Control and Consequence: The Interplay of Agency and Affective Processing During Goal-Directed Behavior

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Index

Summary

The sense of agency describes the subjective experience of controlling our actions and their effects on the environment, constituting a core facet of the human self. By distinguishing between events within and outside our control, it supports goal-directed behavior, enabling us to pursue desirable outcomes and avoid negative ones. While previous research has emphasized sensory and cognitive determinants, relatively little work has examined the sense of agency in the context of goal-directed behavior, where actions are fundamentally related to the processing of affective information. This doctoral thesis addressed this gap, using behavioral and neurophysiological methods to investigate the interplay between the sense of agency and affective processes during goal-directed action. Across three studies, it examined how agency shapes the processing of affective information and how, in turn, outcome value influences the experience of agency.

In Study 1 (**Chapter 2.1**), electroencephalography revealed that choice autonomy enhances midfrontal low-frequency oscillations in response to both positive and negative instrumental feedback, indicating a valence-independent boost in outcome processing under a high sense of agency. Study 2 (**Chapter 2.2**) confirmed this enhancement and indicated that it was driven by the intrinsic value of self-determined action rather than the instrumental value of outcomes. While the effect of choice on early outcome processing was unaffected by valence, later stages revealed valence-specific biases. Complementary agency ratings across Studies 1 and 2 further indicated that participants were sensitive to varying degrees of control over distinct task components.

Study 3 (**Chapter 2.3**) investigated how outcome value influences self-reported sense of agency in a continuous motor control task. Results showed that affective feedback and sensorimotor noise additively influenced agency experience, with lower ratings for negative

than positive outcomes. Consistent with a negativity bias, negative outcomes had a stronger impact on agency experience than positive ones. Between-subject comparisons further revealed that individual differences in the locus of control and depressive symptoms modulated the influence of task-specific agency cues.

In summary, these studies highlight the relevance of affective information in the emergence of agency experience during goal-directed action. The findings demonstrate a reciprocal interplay between the sense of agency and affective processing. Choice-induced enhancements in the neural processing of affective outcomes emphasize the importance of agency in tracking the consequences of our actions and may reflect neurophysiological mechanisms through which agency experience supports adaptive behavior and learning from performance feedback. Conversely, the results support a multifaceted account of the sense of agency, shaped not only by low-level sensorimotor and high-level cognitive processes but also by affective information. Together, these findings advance our understanding of the determinants of agency and suggest neurophysiological mechanisms that may underlie its contribution to goal-directed behavior.

1 General Introduction

To successfully interact with our environment, it is important to assess how much influence we have over our actions and their effects. This requires a differentiation of effects that result from self-generated actions and those that lie outside of our control. The sense of agency refers to the experience of being in control over our actions and the effects that those actions have on our environment (Haggard, 2017).

Theoretical work (Moscarello & Hartley, 2017) and empirical findings (Luo et al., 2022) highlight the functional role of agency experience for guiding goal-directed behavior. Notably, the sense of agency shapes how we perceive, interpret, and respond to events in our environment (Haggard & Eitam, 2015). During goal-directed action, such events often convey feedback about whether an action successfully resulted in its intended outcome (Kaiser, Buciuman, et al., 2021). Successful actions typically lead to outcomes with positive affective value, whereas outcomes of unsuccessful actions are evaluated negatively. Adaptive behavior consequently emerges from repeating actions that yield positive outcomes and modifying or abandoning those associated with negative ones. Importantly, the sense of agency may not only shape how we process affective action effects but also appears to be influenced by the affective value of those outcomes (Kaiser, Buciuman, et al., 2021), suggesting a dynamic, reciprocal relationship between agency and affective processing. As affective processes have received relatively little attention in research on the sense of agency (Gentsch & Synofzik, 2014), however, the nature of this association is not clearly understood. The present thesis aims to investigate the interplay between the sense of agency and affective processes during goal-directed action. Drawing on insights from three empirical studies, it seeks to advance our understanding of the mechanisms through which agency experience may support adaptive, goal-directed behavior.

1.1 The Self and the Concept of Agency

The intuition of having a self is fundamental to human experience. Humans naturally perceive themselves as embodied individuals, distinct from, yet capable of intentionally interacting with their environment (Eitam & Liviatan, 2017). Centuries of philosophical attempts to conceptualize selfhood reflect the profound interest in understanding what constitutes the self and illustrate the central role it plays in the human psyche. Accounts historically range from Descartes' (1637) definition of a self-evident, indivisible entity (see Descartes, 1984) to Hume's (1739) proposition that the self is an illusion (see Hume, 2007). Although no consensus on the nature of the self has been reached to date (Klein, 2012b), phenomena such as the self-reference effect, where people tend to remember self-related information better than non-self-related information (Kihlstrom, 2012; Rogers et al., 1977), indicate the presence of distinct mechanisms underlying self-referential processing. These mechanisms are central to research questions across disciplines.

Investigations range from the development of the self in children (Kollakowski et al., 2023; Rochat, 2003), to an examination of its neurocognitive and neurobiological underpinnings (Gentsch & Schütz-Bosbach, 2011; Kaiser & Schütz-Bosbach, 2018; Murayama et al., 2015), and the search for mechanisms underlying disruptions in the sense of self in clinical conditions such as depersonalization (Sierra & David, 2011), schizophrenia (Klaver & Dijkerman, 2016), and depression (Davey & Harrison, 2022). With the growing interest in building humanoid robots, insights from these lines of research have also inspired approaches to develop an artificial self (Hafner et al., 2020; Kahl et al., 2022). In turn, methods from artificial intelligence research provide novel opportunities for exploring and understanding the human self (e.g., Möller et al., 2021; Sterzer et al., 2016).

As selfhood resists a simple, straightforward definition, studies typically examine analytically distinct subcomponents that influence an individual's self-representation. One of these components is the sense of agency (but see Klein, 2012a for other examples). The sense of agency describes the experience of controlling one's actions and their effects (Gallagher, 2000; Haggard, 2017). Rather than being a purely motoric phenomenon, the sense of agency constitutes a core experiential facet of the self by linking internal intentions with perceived effects in the environment, thereby facilitating goal-directed behavior and adaptive functioning in everyday life (see Kaiser, Buciuman, et al., 2021).

1.2 Determinants of the Sense of Agency

When interacting with the environment, sensory input provides continuous low-level feedback about action control. At a higher level, action intentions as well as situation-specific and long-term control beliefs influence agency experience. In addition, perceived control may be shaped by affective information, such as positive and negative outcomes signaling action success or failure. Thus, the sense of agency is shaped by sensory, cognitive, and affective processes operating at different levels (Kaiser, Buciuman, et al., 2021).

1.2.1 Sensorimotor and Cognitive Influences

At the lower level, the sense of agency reflects an immediate, pre-reflective feeling of control that heavily relies on sensorimotor information (Haggard, 2017). At this level, agency experience largely operates unconsciously and might usually only reach awareness when it is disrupted. For example, grabbing and drinking from a glass of water is usually performed effortlessly and without conscious reflection. Also, when selecting a product from a vending machine, we can typically directly relate our interaction with the user interface to the dispensed product. Yet, when accidentally knocking over the glass, or when the vending machine dispenses a product that we did not intend to purchase, agency experience is disrupted, reflected in a reduced experience of control over our actions and their outcomes.

Importantly, the experience of agency is shaped not only by low-level sensorimotor processes but also higher-level cognitive factors. As such, the opportunity to choose from alternatives, rather than being limited to a single option, is considered a key determinant of perceived control (Barlas & Obhi, 2013; Leotti et al., 2015), and individuals generally prefer having choice over having no choice (Ly et al., 2019). Recent findings suggest that this association is not solely driven by the objective controllability of outcomes but also by the subjective belief in one's ability to influence the environment through choice (Luo et al., 2022). This psychological effect also translates into behavioral benefits in task performance (Luo et al., 2022; Murayama et al., 2015), pointing to a link between choice-induced agency experience and successful behavior regulation.

1.2.2 Affective Influences and Feedback Valence

The affective dimension of the sense of agency has received relatively little attention in both empirical research and theoretical work (Gentsch & Synofzik, 2014; Villa et al., 2022). Crucially, however, much of human everyday behavior is goal-directed, meaning that we engage in certain actions to achieve desired outcomes or to avoid undesirable consequences. As previously illustrated by the example of grabbing a glass of water, the action (grabbing) serves the goal of drinking. Likewise, choosing an item from a vending machine (action) reflects the intention to fulfill a current need (goal; note that a more-fine grained differentiation of action-goal association would also be possible, for instance, by considering sub-steps such as opening the tap to fill the glass with water). In both cases, outcomes signaling action success carry positive affective value, while outcomes of unsuccessful actions are evaluated negatively. These outcomes serve as informative cues that reinforce or discourage the preceding action, thereby contributing to optimal action selection in the future (Karsh & Eitam, 2015). For instance, retrieving a desired chocolate bar from a vending machine signals action success, whereas receiving the wrong item may prompt behavioral adjustments. Since the experience of agency facilitates successful goal attainment (Haggard, 2017), a comprehensive understanding of the sense of agency requires an explicit consideration of affective processes in intentional, goal-directed action alongside sensory feedback and cognitive beliefs (Kaiser, Buciuman, et al., 2021; Wen et al., 2015).

1.2.3 Interindividual Differences: Examples of Locus of Control and Depression

Beyond the relevance of sensory, cognitive, and affective processes for moment-to-moment fluctuations in the sense of agency, stable inter-individual differences in the perceived ability to exert control over the environment, and to adaptively align behavior with personal goals, exist (Gentsch & Synofzik, 2014; Orgaz et al., 2013). Two examples of such differences are the locus of control (LoC) and depression.

