The Separation of External Manifestation and Internal Representation of Volition

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Abstract

Volition is the capacity for autonomous self-control, a core characteristic distinguishing humans from animals and machines, and the cornerstone of physical and mental health and social order. Its external manifestation is voluntary action, while its internal representation is the sense of control. The former denotes actions generated from one' s own will; the latter denotes the belief that the execution of voluntary actions can influence external events. Prior research has predominantly investigated volition through voluntary action, yet individuals concurrently maintain a sense of control when performing such actions. Consequently, these studies have conflated the external manifestation and internal representation of volition. The present study proposes to employ the volition-motivated performance (VMP) paradigm, dissociating voluntary action from sense of control, in conjunction with computational modeling and multimodal neuroimaging techniques (electromyography/electroencephalography/functional magnetic resonance imaging), to systematically elucidate their shared and distinct cognitive neural mechanisms. Based on this approach, we propose the "dual-pathway hypothesis of human volitional processes" : one pathway is associated with voluntary action, reflecting the action attribute of volition; the other is associated with sense of control, reflecting the motivational attribute of volition.

Full Text

Dissociating the External Manifestation and Internal Representation of Volition

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Abstract

Volition—the ability to control oneself voluntarily—represents the central characteristic distinguishing humans from animals and machines, and serves as the cornerstone of physical and mental health and human society. Its main components include voluntary action and control belief. Voluntary action refers to actions based on one' s own will and constitutes the external expression of volition, while control belief refers to the belief that implementing a voluntary action can influence the external world and constitutes the internal representation of volition. Individuals express their volition to the external world through voluntary actions, but they must also possess control belief to ensure the will to implement those actions. Most previous studies have explored volition through voluntary action but have failed to empirically distinguish the effects of control belief from those of voluntary action. Based on an innovative experimental paradigm—the volition-motivated performance (VMP) paradigm—this study proposes to dissociate the effects of control belief from those of voluntary action on cognitive performance (Study 1), and further combine computational models, simultaneous EMG and EEG recordings (Study 2), and functional magnetic resonance imaging (Study 3) to reveal the common and unique dynamic neurophysiological mechanisms and neural basis of voluntary action and control belief. This study will construct a "dual-path hypothesis of human volition processing" : the path of voluntary action, reflecting the action attribute of volition; and the path of control belief, reflecting the motivational attribute of volition.

Keywords: volition, voluntary action, control belief, voluntary choice, volition-motivated performance (VMP) paradigm

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Introduction

Human inquiry into volition has a long history, spanning philosophy, psychology, neuroscience, artificial intelligence, and other fields both ancient and emerging, yet no consensus has been reached. Although researchers from different fields define volition differently, most discussions center on "the ability of individuals to choose or decide autonomously" (Kane, 1996). At the individual level, volition forms the foundation of human physical and mental health; the typical manifestation of many psychosomatic disorders is the inability to control one' s own behavior, as seen in Parkinson' s disease (Ricciardi et al., 2017) and schizophrenia (Daprati et al., 1997). At the group level, volition serves as the cornerstone of human society; for instance, a fundamental premise of lawmaking is that people should be held responsible for actions performed based on their own volition (Christensen et al., 2024; Haggard, 2019).

Volition generally refers to the ability to control oneself voluntarily, particularly in controlling goal-directed actions (Haggard, 2008, 2019): that is, the psychological and behavioral mechanism by which individuals actively initiate, maintain, or adjust actions to achieve goals (Frith, 2013; Kuhl, 1984). A complete volitional process includes both the generation and expression of volition, both of which are indispensable. On one hand, if volition remains only in the internal generation process without being expressed through external behavior, it loses the core characteristic of "teleology" (Haggard, 2019)—volition emerges only to achieve specific purposes, and no purpose can be achieved without external action. On the other hand, if volition is reduced to external action alone without an internal generation process, it loses another core characteristic of "subjectivity" (Haggard, 2019)—volition produces the subjective experience that "I can plan and control actions to achieve goals, and these actions reflect my own intentions." Without an internal processing mechanism, no subjective experience would be possible. Thus, volition generation corresponds to the internal "control belief" —the belief that one' s own actions can influence external events and achieve goals/intentions—while volition expression corresponds to the external "voluntary action" —actions initiated based on one' s own will. Only through external actions that influence the external world can goals/intentions be achieved. Voluntary action is the external manifestation of volition, while control belief is its internal representation.

In the volitional process, voluntary action and control belief are closely related—individuals need to possess control belief (i.e., believe their actions are meaningful and can influence external events to achieve goals/intentions) to be inclined to implement voluntary actions; conversely, when individuals lose control belief (i.e., believe action implementation is meaningless and do not trust that their actions can produce any effect), voluntary actions decrease or disappear, resulting in "learned helplessness" (Huys & Dayan, 2009; Maier & Seligman, 1976). Therefore, when individuals implement voluntary actions, they often simultaneously hold control beliefs (Desantis et al., 2011; Dogge et al., 2012; Huys & Dayan, 2009; Luo et al., 2022; Maier & Seligman, 1976).

Although the external manifestation and internal representation of volition are closely related, research suggests that subjective experience and actual action in the volitional process are dissociable. For example, direct stimulation of specific brain regions can induce the subjective experience of "wanting to move" without producing actual external movement (Desmurget et al., 2009; Fried et al., 1991). This suggests that the external manifestation and internal representation of volition may involve different processing mechanisms. By reviewing previous studies (see "1 Research Status"), we find that because the internal representation process is difficult to measure or manipulate directly, existing research has mostly investigated volition through its external manifestation—immediately implemented voluntary actions—without distinguishing between voluntary action and control belief. Consequently, related findings may be attributable to voluntary action alone, control belief alone, or their combined effects. Therefore, previous studies have failed to further parse volition, and their findings may have confounded the roles of voluntary action and control belief (see "2 Problem Statement"). Thus, attempting to dissociate voluntary action and control belief through non-invasive experimental design represents an important issue worthy of further investigation in human volition research.

