations of evoked brain activity in revealing the patterns of brain activity during mental processing. So, what is the next candidate for the brain mechanisms of mental processing? In the following sections, we will discuss the similarities and differences between spontaneous and evoked brain activities, followed by an inspection of their interactions, and reveal the insufficiency of evoked brain activity in reflecting brain mechanisms underlying mental processing. Afterwards, we propose that enactive brain activity may more accurately reflect the brain mechanisms of mental processing: the brain makes active adaptive behaviours in response to ever-changing internal and external environments. The enactive brain activity aligns with the most recent theories in cognitive and computational neuroscience, presenting fresh concepts and perspectives for comprehending the brain mechanisms of mental processing. Finally, we will discuss the necessity of using innovative indicators and paradigms to investigate the enactive brain activity during mental processing. This paper calls on researchers to pay attention to new advances in cognitive science and explore the brain mechanisms of mental processing based on enactive brain activity.

We searched PubMed, ProQuest, Web of Science, Google Scholar, ScienceDirect, and PsycInfo using the query ('spontaneous brain activity' OR 'evoked brain activity' OR 'enactive cognition' OR 'enactive brain activity' OR 'brain activity') AND ('brain mechanism' OR 'mental processing') to manually search papers that study theories of spontaneous and evoked brain activity as well as enactive brain activity. We also searched the reference lists of the included studies and all studies that cited the included studies, resulting in 41 relevant studies.

Similarities and Differences Between Spontaneous and Evoked Brain Activities

Newly generated neurons develop and mature as they establish connections with other neurons, leading to the formation of intricate neural networks (Avitan *et al.*, 2021). The early development of brain function is predominantly governed by genetic and physical rules, which is further modified by sensory stimuli (Molnár *et al.*, 2020). Notably, spontaneous activity plays a crucial role in the formation of appropriate neural connections during neurodevelopment (Avitan *et al.*, 2021).

On the one hand, in adults, resting-state networks (RSNs) and multiple task-evoked networks manifest considerable spatial congruity (Smith *et al.*, 2009). This result was replicated by another study with an independent dataset (Nickerson, 2018). Overall, the RSNs and task-evoked networks are spatially similar but not identical. To be specific, the similarity between resting and task states ($r = 0.91$) is lower than that between two resting states ($r = 0.99$) and between different task states ($r = 0.95$) (Zhang *et al.*, 2020). Spontaneous brain activity is characterized by the synchronization between specific brain regions, forming intrinsic RSNs (Coito *et al.*, 2019; Smith *et al.*, 2013). So, the evidence reflects a similarity between spontaneous and evoked brain activity. The similarity between spontaneous and evoked brain activities has also been validated in animals: The similarity between spontaneous and evoked activities in the visual cortex increases with age in ferrets during development (Berkes *et al.*, 2011). Researchers have proposed three possible rationales for the congruence between spontaneous and evoked brain activities. First, the pattern of spontaneous brain activity mirrors the pattern of co-activation between brain regions resulting from long-term experience; second, spontaneous brain activity arises from spontaneous cognitive activity that occurs during the state of consciousness awakening; and third, both spontaneous and evoked brain activities are determined by information transmission pathways along nerve fibres in the brain (Gonzalez-Castillo *et al.*, 2021). However, the question of which viewpoint can more plausibly elucidate the similarity between spontaneous and evoked brain remains unresolved.