The LoC reflects trait-like variations in the tendency to attribute events to internal or external causes. A high internal LoC is associated with the belief that events are subject to one's personal control (Nießen et al., 2022; Rotter, 1966). In contrast, a high external LoC reflects the tendency to attribute events to aspects outside of one's personal control, such as chance or fate. Accordingly, an internal LoC has been associated with a stronger sense of agency compared to an external one (Dewez et al., 2019).

Long-term differences in agency experience are also well-documented in psychopathology. Learned helplessness refers to the reinforced belief of lacking control over one's circumstances and is considered a hallmark of depression (Maier & Seligman, 2016). Repeated exposure to uncontrollable aversive events may result in a perceived inability to cope with stressors, resulting in passivity and reduced attempts to exert control. This loss of control may be sustained by biases in perception and cognition, including a preoccupation with negative thoughts, a reduced ability to use positive stimuli for adaptive behavior regulation, and an increased difficulty to disengage from negative information (Gotlib & Joormann, 2010). Thus, depression appears to be closely linked to a generalized reduction in agency experience (Vogel et al., 2024), which may be intricately related to changes in affective processing.

Taken together, the above examples illustrate that the sense of agency is shaped by sensory, cognitive, and affective processes whose impact may be modulated by inter-individual differences. While sensory and cognitive influences have been extensively studied (e.g., Barlas & Obhi, 2013; Gentsch et al., 2012; Gentsch & Schütz-Bosbach, 2011; Gentsch et al., 2015; Haggard et al., 2002; Hughes, 2015; Kaiser & Schütz-Bosbach, 2018; Schwarz, Weller, Klaffehn, et al., 2019; Weiss et al., 2011), affective determinants of the sense of agency remain less well understood. Notably, affective processes may help explain agency-related changes action regulation and the behavioral consequences of long-term changes in perceived control (Kaiser, Buciuman, et al., 2021). In light of these considerations, the present thesis investigates the sense of agency in goal-directed behavior and examines the role of affective processes alongside sensory and cognitive determinants.

1.3 Theoretical Models of the Sense of Agency

A number of theories have been proposed to explain the emergence and disruption of agency experience. These accounts differ in the determinants of the sense of agency they consider and in the phenomena they can explain (Gentsch & Schütz-Bosbach, 2015). The comparator model has been particularly influential in explaining how low-level processes shape agency experience, thereby accounting for the sense of agency in a narrow sense. Other frameworks, such as active inference and the cue integration account, approach the sense of agency at a broader level, incorporating the contributions of higher-level cognitive and affective factors alongside low-level sensorimotor information.

1.3.1 Comparator Model

Over the past two decades, the comparator model has emerged as the prevailing account for describing low-level sensorimotor aspects of the sense of agency (Blakemore et al., 2002; Frith et al., 2000). According to this model, the motor system generates internal forward models that predict the state of the motor system and the sensory consequences of motor commands. These predictions are then compared to actual sensory feedback. This comparison not only supports precise sensorimotor control but is also proposed to underlie the emergence of agency experience. Specifically, the model posits that agency experience arises when predictions generated by the motor system match the actual sensory feedback, whereas a mismatch, reflecting a prediction error, leads to a diminished sense of agency. Although this account has received much empirical support, evidence also suggests that comparing predicted and perceived feedback is neither sufficient nor necessary to induce agency experience (see Synofzik et al., 2008 for a detailed discussion). For instance, a match between intention and effect can also elicit a sense of agency (Schreiner et al., 2025), indicating that the comparator model cannot account for aspects beyond low-level sensorimotor control.

1.3.2 Active Inference and Cue Integration

A broader conceptualization of the sense of agency, incorporating not only sensorimotor processes but also prior beliefs, has been formalized within the active inference framework (Friston et al., 2013). This account extends prediction error minimization (referred to as free energy) beyond motor control. According to the active inference framework, agency experience may be influenced not only by adjustments within the sensorimotor system, but also by updating prior beliefs about one's ability to control actions and their effects, thereby integrating both low-level and high-level determinants of agency experience. This framework provides a formal account of how low-level and high-level processes contribute to the sense of agency. Yet, it does not specify how sensory and cognitive determinants may interact with affective processes to shape the sense of agency during goal-directed behavior.

Drawing on evidence for a dynamic integration of multiple sources of information, the cue integration account offers a framework for explaining how low-level and high-level processes jointly shape agency experience in a specific context (Synofzik et al., 2008; Synofzik et al., 2013). According to this account, the brain performs an optimal integration of different information (referred to as *cues*) that are available prior, during, and after an action, with a consideration of cues according to their availability and reliability for signaling control in a specific situation. Typically, low-level cues from the sensorimotor system are assumed to be most reliable. However, when their reliability is reduced (e.g., because movements are executed involuntarily rather than voluntarily; Moore et al., 2009), or when external cues are highly convincing (e.g., beliefs established through task instructions; Desantis et al., 2011), the latter may receive more weight in estimating agency in a given situation. Crucially, the cue integration framework is one of the first to explicitly describe the role of affective processes, next to sensory and cognitive factors, in shaping the sense of agency. Specifically, affective information, such as the valence of action outcomes, is proposed to shape the integration process by modulating the relative weighting of sensory and cognitive agency cues.

Both active inference and cue integration acknowledge that the sense of agency may manifest across multiple processing levels (Friston et al., 2013; Synofzik et al., 2013). These levels may be associated with distinct cognitive and neurophysiological mechanisms (Kaiser, Buciuman, et al., 2021). For example, the temporal and spatial contingency of actions and their effects may shape the sense of agency through pre-reflective processes that are grounded in the sensorimotor system. Conversely, trait-like control beliefs or choice autonomy involve higher-level cognitive processes that may be independent from moment-to-moment sensorimotor perception. A unified experience of agency is thought to emerge from integrating of these different types of information across processing levels (see also Kahl et al., 2022). In this context, the cue integration framework offers a valuable model of how sensory and cognitive cues interact with affective factors to shape the sense of agency during goal-directed action, thereby forming the conceptual foundation of the present thesis.

Importantly, the sense of agency and its underlying processes interact dynamically. While the experience of agency depends on the availability of different cues of control, it also influences how we process information in our environment. For instance, a large body of work has examined how the sense of agency affects the perception of actions and their outcomes (see e.g., Chambon et al., 2020; Gentsch et al., 2012; Kaiser & Schütz-Bosbach, 2018; Moore et al., 2009). To empirically investigate the interplay of agency and its underlying processes, various manipulations and measures are commonly employed.

1.4 Manipulations and Measures in Agency Research

As the previous chapter has highlighted, the sense of agency is a multifaceted phenomenon. Accordingly, experimental manipulations may target different facets of agency experience (Kaiser, Buciuman, et al., 2021). To induce high or low levels of agency, some studies modify the degree of (intentional) motor control (motor agency; Table 1) or the contingency of an action and its effect (outcome agency; Gentsch & Schütz-Bosbach, 2011; Kaiser & Schütz-Bosbach, 2018; Sidarus et al., 2017b). Conversely, others manipulate cognitive cues related to an action, for example by varying participants' choice autonomy across conditions (choice agency; Barlas & Kopp, 2018; Hassall et al., 2019; Murayama et al., 2015).

To examine the effects of these manipulations on different levels of processing, different measures are commonly employed. As the following sections outline, effects on explicit measures tend to be relatively consistent across manipulations. In contrast, effects on implicit measures are less consistent, suggesting they may differentially shape action and outcome processing (see Kaiser, Buciuman, et al., 2021).

Facet	Manipulation	Self-Report Measure
Motor agency	• Action vs. no action • Fluent vs. disrupted action • Voluntary vs. involuntary action	• Did you cause this action? • How much control did you have over the action?
Outcome agency	• Predictable vs. unpredictable effects • Contingent vs. non-contingent effects	• Did you cause this outcome? • How much control did you have over the outcome?
Choice agency	• Free vs. forced choice	• How much control did you have over the choice?

Table 1. Common approaches to manipulating and measuring facets of the sense of agency, targeting motor, outcome, and choice components of an action. Whereas motor and outcome agency are frequently assessed, measures of choice agency are less commonly reported. Note that the type of manipulation and self-report measure do not always coincide. For example, some studies manipulate motor or choice agency but assess their effects on outcome agency.

1.4.1 Explicit and Implicit Measures

To explicitly assess how different manipulations influence the sense of agency, participants are commonly asked to judge the author of an action and its outcome, or to rate their perceived control over the action and its effects (see Dewey & Knoblich, 2014). Results from these studies indicate that judgments of agency are sensitive to manipulations of processes during the preparatory phase of an action (e.g., free choices are associated with higher agency ratings than forced choices; Schwarz, Weller, Klaffehn, et al., 2019; Sidarus et al., 2017a), the fluency of an action itself (e.g., actions preceded by compatible primes are associated with higher agency judgments than actions preceded by incompatible primes; Sidarus et al., 2017a), and the contingency of outcomes with prior actions (e.g., Farrer et al., 2008; Sato & Yasuda, 2005) or primes (congruent action-effect primes are associated with higher agency ratings than incongruent ones; Gentsch & Schütz-Bosbach, 2011).