This study proposes to use a recently developed paradigm for investigating volition effects—the volition-motivated performance (VMP) paradigm (Luo et al., 2022; also see Luo, Wang, Gu, et al., 2024; Luo, Wang, & Zhou, 2024; detailed introduction of the VMP paradigm appears in "1.6 Volition-Motivated Performance Paradigm")—to develop its variants for dissociating the external manifestation (voluntary action) and internal representation (control belief) of volition. Combined with computational modeling and multimodal neuroimaging techniques (electromyography/electroencephalography/functional magnetic resonance imaging), this approach aims to systematically reveal their shared and specific cognitive-neural mechanisms. Based on these findings, we propose the "dual-path hypothesis of human volition processing" : one path related to voluntary action, reflecting the action attribute of volition; and another path related to control belief, reflecting the motivational attribute of volition.

This study holds both theoretical and practical significance. Theoretically, a multi-faceted and multi-angle analysis of human volition through experimental design, computational models, and neurophysiological techniques will help clarify the common and unique roles of different volitional components, open new perspectives for investigating volitional issues, and deepen our understanding of human volition and even the problem of consciousness. Clinically, "control belief deficit" is closely associated with several mental health issues, such as depression (Huys & Dayan, 2009), learned helplessness (Maier & Seligman, 1976), and schizophrenia (Daprati et al., 1997). By isolating control belief from the volitional process, this study may provide new perspectives for research and treatment of related mental health problems. Industrially, control belief plays an important role in individual interactions with virtual environments or intelligent machines (Wen & Imamizu, 2022). People need to hold control beliefs about virtual environments (or intelligent machines) to complete subsequent tasks, and feedback from these environments directly affects individuals' control beliefs. Investigating control belief and its neural mechanisms will help develop virtual environments or intelligent machines with better control experiences in the future and provide a foundation for artificial intelligence to simulate human control processes.

1 Research Status

Volition has no physical entity and is difficult to measure or manipulate directly. Previous research has developed various paradigms to investigate different aspects of volition (paradigm summary shown in Figure 1 [Figure 1: see original paper]). Among these, voluntary action, as the external manifestation of volition, is easy to observe and measure, and has been extensively studied. Researchers have focused on two main aspects: the generation of voluntary action and the subjective experience of voluntary action ("sense of agency"). Related paradigms mainly include self-generated action, explicit judgment of agency, and implicit measurement of agency. Control belief, as the internal representation of volition, is difficult to measure and quantify, and has been less studied; related paradigms mainly include explicit judgment of control, motivation from control, and the volition-motivated performance paradigm.

However, whether focusing on voluntary action or control belief, existing paradigms all depend on immediately implemented voluntary actions. As mentioned above, individuals implementing voluntary actions often simultaneously hold control beliefs; therefore, previous studies have failed to distinguish the respective roles of voluntary action and control belief. The following sections briefly summarize these paradigms and further demonstrate potential problems in existing research.

Figure 1. Summary of paradigms used in previous studies to investigate volition. Whether focusing on voluntary action or control belief, these paradigms all depend on immediately implemented voluntary actions, and individuals implementing voluntary actions often simultaneously hold control beliefs. Therefore, previous studies have failed to distinguish the respective roles of voluntary action and control belief. Color figures can be viewed in the online version of this article.

1.1 Self-Generated Action Paradigm

When investigating the generation of voluntary action, researchers often require participants to self-generate actions at any time point, typically while simultaneously recording neural activity. Sometimes this is compared with non-voluntarily generated actions (e.g., twitches induced by transcranial magnetic stimulation, actions produced in response to external stimuli). For example, researchers using EEG technology have confirmed that voluntary action generation is preceded by a readiness potential (RP) (Khalighinejad et al., 2018; Libet et al., 1983). Using fMRI technology, they have identified brain regions related to voluntary action planning and execution, such as the supplementary motor area (SMA) and premotor cortex (PMC) (Penfield, 1954; Rizzolatti & Kalaska, 2013). In addition to recording neural activity, researchers have also examined brain damage to infer the neural basis of voluntary action generation. For instance, SMA damage affects the generation of spontaneous actions but not stimulus-driven actions, whereas PMC damage shows the opposite pattern (Passingham, 1987), suggesting the important role of SMA in voluntary action generation.

Brain-computer interface research has found that when using neuromuscular electrical stimulation to induce actions, the peak timing of neuronal electrical activity in the primary motor cortex (M1) coincides with the time when individuals subjectively experience the emergence of action intention (Noel et al., 2025). Furthermore, low-frequency alpha oscillations in M1 before action generation can predict individuals' sense of agency (Bertoni et al., 2025). This suggests that M1 not only plays an important role in voluntary action generation but is also related to the subjective experience of voluntary action.

However, investigating volition through direct voluntary action generation inevitably involves implementing voluntary actions, during which individuals simultaneously hold control beliefs. Therefore, this paradigm cannot dissociate voluntary action from control belief.

1.2 Explicit Judgment of Agency Paradigm

Researchers often refer to the subjective experience of voluntary action as "sense of agency," "sense of control," or "sense of active control" (Haggard, 2017; Tian et al., 2018; Wu et al., 2019; Zhang et al., 2018)—that is, "the experience during voluntary action implementation of feeling that one can control one' s own actions and thereby control external events" (Haggard, 2017; Haggard et al., 2002). Sense of agency accompanies voluntary action implementation and can be subjectively reported through introspection, constituting the explicit judgment of agency paradigm. Related studies often require participants to report the degree to which an action was "made by myself" or "controlled by myself." Higher subjective ratings indicate stronger sense of agency for that action and correspondingly stronger volitional experience (e.g., Georgieff & Jeannerod, 1998; Sirigu et al., 1999).

However, when an action is consistent with the participant' s own actions, even if the agent producing the action is not the participant, the participant still experiences sense of agency (Tsakiris et al., 2005; Wegner & Wheatley, 1999). This suggests that individuals' subjective reports tend to overestimate their own autonomous capabilities, attributing actions actually unrelated to their own volition to themselves. Moreover, requiring individuals to introspect on the subjective experience of voluntary action still depends on voluntary action implementation and cannot dissociate voluntary action from control belief. Therefore, explicit judgment of agency often serves as an auxiliary rather than primary measure in volition research and is not suitable for dissociating voluntary action and control belief based on this paradigm.