On the other hand, many studies have found that spontaneous and evoked brain activities exhibit distinct features. In terms of time scale, the spontaneous actions of extensive neuronal clusters are concentrated in the infra-slow (<0.1 Hz) frequency band, with peaks occurring ∼0.01–0.02 Hz (Mann *et al.*, 2021; Stringer *et al.*, 2019). During cognitive tasks, the infra-slow oscillations are greatly suppressed, resulting in a transition of brain signals towards high frequencies to accommodate rapid mental processing (He *et al.*, 2010). In other words, the frequency of spontaneous brain activity is lower than that of evoked brain activity. In terms of spatial structure, evoked activities exhibit both the inherent network structure seen in spontaneous activities and task-general and -specific network structures (Ao *et al.*, 2021; Cole *et al.*, 2014). Additionally, cognitive tasks alter the intensity and FC of brain activity in brain regions that are not task-specific (Tommasin *et al.*, 2017; Wang *et al.*, 2018), resulting in greater global and local efficiencies of brain networks compared to spontaneous brain activity (Ulloa and Horwitz, 2018). These dissimilar spatiotemporal characteristics suggest that spontaneous and evoked brain activities differ from each other.

Recently, Laumann and Snyder (2021) noted that spontaneous brain activity reflected by blood oxygen level-dependent signals is more closely related to neuroplasticity and homeostasis than to changes in cognitive content dynamics. They summarized that the separation of spontaneous brain activity from cognition and behaviour is manifested in three aspects: first, the topology of the blood oxygen level-dependent signal remains intact during sleep or even anaesthesia, when cognitive activity is greatly diminished or even absent; second, the influence of cognitive tasks on the FC of spontaneous brain activity is minimal; and third, the pattern of FC is relatively stable across multiple scans, although the content of spontaneous cognitive activity varies (Gonzalez-Castillo *et al.*, 2021; Laumann and Snyder, 2021). The evidence suggests that the pattern of spontaneous brain activity is generally stable, with only a minor disturbance caused by cognitive activity.

The Interaction Between Spontaneous and Evoked Brain Activities

Effects of spontaneous brain activity on evoked brain activity

It has long been assumed that spontaneous brain activity that is not triggered by any external stimulus is simply noise and contributes to task variability. However, these spontaneous fluctuations are actually the neural basis for processing external information. In recent years, researchers have suggested that spontaneous brain activity constitutes a fingerprint of the initial state of brain activity (Ferezou and Deneux, 2017). On the other hand, various indicators of spontaneous brain activities can predict evoked brain activities (Benwell *et al.*, 2022; Davis *et al.*, 2020). Therefore, spontaneous brain activities can affect the evoked brain activities and cognitive performance.

Researchers have extensively debated the impact of spontaneous EEG phase on the efficiency of visual stimulation processing, as the excitability and inhibition of neuronal clusters align with distinct phases of EEG activity (Lakatos *et al.*, 2007). Recent studies have further revealed that different indicators of spontaneous EEG activity have unique predictive effects on different aspects of cognitive activity. For example, the phase of the traveling wave between 5 and 40 Hz of spontaneous activity in the extrastriate visual cortex before stimulus presentation could predict the intensity of evoked EEG and the perceptual sensitivity to ambiguous stimuli (Davis *et al.*, 2020). By contrast, the power of alpha before stimulation could foretell the level of awareness in response to weak stimuli, but not perceptual sensitivity (Benwell *et al.*, 2022). In addition, the power-law index of scalp EEG alpha oscillations could predict the speed of cognitive processing (Ouyang *et al.*, 2020). These studies imply that different neural mechanisms and sensitivity indices underlie the speed, accuracy, and sensitivity of cognitive processing. However, most research endeavours continue to rely on a singular indicator, such as ERP, to evaluate various cognitive processing, as opposed to using diverse measuring tools to gauge distinct physical quantities, similar to physical measurement. Therefore, the identification of cognitive-specific indicators of brain activity is a fundamental issue to be addressed in psychological research.