Notably, most studies using self-report measures assess the sense of agency with a single item, treating participants' responses as a global index without distinguishing which specific facet of agency is being evaluated (Moore, 2016). As a result, it remains unclear whether lower ratings in contexts involving, for example, externally determined actions reflect changes in perceived choice autonomy (choice agency), diminished outcome control (outcome agency), or a combination of both (Barlas & Kopp, 2018; Schwarz, Weller, Klaffehn, et al., 2019).

As the majority of studies have assessed self-reported agency in response to sensory action effects, such as sounds or simple visual stimuli, they offer limited insight into how affective feedback influences the sense of agency during goal-directed behavior. Yet, the valence of action outcomes has consistently been found to modulate agency ratings, illustrating the influence of affective processes on outcome perception (Gentsch & Synofzik, 2014; Kaiser, Buciuman, et al., 2021). Specifically, individuals tend to report higher agency for positive outcomes than for negative ones (Barlas et al., 2018; Gentsch et al., 2015). This valence bias has been suggested to arise from cognitive mechanisms that facilitate emotional distancing from undesired action effects (Yoshie & Haggard, 2017) and direct attention towards positive outcomes (Gentsch & Synofzik, 2014), thereby serving an adaptive function in maintaining self-esteem and general well-being (Takahata et al., 2012).

The opposing effects of positive and negative feedback on self-reported control have commonly been associated with a self-serving bias, characterized by an enhanced tendency to take responsibility for positive outcomes (Gentsch & Synofzik, 2014). However, most studies compare agency ratings only between positive and negative feedback, without including a neutral feedback condition (see Villa et al., 2022 for a detailed review). It therefore remains unclear whether the observed effect is primarily driven by positive feedback, by a stronger reduction in agency following negative feedback, or by both. A predominant effect of positive feedback would support the assumption of a self-serving bias. In contrast, a stronger effect of negative feedback would align with prospect theory, which posits that individuals weigh negative events twice as much as positive events (Kahneman & Tversky, 1979). A closer understanding of the nature of this bias, particularly in goal-directed task contexts, would offer valuable insights into the affective mechanisms that may underlie agency-related benefits in behavior regulation.

As previously outlined, long-term inter-individual differences may influence outcome evaluation beyond moment-to-moment fluctuations in perceived control. For example, generalized control beliefs have been suggested to affect the relative weighting of different information during cue integration (Desantis et al., 2012; Gentsch & Synofzik, 2014). Yet, how such beliefs interact with task-specific agency experience remains largely unexplored (Dewey & Knoblich, 2014; Yoshie & Haggard, 2013).

Trait-like variations in the LoC may influence the sensitivity of the sense of agency to outcome valence. As outlined in the cue integration account, low-level sensorimotor cues typically outweigh higher-level cues, such as prior beliefs or evaluative feedback. Stable tendencies to attribute action outcomes to internal or external sources might modulate this process. Some evidence indicates that LoC influences task-specific agency ratings (Carstensen, 2024). Furthermore, recent findings provide initial support for inter-individual differences in how various agency cues are weighted (Chang & Wen, 2025). However, it remains unclear how the LoC shapes the relative influence of affective feedback versus low-level sensorimotor information, particularly in goal-directed tasks where feedback carries motivational relevance.

Likewise, depression-related cognitive and perceptual biases were shown to increase the sensitivity to negative information (Gotlib & Joormann, 2010) and reduce the ability to learn from positive events (Must et al., 2013). Accordingly, the tendency to attribute positive outcomes to oneself appears to be diminished in individuals with depression (Gentsch et al., 2015), indicating changes in the processing of affective information (Gentsch & Synofzik, 2014). Yet, how depressive tendencies influence the integration of affective, sensory, and cognitive cues to shape self-reported agency experience during goal-directed behavior remains largely unexplored. Maladaptive changes in cue weighting may play a functional role in the development of learned helplessness and impaired behavioral regulation in depression (see Kaiser, Buciuman, et al., 2021), underscoring the importance of accounting for individual differences when investigating the interplay of the sense of agency and affective processes during goal-directed behavior.

To evaluate how agency experience influences implicit, pre-reflective stimulus processing, many studies measure intentional binding or sensory attenuation (Moore, 2016). Intentional binding refers to the perceived temporal attraction of actions and their effects, which is typically stronger under conditions of high compared to low agency (Haggard et al., 2002). Conversely, sensory attenuation describes the reduced perceptual or neural response to self-generated compared to externally generated action outcomes (Gentsch & Schütz-

Bosbach, 2015). Both effects may be linked to mechanisms described in the comparator model. Specifically, as outcomes of self-generated (or voluntary) actions are typically more predictable than those of externally generated (or involuntary) actions, they tend to be perceived as occurring closer in time to the action (intentional binding; Moore & Haggard, 2008), and their perceptual or neural impact is suppressed by the sensorimotor system (sensory attenuation; Frith et al., 2000; Gentsch & Schütz-Bosbach, 2015).

While both intentional binding and sensory attenuation have been interpreted as implicit markers of the sense of agency (see Moore, 2016), several studies suggest that they reflect more general phenomena related to the perception of causality and outcome predictability (Grünbaum & Christensen, 2020; Gutzeit et al., 2023; Kaiser, Buciuman, et al., 2021; Kirsch et al., 2019). Supporting this, sensory attenuation has been shown to reverse when predictability is matched for self-produced compared to other-produced outcomes (Kaiser & Schütz-Bosbach, 2018; but see Klaffehn et al., 2019). Likewise, agency-related differences in intentional binding may disappear when action-outcome relations are held constant across high and low agency conditions (Gutzeit et al., 2023). Thus, while intentional binding and sensory attenuation may reflect an enhanced sense of agency in some contexts, they may not validly serve as implicit markers of agency experience in others (Grünbaum & Christensen, 2020).

Moreover, studies on sensory attenuation primarily capture low-level aspects of agency experience, offering limited insight into later stages of outcome processing that reflect higher-level cognitive and affective processes (Kaiser, Buciuman, et al., 2021). Given the importance of the sense of agency for effective behavior regulation, investigating agency-related changes in outcome processing during goal-directed action requires the analysis of both sensory and evaluative markers during outcome presentation. To capture and differentiate these effects with high temporal precision, electroencephalography (EEG) is commonly employed (Kaiser, Buciuman, et al., 2021).

1.4.2 EEG and Neural Outcome Processing

EEG is a non-invasive method to measure electrical activity in the brain (Müller-Putz, 2020). The EEG signal primarily reflects voltage fluctuations in postsynaptic potentials of synchronously firing pyramidal cells in the cortex (Luck, 2014). This signal is recorded using electrodes placed on the scalp according to a standardized positioning system, which ensures consistent mapping between electrode positions and scalp locations. To assess the influence of experimental manipulations on outcome processing, many EEG experiments have focused on extracting event-related potentials (ERPs) or analyzing oscillatory activity during feedback presentation.

ERPs reflect the brain's response to specific sensory, cognitive, or motor-related stimuli (Luck, 2014). To analyze ERPs related to outcome evaluation, the EEG signal is time-locked to outcome presentation (i.e., the event) and averaged over multiple trials, resulting in positive and negative voltage deflections, known as ERP components. To compare outcome processing across experimental conditions, separate ERP waveforms are calculated for each condition, and differences in component amplitudes evaluated. A larger amplitude of a component in one condition compared to another reflects a stronger neural impact of the outcome.

To assess sensory feedback processing, early ERPs, such as the N100 component, can be analyzed. The N100 is a negative-going ERP with maximal amplitude between 100 ms and 150 ms after stimulus onset over parietal, central, and frontal scalp sites (Luck, 2014). In response to visual stimuli, it has been implicated in visuospatial attentional processing (Kaiser & Schütz-Bosbach, 2018; Krigolson et al., 2015). During outcome presentation, N100 amplitude has also been shown to vary with the predictability of action effects (Gentsch & Schütz-Bosbach, 2011;

Kaiser & Schütz-Bosbach, 2018) and the valence of action outcomes (Gentsch et al., 2015), suggesting that affective information is encoded already during early outcome monitoring.

After the sensory features of a stimulus have been processed, later ERP components reflect more elaborate stages of outcome evaluation. One component that has been linked to the evaluation of outcome value is the Reward Positivity (RewP). The RewP is characterized by larger deflections in response to positive and unexpected outcomes, compared to negative and expected ones around 250 to 350 ms after feedback presentation (Bellebaum & Daum, 2008; Proudfit, 2015). Functionally, it has been implicated in the representation of outcome value and the updating of reward prediction errors (e.g., Becker et al., 2014; Zheng et al., 2020). Furthermore, the RewP has been associated with feedback-guided learning, indicating that it reflects neural processes that facilitate goal-directed behavior (Williams et al., 2020).

In addition to ERP analyses, meaningful differences in outcome processing can also be examined by decomposing the EEG signal into its time-frequency components, representing the strength of activity at individual frequencies over time (Luck, 2014). The raw EEG signal contains oscillatory activity across different frequency bands, ranging from delta (< 4 Hz) to gamma (> 30 Hz) oscillations. These frequency bands are associated with distinct brain states. For example, alpha activity (8 – 13 Hz) is commonly observed during relaxed wakefulness, while delta oscillations are associated with deep sleep (Müller-Putz, 2020). Accordingly, changes in the power of individual frequency bands during outcome processing have been linked to alterations in cognitive, affective, and motivational processes (Luft, 2014). During outcome presentation, midfrontal theta (MFΘ) power is typically stronger for negative compared to positive feedback from 200 to 600 ms after feedback onset. Functionally, feedback-related MFΘ activity has been linked to cognitive control and conflict monitoring, thereby supporting performance monitoring and facilitating behavior regulation (Cavanagh et al., 2010; Kaiser, Belenya, et al., 2021).