1.3 Implicit Measurement of Agency Paradigm

To overcome the limitations of subjective reporting methods for agency, researchers have developed paradigms for implicitly measuring agency, the most commonly used being the "intentional binding task" (Haggard, 2017; Haggard et al., 2002). In this task, participants perform an action (e.g., key press), after which an event occurs (e.g., auditory stimulus). Participants must estimate the time interval between the action and event (or the timing of each). Results show that compared with non-voluntary actions, when a voluntary action is performed, participants' time estimates are shorter, a phenomenon called the "intentional binding effect" or "temporal compression effect." The magnitude of this effect reflects the strength of individuals' sense of agency and has been replicated in numerous studies (e.g., Moore et al., 2009; Obhi & Hall, 2011; Schwarz et al., 2019). Related neuroscience research has also found that SMA activation can predict the strength of the intentional binding effect (Kühn et al., 2013). Using transcranial magnetic stimulation (TMS) or transcranial direct current stimulation (tDCS) to disrupt SMA activity in healthy participants weakens the intentional binding effect (Moore et al., 2010; Cavazzana et al., 2015). These findings again suggest the important association between SMA and human volitional processes.

In addition to intentional binding, sensory attenuation (Blakemore et al., 1998; Schafer & Marcus, 1973) has also been used to implicitly measure agency. Similar to the intentional binding task, in sensory attenuation tasks, participants perform an action followed by a sensory stimulus (e.g., visual, auditory, tactile), and participants must judge the intensity of this sensory stimulus. Results show that compared with non-voluntary actions, when a voluntary action is performed, participants' perception of sensory stimulus intensity decreases, with reduced amplitude of related ERP components (e.g., N1) (e.g., Mifsud et al., 2018; Weiss et al., 2011) and reduced activation in primary sensory cortices (e.g., auditory and somatosensory areas) (e.g., Arikan et al., 2021; Reznik et al., 2014), indicating sensory attenuation. The magnitude of this effect is also considered to reflect the strength of sense of agency. It should be noted that the relationship between sensory attenuation and intentional binding effects remains debated; although both relate to sense of agency, they may involve different cognitive processing mechanisms (Borhani et al., 2017; Lindner et al., 2025).

Whether intentional binding or sensory attenuation, their key indicators (time interval between action and subsequent event, judgment of sensory intensity triggered by action) are directly associated with voluntary action implementation. Researchers still cannot distinguish the effects of voluntary action and control belief.

1.4 Explicit Judgment of Control Paradigm

Previous studies investigating control belief have also relied on voluntary action implementation, differing only in perspective. Researchers often use subjective reporting to explore control belief, i.e., explicit judgment of control. These studies typically present specific stimuli as "outcomes"while participants perform voluntary actions and require participants to report the degree to which the "outcome" was caused by their own actions. Research consistently finds that individuals tend to judge "outcomes" that are temporally and spatially closer to voluntary actions as being caused by those actions, even when such causal relationships do not actually exist. This phenomenon is also called the "illusion of control" (Langer, 1975; Thompson et al., 1998; Chen et al., 2010). In addition to directly rating the causal relationship between specific outcomes and actions, one variant of explicit judgment of control requires participants to generate a series of actions (e.g., moving a mouse, joystick) while judging whether stimuli on the screen (e.g., movement of a light point) are consistent with their own actions (e.g., judging whether the trajectory of the light point on the screen matches their mouse movement). Research shows that when the temporal or spatial inconsistency between stimuli and actions increases, participants are more likely to believe the stimulus is not under their control (Applebaum et al., 2025; Wen et al., 2023; Wen & Haggard, 2020), i.e., their control belief weakens.

However, similar to subjective reports of agency, due to the existence of control illusions, individuals' subjective reports tend to overestimate the controllability of the external environment. Moreover, if the "outcome"is too distant temporally or spatially from the voluntary action, individuals are not inclined to establish a connection between the outcome and the action (Matute & Blanco, 2014; Yarritu et al., 2014). Therefore, explicit judgment of control is also more suitable as an auxiliary measure, and similarly depends on immediately implemented voluntary actions, making it impossible to isolate control belief.

1.5 Motivation from Control Paradigm

The motivation from control paradigm attempts to measure control belief through implicit means. Similar to the subjective control reporting paradigm described above, this paradigm presents specific stimuli while participants perform voluntary actions and manipulates the presentation of these stimuli (i.e., manipulates the "outcome" of actions), but does not require subjective reports. Instead, it records indicators such as reaction time and frequency of voluntary actions themselves. Research finds that when "outcomes" are temporally and spatially closer to voluntary actions, participants' voluntary actions become faster and more frequent (Eitam et al., 2013; Karsh et al., 2016), consistent with findings from subjective reporting methods and interpreted as effects of control belief. Further research based on this paradigm has found that the effectiveness of "outcomes" (e.g., manipulating whether an "outcome" is produced or its predictability) also affects participants' reaction times for voluntary actions, and this effect changes dynamically with the effectiveness of the "outcome" (Hemed et al., 2020). This suggests that individuals' control beliefs dynamically adjust with real-time changes in external feedback, and such dynamic adjustment of control beliefs may further influence subsequent voluntary action implementation. Similarly, individuals can dynamically adjust biases in autonomous behavior based on feedback and belief learning to prevent autonomous behavior from being influenced by habitual responses or sequential effects; however, this adjustment is also limited, as individuals find it difficult to eliminate action-outcome dependence (Ota et al., 2024). This suggests that the "action-outcome" relationship plays an important role in forming control beliefs (also see Luo et al., 2022).

However, evaluating control belief using indicators related to voluntary action itself (reaction time, frequency) still requires immediate implementation of voluntary actions and cannot dissociate voluntary action from control belief.