In addition to neural oscillations, the influence of spontaneous brain activity on evoked brain activity is also manifested in the frequency and time course. For example, it has been shown that higher α to low γ (8–50 Hz) EEG power of spontaneous activity before stimulation is associated with stronger desynchronization of evoked activity, lower amplitude at 300–400 ms after stimulation, and lower inter-trial variability at 400–500 ms; whereas higher δ to θ EEG power of spontaneous activity before stimulation is associated with stronger event-related synchronization, higher amplitude at 150–250 ms after stimulation, and higher inter-trial variability (Wainio-Theberge *et al.*, 2021). Another study has found that higher power of alpha and beta bands (8–30 Hz) before stimulus onset is associated with stronger suppression of early (<200 ms) ERP components, as well as stronger enhancement of late (>400 ms) components (Iemi *et al.*, 2019). Considering that distinct time scales/frequencies may be associated with different cognitive and neural activities (Palva and Palva, 2018), it is imperative to examine cognitive or neural activities on appropriate time scales. Although some side effects may occur outside of the appropriate scales, the essential brain mechanisms of cognitive processing remain undetermined.

In summary, diverse indicators of spontaneous brain activity possess the ability to forecast distinct facets of cognitive performance, thereby suggesting that spontaneous activity is not mere noise but rather the underpinning of brain activity. Moreover, it is imperative to consider the selection of suitable neural indicators when investigating the mechanisms of psychological processing.

Effect of evoked brain activity on spontaneous brain activity

Despite the low intensity of evoked brain activity, it can significantly disrupt the spontaneous brain activity. During the execution of cognitive tasks, the FCs among the frontoparietal network, default mode network, and other intrinsic networks are often strengthened, whereas the FCs within the network are attenuated (Ito *et al.*, 2020). It is suggested that the reduction in FC is not caused by the decline in inter-regional communication, but rather the decline in the shared spontaneous activity among brain regions, leading to decreased neural noise and enhanced precision of task signals meanwhile (Ito *et al.*, 2020). In this vein, many studies have found that cognitive tasks are associated with reduced neural noise (Jacobs *et al.*, 2020; Ponce-Alvarez *et al.*, 2015; Wang *et al.*, 2020) and reorganized FC (Cole *et al.*, 2014; Gonzalez-Castillo and Bandettini, 2018; Wang *et al.*, 2019). It is evident that, in addition to the reinforcement of target stimuli and inhibition of distracting stimuli during attention, the brain also has a comprehensive mechanism for reinforcement and inhibition. This mechanism operates by intensifying task-related FC while inhibiting spontaneous FC, thereby optimizing the efficiency of behaviour.

Beyond the intensity of FC, stimulation will initiate the creation of new connection patterns and gradually modify the connection patterns of spontaneous activity. For instance, after the task has been completed, the neural activity pattern that was present during the task can still be decoded in the resting state for a few minutes (Liu *et al.*, 2021), indicating that previous tasks have effects on the spontaneous brain activity (Stringer *et al.*, 2019). Different patterns of spontaneous brain activity were also observed after prolonged and repeated presentation of stimuli. For example, expertise can shape the patterns of spontaneous activity in the resting brain (Dong *et al.*, 2014). In addition, visual perceptual learning appears to modify the covariance structure of spontaneous brain activity among task-related networks, with the degree of visual perceptual learning being relevant to this alteration (Lewis *et al.*, 2009). Regarding the aspect of neural development, Avitan *et al.* found that the developmental trajectories of spontaneous and speckle stimulus-evoked brain activity in zebrafish were similar, but the spatial resemblance between them decreased as the fish matured; the co-activation level and information dimension of the evoked brain activity exceeded those of the spontaneous brain activity in all stages of development (Avitan *et al.*, 2021), supporting the idea that evoked brain activity modifies spontaneous brain activity by expanding its information dimensions. Viewed from this perspective, the prevalent negative interaction between evoked and spontaneous brain activities can be interpreted as the evoked brain activity suppressing the original dimensions of spontaneous brain activity and directing it towards new dimensions. This perspective may yield new ideas for the study of brain plasticity associated with learning and memory.