While the neural generators of ERPs and time-frequency oscillations cannot generally be inferred from the electrode locations on the scalp (Luck, 2014), source localization analyses indicate that both the RewP and feedback-related MFΘ oscillations originate from the anterior cingulate cortex (ACC; Bellebaum & Daum, 2008; Cavanagh & Frank, 2014). The ACC is part of the medial prefrontal cortex and exhibits connections to the midbrain dopamine system, implicated in reward evaluation, as well as to prefrontal and parietal areas involved in decision-making and action selection (Monosov et al., 2020). Accordingly, the ACC is thought to integrate cognitive and affective information to support feedback-driven behavioral adaptation through the instantiation of cognitive control (Yeung et al., 2005).

As previously outlined, many studies have investigated how the experience of agency affects incidental outcome processing. In contrast, relatively few have examined the affective dimension of the sense of agency, specifically, how positive and negative action outcomes are processed during goal-directed behavior (Gentsch & Synofzik, 2014; Kaiser, Buciuman, et al., 2021). In these contexts, choice agency (i.e., contrasting self- with externally determined choices) has been linked to performance benefits (Hassall et al., 2019; Luo et al., 2022; Murayama et al., 2015). Given that affective action outcomes serve as powerful learning signals, such effects may be linked to changes in outcome monitoring. However, existing studies on how freedom of choice influences the processing of affective outcomes present mixed results.

To date, evidence on how choice agency influences the N100 during the processing of positive and negative instrumental feedback is lacking. However, one study has examined the effect of voluntary choice on the processing of emotionally positive and emotionally negative tones in a non-learnable task environment (Niu et al., 2023). This study found no differential effect of self-determined actions on the processing of positive and negative outcomes. Instead, the authors observed larger N100 amplitudes in response to positive compared to negative tones selectively following externally determined actions, indicating a differentiation of outcome value primarily in low-agency contexts. While these findings indicate that manipulations of motor agency and choice agency differentially shape early outcome processing (see findings on stronger N100 self-attenuation for positive compared to negative effects by Gentsch et al., 2015), both lines of research provide initial evidence that affective information can influence early sensory markers of neural outcome processing.

Several studies have investigated agency-related changes during evaluative stages of outcome processing, focusing on markers such as the RewP and MFϴ oscillations (e.g., Bellebaum et al., 2010; Hassall et al., 2019; Weismüller et al., 2019; Yeung et al., 2005; Zheng et al., 2020). In these studies, participants either made self-determined choices or performed externally imposed item selections and subsequently received feedback, presented in the form of monetary gains and losses (or the omission of gains). Results from both learnable (Bellebaum et al., 2010; Weismüller et al., 2019) and non-learnable (Chang et al., 2020; Hassall et al., 2019; Yeung et al., 2005) task environments indicate that RewP amplitude and MFϴ power are enhanced if outcomes follow self-determined choices. While this indicates that having a choice increases the neural impact of affective action outcomes, the cognitive mechanisms underlying this effect remain unresolved.

Given that the RewP and MFϴ have been associated with both outcome valuation and feedback-guided learning (Becker et al., 2014; Cavanagh et al., 2010; Mühlberger et al., 2017), enhanced processing during self-determined choices may reflect the increased value of self-determined outcomes, their greater instrumental relevance for future actions, or a combination of both. One possibility is that enhanced outcome processing results from the inherent valuation of making self-determined choices (Ly et al., 2019). Alternatively, if RewP amplitude and MFΘ power are primarily shaped by the instrumental significance of action outcomes, this might indicate affective outcome processing as a functional mechanism underlying agency-related performance benefits (see Kaiser, Buciuman, et al., 2021).

Another unresolved question is whether choice-induced agency experience differentially affects the processing of positive and negative feedback, or whether it equally enhances the neural impact of both types of feedback during learning. Evidence from a gambling task points toward a stronger impact of negative compared to positive feedback on MFΘ power following free choices (Zheng et al., 2020). In contrast, studies comparing active and observational learning in between-subject designs report a valence-independent increase in MFΘ power (Bellebaum et al., 2010; Weismüller et al., 2019). Clarifying the effect of choice on outcome processing during learning would shed light on whether implicit processes reflect a self-serving bias for positive feedback (Kaiser, Buciuman, et al., 2021), or whether goal-directed tasks might selectively enhance the processing of negative feedback (Bellebaum et al., 2010).

Taken together, current evidence points to a bidirectional relation between the sense of agency and affective processing. However, their interplay during goal-directed behavior remains insufficiently understood. Clarification is needed regarding the relative impact of positive and negative feedback and their interaction with sensory and cognitive cues in shaping the sense of agency. Conversely, it remains unclear how agency experience influences early sensory processing of affective outcomes, and findings on its influence on reward-related neural markers are mixed. Together, these open questions provide the rationale for the current thesis.

1.5 Aims and Scope of the Current Thesis

A large body of work has examined the sensory and cognitive aspects of the sense of agency (e.g., Barlas & Obhi, 2013; Gentsch et al., 2012; Gentsch & Schütz-Bosbach, 2011; Gentsch et al., 2015; Haggard et al., 2002; Hughes, 2015; Kaiser & Schütz-Bosbach, 2018; Schwarz, Weller, Klaffehn, et al., 2019; Weiss et al., 2011). While this has advanced our understanding of important determinants of agency experience in a given situation, much less is known about how affective processes, such as positive and negative outcomes linked to action success or failure, influence this process and, in turn, guide future behavior. To address this gap, this doctoral thesis presents three empirical studies that examine the interplay of the sense of agency and affective information during goal-directed action.

The first two studies (**Chapter 2.1** and **Chapter 2.2**) investigated whether the experience of agency influences the processing of positive and negative feedback in similar or distinct ways. Agency was manipulated by varying participants' freedom of choice during a reinforcement learning task and EEG was recorded to analyze oscillatory activity (**Chapter 2.1**, **Chapter 2.2**) and midfrontal ERPs (**Chapter 2.2**) in response to feedback. To disentangle the cognitive processes underlying agency-related differences in outcome monitoring, Study 2 further explored whether these effects arise from the inherent value of performing self-determined choices or from the instrumental relevance of outcomes for future actions (**Chapter 2.2**). EEG measures were complemented by explicit agency ratings. To differentiate between different facets of agency experience, we separately assessed participants perceived control over their action choices (choice agency) and over the outcomes of these choices (outcome agency).

Study 3 (**Chapter 2.3**) examined how the affective value of action outcomes, sensorimotor control, and stable, trait-like beliefs shape self-reported agency experience during goal-directed behavior. In this behavioral study, participants performed a motor control task in which task difficulty was varied across blocks by introducing sensorimotor noise (i.e., manipulating motor agency). After each trial, participants rated their sense of control (SoC) over the motor control task, providing an index of their sense of agency. To assess the relative impact of positive and negative feedback on these judgments, the task included an equal number of positive, negative, and neutral feedback trials. After the experiment, participants completed questionnaires measuring their internal and external LoC as well as depressive tendencies.

Together, these studies provide novel insights into a currently understudied area of research, the sense of agency in goal-directed action. By examining how freedom of choice influences the neural processing of affective action outcomes, this work sheds light on potential mechanisms through which the sense of agency supports behavior regulation. Conversely, by investigating how affective outcomes influence agency experience in relation to sensory and cognitive cues, it advances our understanding of how different sources of information are integrated to shape agency experience during goal-directed action. Taken together, the findings extend our knowledge of both the determinants of agency experience and its functional relevance for adaptive behavior regulation, highlighting individual and situational factors that may facilitate, or hinder, successful goal achievement.

2 Cumulative Thesis

This chapter presents three peer-reviewed and published empirical studies (**Chapter 2.1**, **Chapter 2.2**, **Chapter 2.3**).

2.1 Freedom of Choice Boosts Midfrontal Theta Power During Affective Feedback Processing of Goal-Directed Actions

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Author Contributions:

Maren Giersiepen conceptualized and administered the study, programmed the experiment, collected, analyzed, interpreted, and visualized the data, and wrote the manuscript. Simone Schütz-Bosbach acquired funding, commented on the manuscript, and contributed to study conceptualization and the interpretation of the results. Jakob Kaiser acquired funding, commented on the manuscript, and contributed to study conceptualization, programming of the experimental code, formal analysis of the data, and the interpretation of the results.

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Freedom of choice boosts midfrontal theta power during affective feedback processing of goal-directed actions

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ABSTRACT

Sense of agency, the feeling of being in control of one's actions and their effects, is particularly relevant during goal-directed actions. During feedback learning, action effects provide information about the best course of action to reinforce positive and prevent negative outcomes. However, it is unclear whether agency experience selectively affects the processing of negative or positive feedback during the performance of goal-directed actions. As an important marker of feedback processing, we examined agency-related changes in midfrontal oscillatory activity in response to performance feedback using electroencephalography. Thirty-three participants completed a reinforcement learning task during which they received positive (monetary gain) or negative (monetary loss) feedback following item choices made either by themselves (free-choice) or by the computer (forced-choice). Independent of choice context, midfrontal theta activity was more enhanced for negative than positive feedback. In addition, free, compared to forced choices increased midfrontal theta power for both gain and loss feedback. These results indicate that freedom of choice in a motivationally salient learning task leads to a general enhancement in the processing of affective action outcomes. Our findings contribute to an understanding of the neuronal mechanisms underlying agency-related changes during action regulation and indicate midfrontal theta activity as a neurophysiological marker important for the monitoring of affective action outcomes, irrespective of feedback valence.