1.6 Volition-Motivated Performance (VMP) Paradigm

The VMP paradigm uses a more purposeful form of voluntary action—voluntary choice (Leotti et al., 2010; Chen & Wu, 2019)—to investigate volition. Voluntary choice provides freedom to decide between different options and is an actively generated goal-directed action (specifying options based on one's own will). However, it is important to note that many factors may drive individuals to produce voluntary choice behavior, with volition being only one possibility. Therefore, in the VMP paradigm, voluntary choice must be compared with "forced choice" (where options are directly specified and participants are required to perform the corresponding key press action), a non-selective voluntary action, to reflect the role of volition. Compared with forced choice, voluntary choice is associated with a stronger sense of agency (Barlas et al., 2018; Caspar et al., 2016; Yavuz et al., 2025). More importantly, compared with forced choice, voluntary choice facilitates subsequent cognitive performance, including time estimation tasks (Murayama et al., 2015), declarative memory tasks (Murty et al., 2015; Ruiz et al., 2023), and reaction time-related tasks (e.g., visual search tasks: Luo et al., 2022; Luo, Wang, Gu, et al., 2024; conflict control tasks: Legault & Inzlicht, 2013; Luo, Wang, & Zhou, 2024). The VMP paradigm investigates the role of volition based on the differential impact of voluntary versus forced choice on subsequent cognitive performance, using the difference in cognitive performance (e.g., task reaction time) between voluntary and forced choice conditions as an indicator reflecting volitional effects (Luo et al., 2022; also see Luo, Wang, Gu, et al., 2024; Luo, Wang, & Zhou, 2024).

A typical trial procedure in the VMP paradigm is shown in Figure 2 [Figure 2: see original paper]. A complete trial includes three phases: cue phase, choice phase, and task phase. Specifically, the cue phase uses different colors to indicate whether the upcoming trial involves voluntary or forced choice. In the choice phase, two neutral pictures are presented. In the voluntary choice condition, participants can voluntarily press a key to select one picture; in the forced choice condition, one picture is pre-specified (surrounded by a box), and participants can only press the key to select the designated picture. In the task phase, the selected picture is presented as the background for a cognitive task (e.g., visual search task). The picture background is task-irrelevant. Research based on this paradigm has found that compared with forced choice, cognitive performance after voluntary choice is facilitated (faster reaction times) (Luo et al., 2022; Luo, Wang, Gu, et al., 2024; Luo, Wang, & Zhou, 2024), and participants' subjectively reported control belief magnitude can predict the magnitude of the facilitating effect of voluntary choice on cognitive performance (Luo et al., 2022). This suggests that cognitive performance indicators in the VMP paradigm can to some extent reflect individuals' control beliefs.

Figure 2. Typical trial procedure in the volition-motivated performance (VMP) paradigm. Cue phase: Different colored circles indicate the choice type for the current trial (voluntary vs. forced choice). Choice phase: Press a key to voluntarily/forcedly select one of two pictures. Task phase: Complete a cognitive

task (visual search task shown here) with the selected picture as background. Note: Fixation points of 0.5–0.8 s appear between phases (cue, choice, task), but are omitted from this simplified flowchart for clarity. Source: Fig. 1 in Luo, Wang, Gu, et al. (2024). Color figures can be viewed in the online version of this article.

However, the key indicator reflecting volitional effects in the current VMP paradigm (cognitive performance after voluntary choice) is still measured immediately after implementing the voluntary action (choice), failing to distinguish the respective effects of voluntary action and control belief. Nevertheless, the advantage of this paradigm over other paradigms is that the measurement indicator (cognitive performance) is completely unrelated to the voluntary action (choice), and the two can be completely separated in time. In contrast, measurement indicators in other paradigms are directly related to voluntary action and cannot be separated. The separability of voluntary action and measurement indicators in the VMP paradigm provides a foundation for dissociating voluntary action and control belief through experimental design (further elaborated in "2 Problem Statement").

2 Problem Statement

As evident from the summary of previous research paradigms above, these paradigms exploring human volition from different angles are all directly associated with immediately implemented voluntary actions. Given that individuals implementing voluntary actions often simultaneously hold control beliefs (Desantis et al., 2011; Dogge et al., 2012; Huys & Dayan, 2009; Luo et al., 2022; Maier & Seligman, 1976), studies using these paradigms inevitably involve both the processing of voluntary action and the processing of control belief. Therefore, previous studies have failed to dissociate voluntary action and control belief. Most studies have generally attributed related behavioral or neural results to "effects of voluntary action" or "effects of volition," but these findings may result from voluntary action alone, control belief alone, or their combined effects. In other words, in several classic volition research paradigms, the dependent variable measuring volitional effects is closely linked to voluntary action implementation and cannot be temporally separated from it, which may be an important factor limiting researchers' ability to dissociate voluntary action and control belief. Moreover, previous volition research has mainly focused on voluntary action itself. Although some classic computational models have explored voluntary action generation (e.g., Blakemore et al., 2000), these models are more action-oriented, with less integration of computational models at the volitional level, which has also limited the parsing of volition to some extent.

The VMP paradigm can provide inspiration for further parsing volition. Compared with the classic voluntary action paradigms mentioned above, the VMP paradigm based on voluntary choice has unique advantages for dissociating voluntary action and control belief. First, in the VMP paradigm, the voluntary action behavior (the key press action to select pictures in the choice phase) is unrelated to the dependent variable measuring volitional effects (cognitive performance in the task phase), allowing complete temporal separation between the two. This separability enables the elimination of voluntary action' s influence on the dependent variable by extending the time interval between voluntary action and the dependent variable (e.g., by 24 hours). However, it is important to note that this separability is also a limitation of using the VMP paradigm to measure volition—the indicator reflecting volition is not measured directly during the process of volition generation and expression (i.e., during the selection process), but is measured indirectly after the volition expression process ends (i.e., after selection completion). This may only reflect certain aspects rather than the full picture of the volitional process. Therefore, directly analyzing brain activity during volition generation and expression using EEG, fMRI, and other techniques is essential.

Second, in the VMP paradigm, the outcome triggered by voluntary action (the background picture appearing in the task phase) is unrelated to the dependent variable measuring volitional effects (cognitive performance in the task phase). Therefore, the relationship between voluntary action and its outcome can be directly manipulated to alter control belief without affecting the cognitive task, thereby investigating how changes in control belief affect subsequent cognitive performance. Previous research has found (Luo et al., 2022) that in the VMP paradigm, when the choice-outcome causal relationship is certain (i.e., the picture selected in the choice phase matches the background picture presented in the task phase), voluntary choice facilitates cognitive performance. However, when the choice-outcome causal relationship is nullified (i.e., the picture selected in the choice phase is unrelated to the background picture presented in the task phase—choice cannot control outcome, and control belief is removed), the facilitating effect of voluntary choice on subsequent cognitive performance disappears. This suggests that based on the VMP paradigm, control belief can be altered by manipulating the "choice-outcome" relationship without changing voluntary action, thereby eliminating the influence of control belief on the dependent variable.