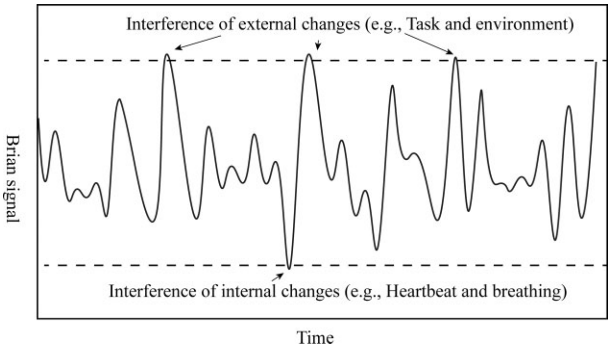

Figure 1: Small perturbations of internal and external stimuli cause adaptive changes in brain activity. The signal between the two dashed lines is made up of enactive brain activity, which is spontaneous and endless. The internal and external stimuli slightly disturb the signal, causing it to surpass the typical range. Enactive brain activity adaptively alters brain signals in response to these disturbances.

The interaction of evoked brain activity and spontaneous brain activity

Considerable evidence suggests that there exists a reciprocal relationship between spontaneous and evoked brain activities. Specifically, spontaneous brain activity modulates evoked brain activity corresponding to different brain states, while evoked brain activity induces alterations in spontaneous brain activity in response to the task context. Throughout this process, the brain actively adapts to and improves the efficiency of processing external stimuli, while external stimuli regulate and reset the state of spontaneous brain activity (Chen and Gong, 2019). For example, Chen *et al.* observed that the transient changes of Ca^{2+} evoked by single stimulus were stronger in the troughs of spontaneous Ca^{2+} oscillations (inhibitory phase); conversely, the stimulus resets the phase of spontaneous Ca^{2+} oscillations to the crest (excitatory phase) (Chen *et al.*, 2020). The interaction between evoked and spontaneous brain activities may be modulated by the 5-hydroxytryptamine (5-HT), considering the fact that 5-HT1A receptors inhibit spontaneous activity in the visual cortex while 5-HT2A receptors inhibit visual evoked responses (Azimi *et al.*, 2020). On the other hand, Stringer *et al.* found that spontaneous brain activity existed in the whole brain and was orthogonal to evoked brain activity, and the two overlapped in only one dimension (Stringer *et al.*, 2019).

In summary, it is largely unclear how spontaneous and evoked brain activities bilateral interact with each other. Nonetheless, the intricate interplay between them determines that the brain mechanism of mental processing cannot be adequately explicated through evoked brain activity, nor can it be precisely unveiled through the unilateral impact of spontaneous brain activity and evoked brain activity. Rather, the brain activity should be perceived as a dynamic entity that evolves over time, it is capable of modifying itself in response to slight disturbances from both internal and external stimuli (see Fig. 1). These recent findings on brain activity align with the perspective of enactive cognition.

Enactive Brain Activity: A Unified Explanation of Brain Activity by the Enactive Cognition

The mental processing mechanism of the brain based on the framework of enactive cognitive theory