1. Introduction

Sense of agency, the feeling of being in control of one's actions and their perceivable results in the environment (Gallagher, 2000; Haggard, 2017; Haggard & Eitam, 2015), is crucial in constructing a sense of self (Gentsch & Schütz-Bosbach, 2015). Contingent upon situational demands, moment-to-moment fluctuations in agency experience continuously affect an individuals' self-representation (Gallagher, 2013; Haggard, 2017; Hommel, 2015; Verschoor & Hommel, 2017). To manipulate the sense of agency, many studies have asked participants to either freely choose from different response options or forced them to select a predetermined option (e.g., Barlas et al., 2017; Barlas & Kopp, 2018; Barlas & Obhi, 2013; Hassall et al., 2019; Murayama et al., 2015; Zheng et al., 2020). The current study extends previous work by investigating how freedom of choice influences the neural processing of performance feedback in a motivationally salient learning context.

Understanding the functional role of freedom of choice in the emergence of agency experience is most relevant in situations where agents need to effectively interact with their environment to accomplish their goals (Leotti et al., 2015; Ly et al., 2019; Murayama et al., 2015). When trying to reach a goal, affective feedback in the form of positive and negative action effects, signals whether behavioral adjustments are required to attain desired outcomes and avert undesirable ones in the future. An agents' belief in the ability to effectively translate the presented feedback into subsequent action adaptation thus likely contributes to its utilization during goal-directed actions (Moscarello & Hartley, 2017).

Functional magnetic resonance imaging (fMRI) studies suggest that the anterior cingulate cortex (ACC) facilitates the evaluation of affective feedback (e.g., Bush et al., 2002; Calabro et al., 2023; Luft, 2014; Marco-Pallarés et al., 2007). These findings are corroborated by electroencephalographic (EEG) recordings that provide a direct measure of brain activity with high temporal precision (Foti et al., 2015; Kaiser et al., 2021; Luft, 2014). To date, most EEG studies have focused on event-related potentials (ERPs) to assess the neuronal mechanisms of affective feedback processing. Among them, the feedback-related

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negativity (FRN) is the most frequently examined ERP (also referred to as Reward Positivity; Luft, 2014; Proudfit, 2015). The FRN is a negative going component with higher amplitude for negative than positive feedback, commonly peaking 250–350 ms after feedback onset (see Luft, 2014). Consistent with its maximal deflection at midfrontal scalp sites, the ACC has been proposed as the neural generator of the FRN (Hauser et al., 2014). Importantly, some studies indicate an increase in FRN amplitude for self-, rather than externally determined action outcomes during reinforcement learning, indicating an influence of agency on feedback processing in the ERP domain (e.g., Bellebaum et al., 2010; Weismüller et al., 2019; Yeung et al., 2005).

While ERPs provide valuable insights into the influence of agency on affective feedback processing, recent research has highlighted the crucial role of oscillatory activity for feedback processing (Beste et al., 2023; Cavanagh & Frank, 2014; Luft, 2014). More specifically, midfrontal oscillations in the theta range (4–7 Hz) are believed to represent a central mechanism for the updating of task-relevant information, indicated by an increase in oscillatory power in response to performance feedback (e.g., Cavanagh et al., 2010; Kaiser et al., 2021; Luft et al., 2013; Weismüller et al., 2019). During feedback presentation, negative action outcomes typically evoke larger theta power than positive outcomes (e.g., Kaiser et al., 2021; Luft et al., 2013). This power increase for negative outcomes has been suggested to partially reflect cognitive control processes associated with the ACC (Cavanagh & Frank, 2014; Holroyd & Umemoto, 2016; Kaiser et al., 2019; Luft et al., 2013; Weismüller et al., 2019; Zheng et al., 2020). In addition, several studies report a relation of feedback-induced midfrontal theta power and learning success, with mixed findings whether this association is driven only by negative (Luft et al., 2013; Van de Vijver et al., 2011) or both negative and positive feedback (Kaiser et al., 2021).

Given that agency experience enhances our ability to effectively reach our goals (Cordova & Lepper, 1996; Eitam et al., 2013; Murayama et al., 2015), as well as the importance of midfrontal theta oscillations for the processing of affective feedback, it is reasonable to assume that activity in this frequency range is sensitive to the experience of agency during goal-directed actions. Thus, changes in agency experience are expected to modulate feedback-driven midfrontal theta activity. Yet, most previous studies investigated how sense of agency influences the processing of arbitrary, neutral action outcomes, for example, by letting participants actively produce or passively perceive sensory action effects without any rewarding or punishing value (e.g., Gentsch & Synofzik, 2014; Haggard & Eitam, 2015; Kaiser et al., 2021). In these studies, actively produced, compared to passively perceived action effects typically elicit decreased neural reactivity (Brown et al., 2013). This attenuation effect is assumed to result from the neural cancellation of sensory feedback that can be predicted for self- but not externally induced action effects (Gentsch & Schütz-Bosbach, 2015). However, neutral, in contrast to instrumental affective outcomes, carry no rewarding or punishing value and may thus be less relevant for subsequent action selection. Therefore, results from studies employing non-affective action outcomes leave open how the sense of agency influences the processing of affective feedback in motivationally salient contexts.

To study how freedom of choice and associated agency experience influence feedback processing during goal-directed actions, experimental tasks should ensure that action outcomes carry positive and negative affective value and implement reward schemes that provide agents with the possibility to learn item-outcome associations to adapt their behavior accordingly (Eitam et al., 2013; Moscarello & Hartley, 2017). However, most studies investigating the influence of sense of agency on affective feedback processing employed randomized reward schemes at chance level, with half of the trials providing positive and negative feedback, respectively (e.g., Gentsch et al., 2015; Hassall et al., 2019; Mei, Yi, et al., 2018; Mühlberger et al., 2017; Yeung et al., 2005; Zheng et al., 2020). This offers the advantage of ensuring an equal number of trials with positive and negative feedback, which enables us to consider expectancy effects that might influence the processing of affective action outcomes. However, when actions result in reward or loss feedback solely by chance, the instrumental value of action outcomes decreases. This renders performance feedback uninformative for selecting the best course of action, thereby potentially reducing the perceived relevance of action outcomes in these studies. As feedback-evoked midfrontal theta activity seems to be particularly relevant during goal-directed actions (Cavanagh et al., 2010), the neural processing of affective feedback conceivably differs, if action outcomes can be used to determine the best course of action, compared to when not.

From the studies focusing on agency-related changes in affective feedback processing, only a few have specifically investigated valence-specific effects. These studies aimed to determine whether the sense of agency primarily impacts the processing of negative or positive performance feedback. However, among the studies that explored this, inconsistent effects were found (see Kaiser et al., 2021). For midfrontal theta activity, two studies report an increased impact of feedback, operationalized as monetary gains and losses, for active compared to passive choices (Weismüller et al., 2019; Zheng et al., 2020). Whereas the effect of feedback valence did not differ for active and passive choices in one study (Weismüller et al., 2019), the other study found a larger impact of choice on theta power for negative, compared to positive feedback (Zheng et al., 2020). Thus, it is currently unclear, whether freedom of choice leads to a general enhancement, or a valence-specific bias in the processing of affective feedback. A selective increase in midfrontal theta power for either positive or negative feedback could be seen as evidence that sense of agency induces an affective processing bias. For example, some studies suggested that humans feel more agency for positive than negative action outcomes, suggesting a self-serving processing bias for positive feedback (Forsyth, 2008; Gentsch et al., 2015; Kaiser et al., 2021).

Building upon previous work, the current study aimed to clarify how the sense of agency, manipulated by varying freedom of choice in a within-subjects design, influences the processing of affective feedback in a motivationally salient context. Using EEG, we measured neural reactivity to positive and negative feedback while participants completed a reinforcement learning task. Importantly, whereas in most previous studies, reward and punishment was determined by chance alone, we implemented a reward schedule that allowed participants to maximize their rewards through learning. By granting a performance-dependent monetary bonus at the end of the experiment, we additionally warranted the affective value of action outcomes. Building on previous work (Cavanagh & Frank, 2014; Luft et al., 2013; Weismüller et al., 2019; Zheng et al., 2020), we expected a larger increase in theta power for monetary losses compared to gains. In addition, as performance feedback was informative for subsequent action selection during free-, but not during forced-choice blocks, we expected an increase in feedback-induced midfrontal theta activity, if participants were endowed with the freedom to choose between different response options (Weismüller et al., 2019; Zheng et al., 2020). Crucially, we also examined whether the effect of choice differed for positive and negative feedback. We thereby aimed to clarify whether freedom of choice induces a valence-specific processing bias, meaning a selective increase in the processing of either positive or negative feedback, or a general enhancement in the processing of affective action outcomes. We complemented our neurophysiological measure on agency-related differences in feedback processing with explicit agency ratings. Participants were asked to indicate whether they felt they had freedom to choose their actions or influence the amount of money they gained. To conclude, using explicit agency judgments and EEG to measure the neural activity during the presentation of affective feedback following free and forced choices in a reinforcement learning task, we aimed to elucidate the role of sense of agency during goal-directed actions.