Third, the effect of voluntary choice facilitating cognitive performance in the VMP paradigm shows cross-task and cross-effector consistency, representing a stable and reliable method for quantifying volitional effects. On one hand, research based on the VMP paradigm has found that the facilitating effect of voluntary choice on subsequent cognitive performance consistently exists across various cognitive tasks, including visual search tasks (Luo et al., 2022; Luo, Wang, Gu, et al., 2024) and multiple conflict control tasks (including Flanker, Stroop, Simon, Stroop-Simon, and Flanker-Simon tasks) (Luo, Wang, & Zhou, 2024). That is, regardless of how the cognitive task changes, the facilitating effect of voluntary choice on cognitive performance (mainly facilitating response speed) can be demonstrated across these tasks. On the other hand, research based on the VMP paradigm has also found that the facilitating effect of voluntary choice is independent of the effector used for selection—whether selecting by hand (i.e., participants press keys with fingers), foot (i.e., participants press pedals with left/right foot), mouth (i.e., participants verbally state their choice, which is then pressed by the experimenter), or eye (i.e., based on eye tracker capturing gaze position, participants select by fixating on the desired option), the facilitating effect of voluntary choice on cognitive performance can be observed (Luo, Wang, Gu, et al., 2024). These findings all suggest the "domain-general" nature of the VMP effect.

Fourth, the VMP paradigm evaluates the role of volition based on performance in specific cognitive tasks, which facilitates using computational models to distinguish different cognitive processing components within the task to characterize volitional influences in detail. Many classic computational models are applicable to cognitive tasks in the VMP paradigm. For example, the drift diffusion model (DDM) (Ratcliff & McKoon, 2008) applies to most "two-alternative forced-choice (2AFC)" cognitive tasks and has spawned multiple variants for different specific tasks. In VMP-based research, researchers have begun using a variant of DDM—the EZ-diffusion model (Wagenmakers et al., 2007)—to fit visual search tasks (Luo et al., 2022; Luo, Wang, Gu, et al., 2024). Another study used another DDM variant—the diffusion model for conflict tasks (DMC) (Ulrich et al., 2015)—to fit conflict control tasks (Luo, Wang, & Zhou, 2024). These model fittings allow researchers to go beyond reaction time and error rate to analyze different processing components in cognitive tasks in detail. For example, DDM's drift rate parameter may relate to internal cognitive processing, the boundary parameter may relate to response bias, and non-decision time may relate to response execution. Such detailed model parameter analysis helps reveal how volition specifically affects different cognitive components to deepen understanding of volitional cognitive mechanisms.

In summary, although current VMP paradigm research has not yet distinguished between voluntary action and control belief, dissociating the two based on this paradigm is clearly feasible. Therefore, this study proposes to use the VMP paradigm to dissociate the external manifestation (voluntary action) and internal representation (control belief) of volition, combined with behavioral computational models and multiple neurophysiological techniques (including EMG, EEG, fMRI), to reveal their unique/common cognitive-neural mechanisms.

3.1 Research Framework and Objectives

This study aims to design variants based on the VMP paradigm to dissociate the roles of voluntary action and control belief in volition's influence on cognitive performance. It will further combine computational models and multiple neurophysiological techniques to reveal the common and separate cognitive-neural mechanisms through which voluntary action and control belief influence cognitive processing. The research framework and technical route are shown in Figure 3 [Figure 3: see original paper].

Study 1 will dissociate the effects of voluntary action and control belief in human volition through experimental design, and use computational models (the diffusion model for conflict tasks, DMC) to separate different components in cognitive processing, thereby revealing the unique and common influences of voluntary action and control belief on cognitive processing at the behavioral level.

Study 2 will use simultaneous high-temporal-resolution EMG and EEG recording techniques to reveal the unique and common dynamic changes of voluntary action and control belief at the muscle level (action) and brain level (belief) during their influence on cognitive processing, thereby revealing the dynamic neurophysiological mechanisms through which volition influences cognitive performance.

Study 3 will use fMRI technology to reveal the unique and common neural basis, functional connectivity, and activation patterns through which voluntary action and control belief influence cognitive processing at the blood oxygenation level-dependent (BOLD) signal level, thereby revealing the neural mechanisms through which different volitional components influence cognitive performance.

Figure 3. Research framework and technical route. Black boxes represent research questions, blue boxes represent research paradigms, green boxes represent research content, yellow boxes represent technical methods, and red boxes represent corresponding scientific questions. In this study, the influence of volition on cognitive performance is mainly evaluated through the effect of voluntary choice on Simon task performance. Color figures can be viewed in the online version of this article.

3.2 Key Experimental Paradigm Design

This study will use performance on the Simon task (Hommel, 2011; Simon & Rudell, 1967) as the indicator for evaluating volitional effects in the VMP paradigm. The Simon task is a classic conflict control task requiring participants to respond to stimuli presented on the left or right side of the screen while ignoring stimulus location. When stimulus location is inconsistent with the correct response effector location (e.g., stimulus appears on the left but correct response is with the right hand), cognitive performance declines (conflict occurs). This task was selected for the following reasons: First, the cognitive processes involved in the Simon task are relatively clear and easily separated and interpreted using neurophysiological techniques (Egner, 2008; Wang et al., 2021). Second, based on the VMP paradigm, voluntary choice has been found to facilitate Simon conflict resolution (Luo, Wang, & Zhou, 2024), indicating that the Simon task is sensitive to voluntary choice effects. Third, the Simon task is suitable for fitting with the specialized computational model for conflict tasks, DMC (Ulrich et al., 2015), which can separate different cognitive processing components in conflict tasks at the model level (e.g., Luo, Wang, & Zhou, 2024; Mittelstädt et al., 2022).

The specific experimental procedure is shown in Figure 4 [Figure 4: see original paper]. The experiment is conducted over two days. On Day 1, participants first complete the general VMP paradigm task to obtain the combined effects of voluntary action and control belief. After 24 hours (Day 2), participants complete two variants of the VMP paradigm—Variant isolates the unique effect of voluntary action while eliminating control belief effects; Variant isolates the unique effect of control belief while eliminating voluntary action effects (the order of completing the two VMP variants is counterbalanced between subjects).