Enactive cognition is viewed as the third approach of cognitive science subsequent to the information processing and embodied cognition orientations (Ye *et al.*, 2019). The information processing model of cognition considers that information is input through sensory systems, and output through behaviour, emphasizing the role of the brain as a complex computer program in cognition (Foglia and Wilson, 2013); on the other hand, embodied cognition holds that the body shapes mental activities, and there is no separation between cognition, the body, and the real environment (Foglia and Wilson, 2013); some scholars have proposed that enactive cognition is generated in the action of the organism and is rooted in the coupling and interaction between the organism and the environment to guide the individual to take more effective actions (Ye *et al.*, 2019). Individuals actively regulate the continuous activity and interact with the environment; therefore, the brain does not passively build models, but exists to support and guide actions (Kirchhoff, 2013). Within the framework of enactive cognition, individuals primarily interact with the world through prediction or expectation. In this process, the brain continually adjusts its activities pertaining to the task at hand to maintain equilibrium with the environment (Bolt *et al.*, 2017). Even during the resting state, the brain constantly processes an extensive range of stimuli and behaviours to prepare for forthcoming encounters with the environment (Pezzulo *et al.*, 2021). Under this framework, the spontaneous brain activity is capable of responding to changes in the internal and external environment and making adaptive adjustments. Therefore, unlike the dichotomy of spontaneous and evoked brain activities, the enactive brain activity posits that brain signals are a continuous and ever-changing time series. The dynamic signal includes the brain's active prediction and its adjustment based on the stimuli it receives. This is in line with the opinion that spontaneous brain activity contains three components: neuroplasticity, homeostasis, and real-time cognitive activity (Laumann and Snyder, 2021). To be specific, neuroplasticity comprises Hebbian plasticity and homeostatic plasticity. Spontaneous brain activity is influenced, on the one hand, by the history of previous co-activation, and, on the other hand, is modulated by various homeostatic plasticity mechanisms that balance excitation and inhibition and return the mean firing rate to its previous level. Importantly, synaptic homeostasis and consolidation are inseparable (Axmacher *et al.*, 2009; Kavalali and Monteggia, 2020). Homeostasis means that each part of the brain alternates between on-line and off-line states, which can occur simultaneously in different parts of the brain (Abbott and Nelson, 2000; Laumann and Snyder, 2021). Spontaneous brain activity was also affected by task elicitation, with measurable differences in FC induced by different tasks (Cole *et al.*, 2014; Gratton *et al.*, 2016; Krienen *et al.*, 2014). Ultimately, the brain simulates the 'body in the world' along two dimensions—externally directed behaviours and internally directed feelings, resulting in specific functional organizations (Rossi *et al.*, 2019).

Paradigms and algorithms for enactive brain activity

This innovative perspective of enactive brain activity shows great potential in elucidating the brain mechanisms that underpin mental processing; it also engenders new questions such as, how can we trace the brain activity during enactive cognition? We will elaborate from two aspects: the paradigm and algorithm of enactive brain activity.

Finn pointed out that the research paradigm of human brain imaging has undergone a third wave, transitioning from the conventional task paradigm to the resting-state design and, currently, to the task-resting integrated design (Finn, 2021). The core concern of integrated design lies in the dynamics of brain activity across diverse task- and resting-states.

Another paradigm that has emerged in recent years is the steady-state design, in which a single task is presented at a fixed frequency (e.g. once every 10 seconds or 0.1 Hz) in a block to probe the brain mechanisms of specific mental processes (Baldauf and Desimone, 2014; Wang *et al.*, 2016). The steady-state design ensures a stable and predictable environment for the brain to operate in. This allows for the allocation of mental resources towards specific cognitive processes and reduces the disruptive effects of fluctuating expectations between trials. Consequently, it mitigates the impact of expectations on the content of mental processing and minimizes inter-trial variability in cognitive performance. Steady-state designs reduce uncertainty, increase stability, and improve signal-to-noise ratios, thus allowing for more robust detection of brain mechanisms for specific mental processes (Gao *et al.*, 2018). With the emergence of innovative paradigms suitable for probing enactive brain activity, a more refined exploration of brain mechanisms of mental processing has become feasible.

The enactive cognition theory is supported by mathematical models. These models also provide a reference for measuring enactive brain activity. The dynamic system theory posits that enactive brain activity can access multiple possible states, whereas external inputs cause it to fall into a specific state, resulting in a reduction of variability (Ponce-Alvarez *et al.*, 2015). Variability reduction can be understood as the relevant parts of the brain formulating a mutually constrained system, allowing the whole brain to enter and maintain a task-appropriate functional configuration (Bolt *et al.*, 2017).

Similarly, the Bayesian theory suggests that enactive brain activity forms expectations or a prior probability of all possible external environments by sampling a large number of states. Once sensory information representing the true state of the external world is combined into the system, the prior probability becomes a posterior probability, which essentially diminishes uncertainty and restricts the number of sampled states (Ferezou and Deneux, 2017). This perspective asserts that enactive brain activity actively engages in a process of inference about the environment, systematically examining all potentialities based on accumulated experience, even during periods of resting- or sleeping-states (Ferezou and Deneux, 2017).