2. Methods

2.1. Participants

Eligibility criteria for participation included English language proficiency, an age between 18 and 45 years, absence of acute neurological or psychiatric disorders, no current intake of medications affecting neural functioning, and normal or corrected-to-normal visual acuity without color vision deficiencies. Thirty-three participants (22 female, 11 male, 30 right-handed) participated in the study. After terminating data collection, one participant was excluded due to an exceedingly high error rate across free- and forced-choice blocks (i.e., > 2.5 standard deviations from the mean; 51.99%). Two additional participants were excluded after pre-processing, owing to noise artifacts that resulted in less than 50 trials for the main analysis in at least one experimental condition (see Data preprocessing). The final test set thus consisted of 30 participants (20 female, 10 male, 27 right-handed) with a mean age of 24.8 years ($SD = 4.1$), the sample size being in line with previous studies in this field (e.g., Kaiser et al., 2021; Luft et al., 2013; Weismüller et al., 2019; Zheng et al., 2020). Participants were compensated with participation credits or financial reimbursement (9 Euro per hour). In addition, participants received a performance-dependent bonus of up to 8 Euro (see Procedure and experimental task). Study approval was obtained by the ethical board of the Department of Psychology at the Ludwig-Maximilians-University Munich and all participants provided written consent at the beginning of the experimental session.

2.2. Apparatus and measurement setup

EEG recording employed 64 active electrodes, positioned according to an extended version of the international 10–20 system (actiCAP snap, Brain Products, Munich, Germany). Electrode FCz was used as an online reference and one additional ground electrode was placed at location Fpz. Data was recorded using BrainAmp DC amplifier (BrainVision) and digitized with a sampling rate of 500 Hz. An online bandpass filter with half-amplitude cutoffs of 0.016 Hz and 250 Hz was applied. Electrode-to-skin impedances were kept below 20 kΩ throughout the experiment.

2.3. Procedure and experimental task

The experimental task was written in MATLAB R2020B, using Psychophysics Toolbox extensions (Psychtoolbox Version 3; Brainard & Vision, 1997). Participants were seated approximately 90 cm in front of a 24-inch monitor on which the task was presented. To study changes in affective feedback processing as a function of sense of agency, we implemented a reinforcement learning paradigm, varying the degree of choice within participants (free-choice/forced-choice) across blocks (Fig. 1). All stimuli were presented on a grey background, with a visual angle of 1.2°.

At the start of each trial, participants had to fixate the white cross presented at the center of the screen (1.5 s). Subsequently, two items in the form of differently colored squares appeared horizontally aligned adjacent to the center (1.0 s). During free-choice blocks, participants were asked to choose one of the two items by pressing the left- or the right-arrow key with their right index finger. During forced-choice blocks, the computer pre-selected one item, indicated by a white rectangle around one of the squares, and participants' only option was to confirm the computer's choice with the corresponding button press. Following keystrokes, participant choices were confirmed with a black rectangle around the selected stimulus for 1.0 s. Next, participants were presented with feedback for item selections (1.0 s). For each block, one of the two colored squares was randomly allocated to be the high-value item, while the other one was allocated to be the low-value item. High-value item selections resulted in a gain of 4 cents (positive feedback) in 75% of all trials. The selection of the low-value item resulted in a loss of 2 cents (negative feedback) in 75% of all trials. Employing gains twice as large as losses was based on research showing that humans value losses approximately twice as much as gains (Proudfit, 2015; Tversky & Kahneman, 1992). Participants were naïve to the allocated action-effect probabilities at the start of each block. To maximize gains and minimize losses, they thus had to use the feedback to learn the item-outcome associations within each block. The implemented probabilities allowed participants to build stable outcome predictions, while still encouraging the exploration of all response options.

Importantly, participants could only freely choose between the items during free-choice blocks (high agency), but not during forced-choice blocks (low agency). If participants failed to give a response or selected the item not chosen by the computer, they were told to 'Respond Faster!' or that the 'Wrong Key [was] Pressed!'. To warrant motivational salience of action effects, participants received the reward they earned during their two most successful free- and forced-choice blocks in the end of the experiment. Depending on participants' (non-) response, trial durations varied between 3.5 s and 4.5 s. Participants completed a total of 640 trials, split into eight blocks, consisting of 80 trials each. There were four blocks for both the free-choice and the forced-choice condition, resulting in 320 trials per agency condition. A switch between free- and forced-choice blocks occurred after every second block. All participants started with two free-choice blocks. Unbeknown to participants, the trial-wise location of the high-value and low-value item as well as the computer choices during forced-choice trials exactly mimicked those of the free-choice trials from the two preceding blocks, thereby resulting in the same order and frequency of high-value and low-value item selections in free- and forced-choice blocks. Participants' confirmation of externally determined item choices ensured that they paid attention to item selections made in forced-choice blocks and that they performed the same motor actions in both agency conditions. Consequently, the only aspect differing between the two conditions was whether participants were endowed with the freedom to choose or not.

The colors of the items were randomly selected from eight previously

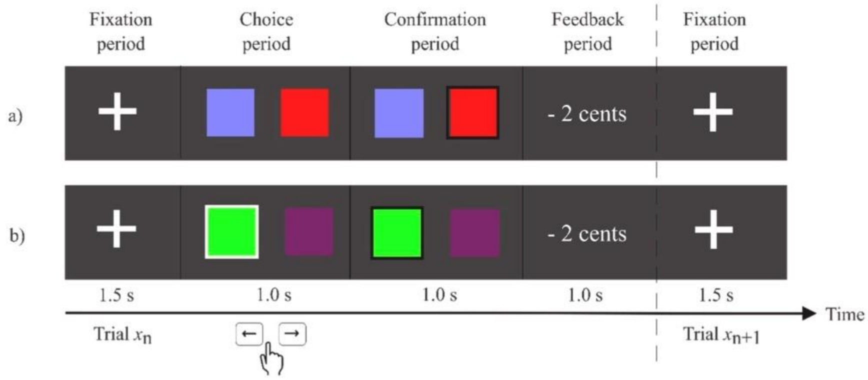

Fig. 1. Schematic task overview. After fixation, participants either a) chose one of the two items presented on screen (free-choice), or b) selected the item chosen by the computer (forced-choice), indicated by a white rectangle around the stimulus. Choices were confirmed with a black rectangle around the selected item. Probabilistic affective feedback was presented as action effect. Free- and forced-choice trials varied across blocks. Item colors and associated gain and loss probabilities remained the same within but changed between blocks.

generated stimulus pairs, such that each stimulus pair was used in exactly one block per participant. To ensure good stimulus discriminability, and to prevent illusory carry-over effects from learning in previous blocks, all stimuli were created to be maximally perceptually different to each other and the background by reference to the CIELAB color space (Holy, 2022). Within each block, both items occurred equally often on the left and right side of the screen in a randomized order. In addition, choosing the high- or low-value item resulted in the corresponding positive or negative feedback in 75% of the trials on each side.

At the end of each block, participants were informed about their monetary gain in the current block and the choice context of the following block. In addition, participants were asked to indicate their agency experience in a paper-pencil format. Participants reported their agreement with two statements (statement 1: 'I was free to choose any item I wanted this block.'; statement 2: 'I was in control over the amount of money I gained in this block.') on a bipolar quasi-continuous scale (Chimi & Russell, 2009), ranging from *Strongly Disagree* to *Strongly Agree*. The items were adapted from previous studies using explicit agency measures (Beyer et al., 2017; Dewey & Carr, 2013). While statement 1 asked participants to state in how far they could influence item choices (choice agency), statement 2 asked them to indicate the degree to which they had control over the feedback they received (outcome agency). Assessing outcome agency in addition to choice agency owed to findings from prior research, showing that the extent of self-determined action influences an agents' perceived control over action outcomes (Barlas et al., 2018). Statement 2 also served to control for participants' potential insight into the pattern of computer choices during forced-choice blocks. In case participants noticed that computer selections mimicked their choices from previous free-choice blocks, and were therefore always contingent on participant behavior, they would be expected to experience similar outcome agency during free- and forced-choice blocks. After filling out the questionnaire, participants could proceed to the next block in a self-paced manner.

The experimental session took approximately 1 h and 45 min per participant. To allow familiarization with the task, all participants completed 10 free-choice and 10 forced-choice practice trials in the beginning of the experiment. To prevent insight into the implemented reward probabilities and the identical sequence of free-choice and forced-choice trials, item locations, computer choices, and feedback valence were determined randomly during practice trials.

2.4. Data analysis

2.4.1. Behavioral analysis

To assess learning progress within free-choice blocks, we categorized each trial as correct (i.e., high-value item choice) or incorrect (i.e., low-value item choice) and summarized performance as the cumulative proportion of correct actions over bins of five trials. We used a paired samples t-test (two-sided) to evaluate whether participants successfully acquired the implemented item-outcome associations, testing whether the proportion of participants' high-value item choices was significantly larger than the proportion of low-value item choices across all free-choice blocks.

The experimental task was designed to only differ in the degree of choice across conditions. However, it is important to consider that free- compared to forced-choice trials may differ in reaction times. These variations in motor activation timing could potentially influence neuronal activity during feedback presentation in the progression of the trial. In addition, a high occurrence of non-responses in either the free- or forced-choice blocks could unintentionally introduce a disparity in the frequency of positive and negative feedback between the different agency conditions. We therefore tested for differences in reaction times and the proportion of positive and negative feedback between free- and forced-choice blocks using paired samples t-tests (two-sided).