The general VMP paradigm (Figure 4A) consists of cue, choice, and task phases (Luo et al., 2022). The cue phase uses different colors to indicate whether the current trial involves voluntary or forced choice. In the choice phase, participants either voluntarily select one of two pictures (voluntary condition) or must select a pre-specified picture (forced condition). The task phase then presents the selected picture as a task-irrelevant background while participants complete the Simon task. In the general VMP paradigm, participants both implement voluntary actions and hold control beliefs (i.e., believe their selected picture can appear as the background). The influence of volition on cognitive performance includes both voluntary action and control belief effects (combined effect).

VMP Variant (Figure 4B) aims to eliminate control belief while retaining only voluntary action effects. Its key difference from the general VMP paradigm is that the background picture in the task phase is always fixed and unchanging, unrelated to participants' choices in the choice phase. This breaks the "choice-outcome" causal relationship, leading participants to recognize that "the presented picture is not what I selected, not my own will; my choice cannot influence the outcome." In this variant, participants implement voluntary choice actions but lack control belief. The effectiveness of this manipulation in eliminating control belief has been validated in previous research (Luo et al., 2022).

VMP Variant (Figure 4C) aims to eliminate voluntary action while retaining only control belief effects. Its key difference from the general VMP paradigm is the absence of a choice phase—participants do not need to implement any selection action. The cue phase uses different colors to inform participants whether the upcoming picture is one they voluntarily selected yesterday or one they were forced to select yesterday (i.e., directly informing participants of the picture' s origin without requiring selection). The task phase then directly presents the picture background to initiate the Simon task. Thus, participants do not implement any voluntary action before cognitive task initiation but can establish control beliefs based on cue information—participants can recognize that "this picture is what I selected yesterday, representing my own will."

Figure 4. The volition-motivated performance (VMP) paradigm and its variants. (A) General VMP paradigm. Cue phase: Different colors indicate upcoming choice type (voluntary vs. forced choice). Choice phase: Press a key to voluntarily/forcedly select one of two pictures. Task phase: Complete Simon task with selected picture as background. In the general VMP paradigm, volition' s influence on cognitive performance includes both voluntary action and control belief effects (combined effect). (B) VMP Variant . Compared with the general VMP paradigm, the background picture in the task phase is always fixed

and unchanging, unrelated to choices in the choice phase. This variant aims to eliminate control belief while retaining only voluntary action effects. (C) VMP Variant . Compared with the general VMP paradigm, there is no choice phase. Cue phase: Different colors indicate upcoming picture type (yesterday' s voluntary choice vs. yesterday' s forced choice). Task phase: Present corresponding picture background for Simon task. This variant aims to eliminate voluntary action while retaining only control belief effects. Note: Fixation points of 0.5–0.8 s appear between phases (cue, choice, task), but are omitted from this simplified flowchart for clarity. Color figures can be viewed in the online version of this article.

3.3 Research Plan

(1) Study 1: Dissociating the Effects of Voluntary Action and Control Belief on Cognitive Performance

Based on the general VMP paradigm and its variants (see "3.2 Key Experimental Paradigm Design"), Study 1 will use behavioral experimental techniques to investigate the unique and common influences of voluntary action and control belief on cognitive task processing. The experiment is conducted over two days. On Day 1, participants complete the general VMP paradigm task to obtain the combined effects of voluntary choice and control belief. On Day 2 (24 hours later), participants complete two VMP variants (counterbalanced between subjects): VMP Variant eliminates control belief while retaining only voluntary action effects; VMP Variant eliminates voluntary action while retaining only control belief effects. The DMC model (Ulrich et al., 2015) will be used to fit Simon task performance to separate different components in cognitive processing, ultimately revealing how different volitional components influence different cognitive components at the behavioral level.

Primary measures and data analysis: Model-free analysis will focus on Simon task reaction time and accuracy, using a 2 (Simon stimulus congruency: congruent vs. incongruent) × 2 (choice type: voluntary vs. forced) × 3 (task type: general VMP paradigm, VMP Variant vs. VMP Variant) repeated measures ANOVA. Further DMC model analysis will separate task-relevant and task-irrelevant action activations in the Simon task (Luo, Wang, & Zhou, 2024). DMC main parameters include: (1) evidence accumulation rate for task-relevant action activation (c); (2) peak activation of task-irrelevant action (A); (3) time required for task-irrelevant action activation to reach peak (tpeak); (4) decision boundary (b); and (5) non-decision time (Rmean). The same ANOVA will be performed on optimal parameters.

Expected main results: Model-free analysis of Simon task reaction time should show a significant three-way interaction. Specifically, in the general VMP paradigm, voluntary choice overall accelerates Simon task reaction time while reducing the Simon effect; however, in VMP Variant , voluntary choice only accelerates Simon task reaction time overall, while in Variant , it only reduces the Simon effect. DMC model analysis should show main effects concentrated on peak activation of task-irrelevant action (A): the pattern in Variant should match the general VMP paradigm (voluntary choice reduces A), while Variant should not show this effect.

(2) Study 2: Dynamic Processes of Voluntary Action and Control Belief Influencing Cognitive Performance

Building upon Study 1' s findings, Study 2 will use high-temporal-resolution simultaneous EMG and EEG recording techniques to investigate the unique and common dynamic changes of voluntary action and control belief at the muscle level (action) and brain level (belief) during their influence on cognitive processing. It will further combine DMC model fitting to explore correspondences between different cognitive processing components and electrophysiological indicators, ultimately revealing the dynamic neurophysiological mechanisms through which volition influences cognitive performance. The paradigm is identical to Study 1 but with additional simultaneous EMG and EEG recording.

Primary measures and data analysis: Model-free and DMC model analyses are identical to Study 1. For EMG data, the focus will be on analyzing EMG signal magnitude in critical time windows: after cue presentation, after option presentation, before action implementation, and after Simon stimulus presentation. For EEG data, key components include the contingent negative variation (CNV) during the cue phase, readiness potential (RP) during the choice phase, and posterior contralateral negativity (N2pc) and lateralized readiness potential (LRP) during the task phase. Further analysis will combine temporal patterns of EMG and EEG signals for representational similarity analysis (RSA) to explore coupling between the two types of electrophysiological signals. Finally, individual difference analyses will be conducted based on electrophysiological indicators and DMC model parameters. Additionally, in paradigms investigating control belief alone, memory-related EEG components—frontal negative potential (FN400, Rugg & Curran, 2007)—will be examined, which may relate to control belief establishment.