While these theories provide different perspectives on how the brain adapts to external stimuli, Friston attempted to establish a unified interpretation framework for brain activity patterns as a complex system using the free-energy principle (Friston, 2010). According to the free-energy principle, the brain, like living organisms, is a self-organizing system that engages in various adaptive behaviours to sustain its survival and reproduction. It is not a passive recipient of perceptual inputs, but rather a predictor that conforms to a generation model. The brain minimizes prediction errors and generates adaptive behaviours with a recursive process that matches internally generated prior predictions with stimulus input from the external environment. These theories support the notion that the brain actively adapts to the environment through enactive cognition, thus preserving a unified theoretical, computational, and empirical account for the patterns of brain activity during mental processing.

Numerous empirical studies have emerged in recent years that support the aforementioned models, affirming that activity patterns of the brain are control-oriented rather than simply representations of the external world. Accordingly, enactive brain activity represents a collection of brain states formed by the continuous internalization of behavioural–perceptual circuits, which can be automatically activated in the future when required (Pezzulo *et al.*, 2021).

Conclusion: From Spontaneous and Evoked Brain Activities to Enactive Brain Activities

Since evoked brain activity is only a small part of brain activity, and spontaneous brain activity is the main form of brain activity that interacts with evoked brain activity, neither the relatively weak evoked brain activity nor the static interaction between spontaneous and evoked brain activities is sufficient to unveil the brain mechanisms of mental processing. Enactive cognition offers a solution to this problem: the brain proactively reacts to the ever-changing internal and external environments, producing adaptive behaviours by diminishing the discrepancy between expected outcomes and actual inputs. Therefore, the enactive brain activity, as a unified entity, is capable of effectively representing the unceasing interaction between spontaneous and evoked brain activities. Furthermore, it has been demonstrated by theoretical, computational, and empirical studies that the brain is actively adapting to the environment, rather than passively responding to stimuli. These findings suggest that enactive brain activity can depict the brain mechanism of mental processing more succinctly (one signal vs. two interacting signals) and comprehensively (the complete dynamic process vs. a static facet).

The viewpoint of enactive cognition can improve the reliability and validity of cognitive-related brain imaging. Due to the low signal-to-noise ratios and high inter-trial variability in evoked brain activity, most neuroimaging studies have low reliabilities. According to a meta-analysis conducted by Elliott and colleagues, the mean retest reliability for task-state activation was found to be merely 0.397, while the range for area-of-interest activation was between 0.067 and 0.485 (Elliott *et al.*, 2020). Psychological and behavioural researchers are also confronted with a severe crisis of repeatability, largely due to the prevalence of publishing bias and excessive reliance on nihilistic hypotheses (Hu *et al.*, 2016). For instance, Stanley *et al.* assessed the statistical validity of nearly 8000 psychology papers and found that only 8% of the studies had adequate statistical validity (Stanley *et al.*, 2018). The enactive cognition gets rid of the dependence on weak evoked brain activity and unstable inter-trial variability, and explores the brain mechanisms of mental processing from the holistic and dynamic nature of brain activity. The reliability and validity of cognitive neuroscience could be significantly improved through these advancements.

In summary, the investigation into the brain mechanisms of mental processing is facing a significant challenge. Taking the brain as a complex system and exploring the enactive brain activity from an active and self-organizing perspective may afford a crucial prospect for the current crisis. The innovative perspective and related paradigms have the potential to enhance the reliability and validity of neuroimaging studies, while also introducing fresh insights into the brain mechanisms of mental processing.

Author Contributions

Y.F.W.: conceptualization and funding acquisition; C.Z., Y.F.W., X.J.J., J.H.Y.: review and editing.

Conflict of Interest

All authors declare no conflicts of interest concerning this work.

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