To evaluate whether our manipulation was successful in inducing either high or low levels of sense of agency and to assess whether participants' feeling of control over action outcomes varied between free- and forced-choice blocks, a repeated measures analysis of variance (ANOVA) with the factors CHOICE (free-choice/forced-choice) and RATING (choice agency/outcome agency) was performed on the questionnaire responses. To this end, participants' agency ratings were quantified as percentages, computed as the degree of agreement with statement 1 and statement 2 for free- and forced-choice blocks separately (Wegner & Wheatley, 1999). Greenhouse Geiser corrections were applied if sphericity was violated. Interaction effects were subsequently examined using paired-samples t-tests (two-sided), and test statistics corrected for multiple comparisons using Holm's method (1979).

Statistical tests employed an alpha level of .05 and effect sizes for all tests are reported using Cohen's d (small effect: $d = 0.20$; medium effect: $d = 0.50$; large effect: $d = 0.80$) or partial-eta-squared (small effect: $\eta_p^2 = .01$; medium effect: $\eta_p^2 = .06$; large effect: $\eta_p^2 = .14$; Cohen, 1988). We additionally examined the data by estimating Bayes Factors (*BF*) for individual tests using Bayesian Information Criteria (Wagenmakers, 2007). *BF*s quantify the evidence for the null hypothesis (H_0) as well as the alternative hypothesis (H_1), and allow to evaluate the likelihood of observing the alternative hypothesis ($\mu_1 \neq \mu_2$) compared to the null hypothesis ($\mu_1 = \mu_2$; weak evidence for H_1: $BF_{10} = 1–3$; positive evidence for H_1: $BF_{10} = 3–20$; strong evidence for H_1: $BF_{10} = 20–150$; very strong evidence for H_1: $BF_{10} > 150$; Raftery, 1995). Behavioral analyses were performed in MATLAB R2020B and RStudio.

2.4.2. Time-frequency analysis

2.4.2.1. *Data preprocessing.* We performed data pre-processing offline within MATLAB R2020B, using custom-written scripts and Fieldtrip toolbox (Oostenveld et al., 2011). The EEG signal was filtered using a Butterworth Infinite Impulse Response two-pass filter (high-pass: 1.0 Hz; low-pass: 40 Hz; roll-off: 6 dB/octave) and re-referenced to an average of all active electrodes (see Kaiser et al., 2021). Trial-wise epochs of 4500 ms, from 2000 ms prior to 2500 ms post feedback onset, were extracted. To save processing time, the data were down-sampled to 250 Hz. Artifacts due to eyeblinks and eye movements were identified using independent component analysis (using the runica algorithm implemented in Fieldtrip) and removed, resulting in the exclusion of one to four components ($M = 2.6$ components, $SD = 0.8$) per participant. The remaining components were projected back to the data at channel level. To identify trials with substantial noise, voltage deflections exceeding $\pm$ 100 μV were identified in the baseline corrected dataset, using 200 ms prior to feedback onset as baseline. Noisy trials were subsequently removed from the non-baseline corrected data, resulting in a mean removal of 5.3% ($SD = 3.8$, range: 0.2–16.7) of all trials. Further, one to two exceedingly noisy electrodes were removed for four participants ($M = 1.3$ electrodes, $SD = 0.5$) and replaced with spherical spline interpolation using the Fieldtrip function *ft_channelrepair* (see also Perrin et al., 1989). Next to removing noisy data, trials for which participants did not receive feedback (either because they did not respond within the 1000 ms time window of stimulus presentation, or because they chose the item not indicated by the computer during forced-choice blocks) were excluded from further analyses, resulting in an average removal of 16.4 trials ($SD = 17.1$, range: 1–72).

Successful reinforcement learning implies a gradual decrease in low-value item choices within each block. This pattern was also reflected in participants' behavior in the current study (see Behavioral results). As expected, over the course of each block, participants selected high-value items most of the time, leaving only an exceedingly low number of trials with low-value item choices. We thus focused our main statistical analysis on trials with high-value item choices, resulting in an average exclusion of 83.9 trials ($SD = 67.1$, range: 12–288). Finally, participants were excluded from subsequent analyses, if less than 50 trials were retained for the main analysis in at least one condition after preprocessing (a priori criterion, see Kaiser & Schütz-Bosbach, 2021), leading to an exclusion of two participants. The final dataset comprised of 30 participants with an average of 521.4 trials (SD = 50.6, range: 436–602). Condition wise averages are depicted in Table 1.

To increase topographical specificity, a Surface Laplacian, using the spherical spline method (Perrin et al., 1989) with a polynomial degree of 10 (Cohen, 2014), was applied to the pre-processed data (*ft_scalpcurrentdensity*). Condition-wise averages for the time-frequency data depicting midfrontal oscillatory activity were calculated over a time window from –500 ms to2000 ms relative to feedback onset. This time window exceeded the time period of interest to avoid edge effects (Cohen, 2014). For precise localization of frequency information in time, Morlet wavelet convolution was applied, with cycles and frequency linearly increasing from three to eight, and 2 Hz to20 Hz, respectively (Cohen, 2014; Kaiser & Schütz-Bosbach, 2021). Each sample from the time-frequency epochs of all electrodes was baseline corrected using the average power over all trials and converted to the decibel (dB) scale (dB = 10 *log10[power/baseline]), with a baseline window ranging from −300 ms to −100 ms relative to feedback onset (Kaiser et al., 2022).

2.4.2.2. Statistical analysis. The primary goal of our analysis was to assess changes in the neuronal processing of affective feedback as a function of sense of agency. Theta oscillations associated with feedback processing have frequently been reported to be most prominent over FCz and adjacent electrodes (e.g., Hajihosseini & Holroyd, 2013; Kaiser et al., 2021; Luft et al., 2013). We thus created time-frequency maps and performed statistical analyses using the averaged activity over electrodes Fz, FCz, FC1, and FC2. Topographical plots, depicting average theta power from 200 ms to 600 ms after feedback onset (Cohen et al., 2007; Luft et al., 2013), confirmed that activity was strongest around these scalp sites, especially for free-choice trials with negative feedback (Fig. 2).

We used cluster-based permutation analysis over the specified scalp sites to assess the main effects of choice, feedback valence, and their interaction (Maris & Oostenveld, 2007) during feedback presentation. Univariate repeated measures ANOVAs (*ft_statfun_depsamplesFunivariate*) were performed to quantify the main effects for the factors CHOICE (free-choice/forced-choice) and VALENCE (positive/negative) at the sample level. To examine whether the neural impact of choice depended on feedback valence, contrasts for a CHOICE x VALENCE interaction were calculated by subtracting mean power values evoked by negative feedback from mean power values evoked by positive feedback within each choice condition. Both conditions were subsequently entered as factors in the univariate ANOVA and sample significance determined identically to the main effect analyses. To examine the distinct effect of choice for both positive and negative feedback, we performed additional contrasts of free- and forced-choice trials for each level of feedback valence separately via two-sided cluster-based permutation t-tests (*ft_statfun_depsamplesT*).

Significance of individual data points was evaluated against at an alpha level of .05, and samples passing the significance threshold clustered based on temporal and spectral features. We subsequently computed cluster-level statistics, defined as the sum of the F-values (or t-values, respectively) within each cluster. To evaluate significant differences across conditions, we applied the Monte Carlo Method to the largest of these clusters using 1000 random permutations of the original data. This method calculates p-values under the permutation distribution for data consisting of temporally and spatially adjacent data points by estimating the probability with which the condition-wise cluster data come from the same, or different distributions, while simultaneously controlling for the false alarm rate (Maris & Oostenveld, 2007).

Table 1
Mean Number of Trials (and Standard Deviations) for Each Combination of Trial Type (Free-Choice, Forced-Choice) and Feedback Valence (Positive, Negative) in the Final Dataset.

Trial type	Feedback valence	
	Negative	Positive
Free-choice	66.5 trials (6.4)	196.9 trials (19.5)
Forced-choice	65.3 trials (6.3)	192.9 trials (20.4)

3. Results

3.1. Behavioral results

Averaged over entire blocks, participants chose the high-value item significantly more often (M = 88.1%, SD = 7.2, range: 226–312) than the low-value item (M = 11.9%, SD = 7.2, range: 5–83), indicating that they were successful in learning the implemented item-outcome associations, $t(29) = 28.29$, $p < .001$, CI 95% [221.6, 256.1], Cohen's $d = 10.26$, $BF_{10} > 10^6$ (Fig. 3).

Reaction times had a mean latency of 524.80 ms ($SD = 58.56$, range: 424.41–681.55) and did not significantly differ between free- and forced-choice trials, $M_{\text{diff}} = 2.88$ ms, $t(29) = 0.63$, $p = .54$, CI 95% [− 6.53, 12.28], Cohen's $d = 0.05$, $BF_{10} = 0.23$. Participants received positive feedback on an average of 68.5% (SD = 3.9) trials and earned a final monetary bonus of 7.20 Euro (SD = 0.62, range: 5.64–7.92). No significant differences between free- and forced-choice blocks could be found for the proportion of positive feedback ($M_{\text{diff}} = 1.7$ trials, $t(29) = 1.48$, $p = .15$, CI 95% [− 0.64, 4.04], Cohen's $d = 0.12$, $BF_{10} = 0.52$), or negative feedback, $M_{\text{diff}} = -0.37$ trials, $t(29) = -0.50$, $p = .62$, CI 95% [− 1.87, 1.13], Cohen's $d = -0.03$, $BF_{10} = 0.22$. To conclude, reaction times and the rate of positive and negative feedback did not differ between free-choice and forced-choice blocks.