Expected main results: Behavioral data should replicate Study 1 findings. For electrophysiological signals, we expect that in the general VMP paradigm, both CNV patterns during the cue phase and RP patterns during the choice phase can predict choice type and the influence of voluntary choice on cognitive performance. In VMP Variant , this predictive effect should be mainly in choice phase RP; in Variant , mainly in cue phase CNV. EMG and EEG signals within the same phase should be mutually predictive, but prediction accuracy should differ across variants: highest in the general VMP paradigm, moderate in Variant , and lowest in Variant .

(3) Study 3: Neural Basis of Voluntary Action and Control Belief Influencing Cognitive Performance

Replicating Study 1' s findings, Study 3 will use high-spatial-resolution fMRI technology to investigate the unique and common neural basis, functional connectivity between brain regions, and differences in brain activation patterns of voluntary action and control belief. It will further combine DMC model fitting to explore relationships between different cognitive processing components and brain activation, functional connectivity, and whole-brain or regional activation patterns, ultimately revealing the neural mechanisms through which volitional components influence cognitive performance. The paradigm is essentially the same as Study 1 but with adjustments suitable for fMRI research.

Primary measures and data analysis: Model-free and DMC model analyses are identical to Study 1. For fMRI data, general linear model results will focus on activation of SMA, insula (INS) during cue and choice phases, SMA and M1 during task phase (e.g., Wang et al., 2019), and reward-related brain regions during different phases (e.g., striatum, Leotti & Delgado, 2011; Murayama et al., 2015; Murty et al., 2015). Functional connectivity analysis will primarily use SMA and INS as seed regions to explore their functional connectivity with other brain regions. Brain activation pattern differences will be analyzed mainly through RSA to examine whole-brain activation patterns and activation pattern differences in SMA and INS across different phases (e.g., cue vs. choice phase). Additionally, in VMP Variant , memory-related brain region hippocampus (Murty et al., 2015) will be examined, which may relate to control belief establishment.

Expected main results: Behavioral data should replicate Study 1 findings. At the neural level, we expect that in the general VMP paradigm, activation level and patterns of SMA during both cue and choice phases can predict choice type and the influence of voluntary choice on cognitive performance, and brain activation patterns during the cue phase can predict those during the choice phase. In VMP Variant , similar predictive effects should be observed only in choice phase brain activation; in Variant , only in cue phase brain activation. Brain activation patterns within the same phase should not be mutually predictive between the two variants.

4 Theoretical Construction

Although previous studies have designed different paradigms to explore human volition from various angles, these studies all depend on immediately implemented voluntary actions (the external manifestation of volition), while individuals implementing voluntary actions simultaneously hold control beliefs (the internal representation of volition). Therefore, previous studies have not dissociated the external manifestation and internal representation of volition. This study proposes to directly separate voluntary action and control belief in the volitional process and, based on existing findings, construct the "dual-path hypothesis of human volition processing" (see Figure 5 [Figure 5: see original paper]). The following sections elaborate on the basis for this construction.

Figure 5. Dual-path hypothesis of human volition processing. Red content represents the control belief-related path, possibly related to the brain reward system, reflecting the motivational attribute of volition, which may influence response bias in subsequent cognitive tasks. Blue content represents the voluntary action-related path, possibly related to the brain action system, reflecting the action attribute of volition, which may influence response execution in subsequent cognitive tasks. Green content represents observable results or effects in the external world. Control belief is the basis for generating voluntary action, while the consistency between actual outcomes of voluntary action and expected outcomes in control belief in turn modulates the strength of control belief. Color figures can be viewed in the online version of this article.

First, in neuroscientific research on volition, findings can be divided into two categories: "action-related" effects and "action-unrelated" effects, suggesting that the external manifestation and internal representation of volition may have different neural bases. Specifically, (1) in the "action-related" aspect, EEG studies have found that voluntary actions can elicit stronger RP components (Khalighinejad et al., 2018; Libet et al., 1983), and RP may originate from SMA (Shibasaki & Hallett, 2006), suggesting SMA' s important role in volition expression. Additionally, fMRI studies have found SMA activation during voluntary action implementation (Penfield, 1954; Rizzolatti & Kalaska, 2013), and SMA activation level is related to sense of agency (Cavazzana et al., 2015; Kühn et al., 2013; Moore et al., 2010). These studies again emphasize the close connection between SMA and human volitional processes, with SMA being an important brain region related to action planning. (2) In the "action-unrelated" aspect, research has mainly found "reward-like effects" of volition expression (voluntary choice), i.e., when individuals anticipate making voluntary choices, reward-related brain regions such as the striatum are activated (Leotti & Delgado, 2011; Murayama et al., 2015; Murty et al., 2015), suggesting an association between volition expression and reward circuits. Expressing personal volition may enhance individual motivation, similar to obtaining rewards. Thus, neuroscientific research on volition suggests that human volitional effects may involve two paths: an action-related path (RP, SMA-related) and an action-unrelated path (reward-related).

Second, in behavioral computational modeling research on volition, changing control belief alters the pattern of volition' s influence on different cognitive components, suggesting that volition expression's influence on cognitive performance may involve two paths: one related to control belief and another unrelated to control belief (related to voluntary action). Specifically, in Luo et al. (2022), individuals expressed volition through voluntary choice, facilitating subsequent cognitive performance. More importantly, using the EZ-diffusion model (Wagenmakers et al., 2007), a variant of DDM, to fit the data and decompose the influence of voluntary choice on different cognitive components, results showed that for the non-decision time parameter, voluntary choice reduced non-decision time regardless of whether choice outcomes were controllable (i.e., regardless of control belief). Therefore, control belief may be unimportant in this process; what matters is the "action" of voluntary choice itself. Activation of the brain action system (e.g., SMA) triggered by voluntary action (Cunnington et al., 2002; Deiber et al., 1999) may generally facilitate subsequent action execution, thereby shortening non-decision time. For the decision boundary parameter, when individuals could control choice outcomes (i.e., held control belief), voluntary choice (compared with forced choice) lowered the decision boundary, but when individuals could not control outcomes (i.e., no longer held control belief), voluntary choice no longer affected the decision boundary. This suggests that control belief may make individuals' responses more liberal. Correspondingly, research has found that providing rewards also lowers individuals' decision boundaries, making responses more liberal (Bowen et al., 2020; Luo et al., 2020), which coincides with the aforementioned "association between volition expression and reward effects." Conversely, depressed patients not only fail to show the effect of reward lowering decision boundaries (Henriques & Glowacki, 1994) but instead show higher decision boundaries than healthy controls, i.e., more conservative responses (Lawlor et al., 2020), suggesting that loss of control belief may be related to "transient depressive states." Additionally, reinforcement learning model-based research has found that positive outcomes triggered by voluntary choice receive higher weight in the learning process compared with forced choice (Chambon et al., 2020). In summary, these studies again suggest that volitional effects may involve two aspects: voluntary action-related (influencing response execution) and control belief-related ("reward-like effects," influencing decision boundaries).

Third, based on the above previous research, this study directly separates the external manifestation (voluntary action) and internal representation (control belief) of volition and will further combine multimodal data including behavioral computational models (DMC model), electrophysiological signals (EMG and EEG data), and BOLD signals (fMRI data) to verify similarities and differences in effects produced by voluntary action and control belief, thereby inferring similarities and differences in their processing. This can provide direct evidence for the "dual-path hypothesis of human volition processing." Specifically, on one hand, we will focus on response-related indicators/brain regions—such as DMC model parameters including peak activation of task-irrelevant action (A) and time to peak (tpeak), non-decision time (Rmean), EMG data, choice phase RP and task phase LRP in EEG data, and activation of SMA, PMC, and M1 in fMRI data during cue, choice, and task phases—which may relate to the voluntary action path of volition. On the other hand, we will focus on non-response-related (e.g., reward) indicators/brain regions—such as DMC model parameters including decision boundary (b) and evidence accumulation rate for task-relevant action activation (c), CNV during cue phase and N2pc during task phase in EEG data, and activation of INS and striatum during cue and choice phases in fMRI data—which may relate to the control belief path of volition. In this study' s design (see Figure 4), the general VMP paradigm includes both voluntary action and control belief, VMP Variant eliminates control belief and retains only voluntary action, and VMP Variant eliminates voluntary action and retains only control belief. If the volitional process can indeed be distinguished into voluntary action and control belief paths, then response-related indicator/brain region result patterns should be mutually predictable between the general VMP paradigm and VMP Variant (both include voluntary action), while non-response-related indicator/brain region result patterns should not be mutually predictable between the general VMP paradigm and VMP Variant (the former includes control belief, the latter does not). Similarly, response-related indicator/brain region result patterns should not be mutually predictable between the general VMP paradigm and VMP Variant (the former includes voluntary action, the latter does not), while non-response-related indicator/brain region result patterns should be mutually predictable between the general VMP paradigm and VMP Variant (both include control belief).

Fourth, in the "dual-path hypothesis of human volition processing," the voluntary action path and control belief path are not completely independent but closely related and mutually influential. On one hand, only with control belief (believing voluntary action can influence the external world) will individuals be inclined to implement voluntary actions. This is also an important reason why individuals easily develop "illusions of control" (overestimating the causal link between voluntary action and external effects) (Langer, 1975; Thompson et al., 1998; Chen et al., 2010). Conversely, when individuals lose control belief, voluntary actions decrease or disappear, resulting in "learned helplessness" (Huys & Dayan, 2009; Maier & Seligman, 1976). On the other hand, outcomes triggered by voluntary actions also feedback to modulate control belief—if voluntary actions produce expected outcomes, control belief may be strengthened; conversely, if outcomes are inconsistent with expectations, control belief may be weakened (see Figure 5). VMP paradigm research has found (Luo et al., 2022) that the facilitating effect of voluntary choice on subsequent cognitive performance strengthens over time. This suggests that individuals' control beliefs are reinforced through repeated "voluntary choice-outcome confirmation" processes (selected pictures are presented as task backgrounds), and when voluntary choice cannot influence outcomes, the facilitating effect disappears. In summary, the volitional process is not static; its dynamic changes are reflected in the mutual modulation between the voluntary action path and control belief path.

Finally, it is important to note the issue of neural overlap: the neural basis hypothesized for the control belief path (reward system) lacks specificity—the reward system also participates in many other non-volitional cognitive processes, such as risk calculation (Rolls et al., 2022), motivation regulation (Kringelbach & Berridge, 2016), and habitual behavior (Wood & Rünger, 2016). The internal representation process of volition may involve multiple reward-related cognitive processes, such as generating behavioral motivation (Leotti et al., 2010), value calculation of action-outcome associations (Murayama et al., 2015), and reinforcement learning based on behavioral outcomes (Chambon et al., 2020). Therefore, the reward system may be a "necessary" but not "exclusive" neural basis for the control belief path. One possible mechanism is that although multiple different cognitive processes involve the reward system, these processes have different neural representation patterns within it. However, this study does not include other cognitive tasks related to the reward system and thus cannot verify whether control belief has a unique neural representation pattern. Future research should consider incorporating new variables that can activate the reward system (e.g., behavioral risk) and use dissociation designs with control belief variables, employing neural decoding analyses to verify the unique neural representation pattern of control belief.

The "dual-path hypothesis of human volition processing" expected to be constructed in this study (see Figure 5) can finely distinguish the roles of the external manifestation (voluntary action) and internal representation (control belief) of human volition. We hypothesize that the human volitional process involves simultaneous processing through two paths: one path related to voluntary action, reflecting the action attribute of volition (action anticipation, planning, execution, etc.), e.g., expressing volition may facilitate subsequent response execution; another path related to control belief, reflecting the motivational attribute of volition ("reward-like effects"), e.g., expressing volition may influence individuals' decision boundaries (response bias), and restricted volition may be related to depression, etc. In summary, human volition may possess dual attributes of action and motivation, forming a complete volitional process through dual-path processing.

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Note: Figure translations are in progress. See original paper for figures.