Inspection of participants' agency ratings for choice and outcome agency measures revealed five extreme outliers (defined as values < [1st quartile – 3 *interquartile range] or > [3rd quartile + 3 * interquartile range]). Reported results are based on the dataset including outliers, as their exclusion did not affect the results. The repeated measures ANOVA revealed a large effect of CHOICE on agency experience, $F(1, 29) = 169.16$, $p < .001$, $\eta_p^2 = .854$, $BF_{10} > 10^6$. Participants experienced greater agency during free- (M = 69.76%, SD = 23.37) compared to forced-choice blocks (M = 9.52%, SD = 16.90). In addition, we found evidence for a significant effect of RATING on agency experience, $F(1, 29) = 16.60$, $p < .001$, $\eta_p^2 = .364$, $BF_{10} = 0.69$. Participants reported greater levels of choice agency (M = 45.13%, SD = 40.97) than outcome agency (M = 34.15%, SD = 30.62) across blocks. The CHOICE x RATING interaction was also significant, indicating that the effect of choice differed for the two agency ratings, $F(1, 29) = 14.21$, $p < .001$, $\eta_p^2 = .329$, $BF_{10} = 28.70$. Post-hoc analyses revealed a larger effect of CHOICE on choice agency ratings (i.e., 'I was free to choose any item I wanted in this block.'), $t(29) = 12.04$, CI 95% [0.58, 0.82], $p < .001$, Cohen's $d = 3.41$, $BF_{10} > 10^6$, than on outcome agency ratings (i.e., 'I was in control over the amount of money I gained in this block.'), $t(29) = 10.40$, $p < .001$, Cohen's $d = 2.88$, $BF_{10} > 10^6$ (Fig. 4). The results indicate that our manipulation was successful in influencing agency experience between free- and forced-choice blocks. The larger effect of CHOICE on choice agency than outcome agency ratings additionally shows that participants were sensitive to their variable influence on item choice and action outcome, wherein self-determined choices did not always result in the desired outcome (i.e., a monetary gain).

3.2. Midfrontal oscillatory activity

Fig. 5 depicts time-frequency maps for midfrontal oscillatory power relative to feedback onset. Results of cluster-based permutation analyses for the main effects of choice, feedback valence, as well as their interaction are shown in Fig. 6.

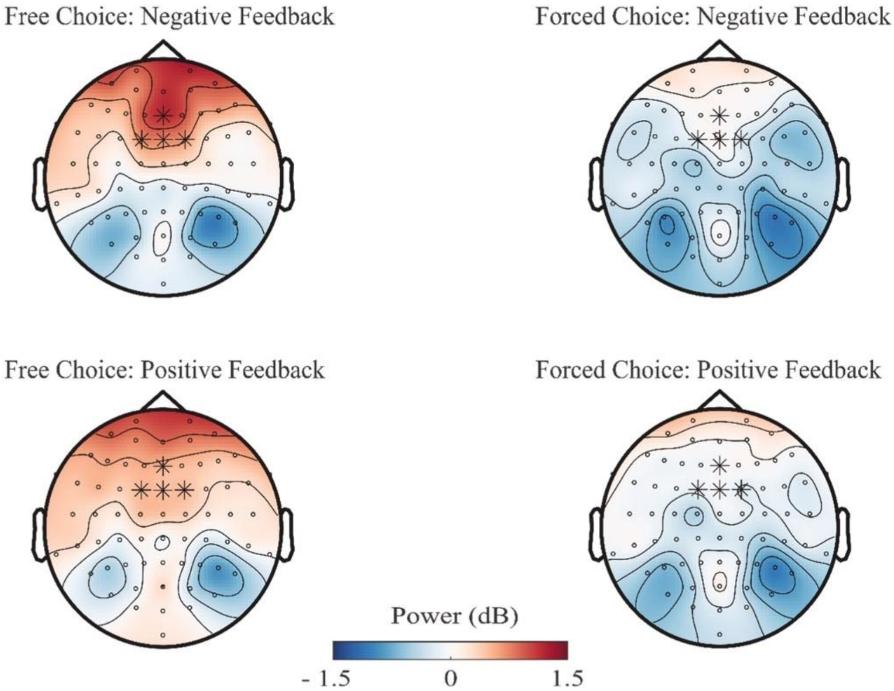

Fig. 2. Topographical plots showing oscillatory activity in the theta range (4–7 Hz) 200 600 ms post feedback onset. Stars mark electrodes used for statistical analyses.

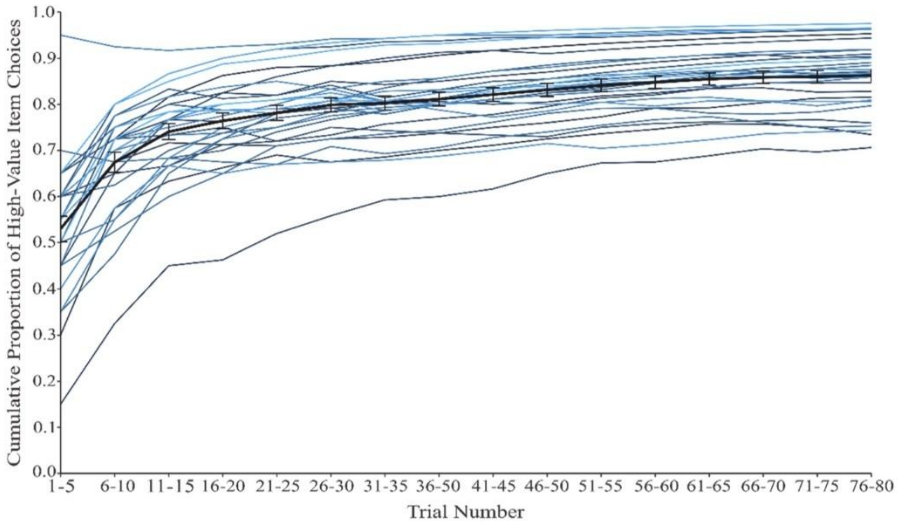

Fig. 3. Cumulative proportion of high-value item choices across trials. Blue-shaded lines indicate learning curves of individual participants, averaged over all free-choice blocks. The black line depicts the grand average of choice behavior across all participants, including standard errors.

Our analyses revealed a significant effect of CHOICE on feedback processing over midfrontal electrodes, encompassing low frequency oscillations mainly in the theta range and starting with feedback onset, 0–930 ms, $p = .001$. Free-choice trials elicited greater theta power during feedback presentation than forced-choice trials. An average power difference of 0.69 dB (SD = 0.22) could be observed for the detected cluster. The ANOVA for the main effect of VALENCE revealed a significant power difference between trials with negative and positive feedback, confined to the theta range and starting with feedback onset, 0–510 ms, $p = .022$. Compared to trials with positive feedback, trials with negative feedback elicited greater theta power ($M\Delta = .29$ dB, SD = 0.09) during feedback presentation. We did not find a significant effect for the interaction of the factors CHOICE and VALENCE during the specified time window. This indicates that changes in the sense of agency affect the processing of positive and negative feedback, as observable in midfrontal theta activity, in comparable ways. Additional contrasts confirmed the significant difference between free and forced choices for both positive and negative feedback (Fig. 7). Free- compared to forced-choice trials significantly increased activity in the theta range after the onset of negative feedback, 0–830 ms, $M\Delta = .85$ dB, $SD = 0.24$, $p = .001$. For positive feedback, a significant increase in theta power could be observed for free- compared to forced-choice trials for the whole duration of feedback presentation, 0–1000 ms, $M\Delta = .60$ dB, SD = 0.16, $p = .004$.

4. Discussion

The current study investigated the impact of changes in the sense of

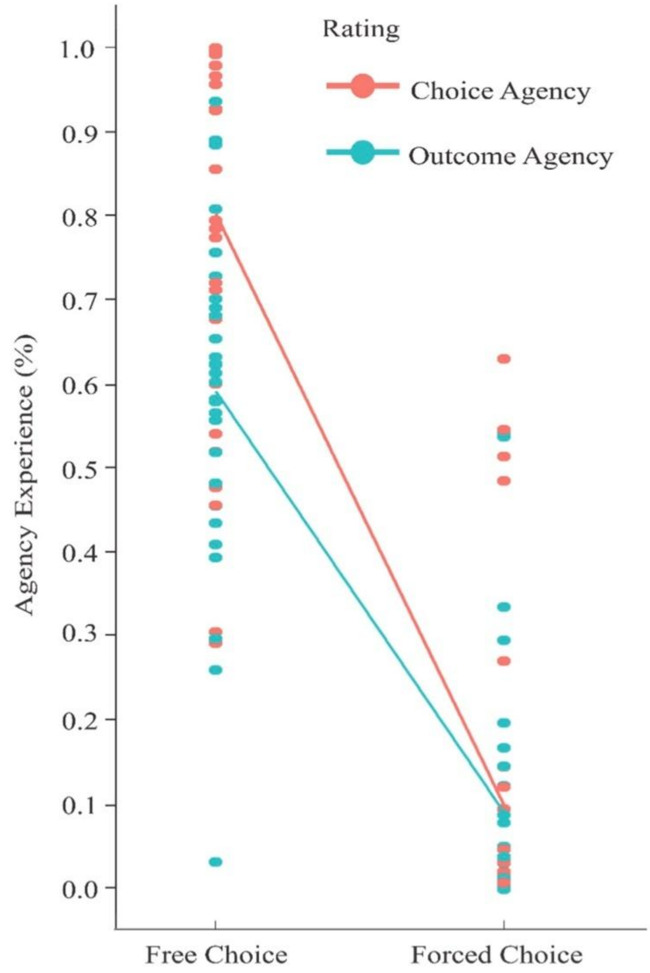

Fig. 4. Participants' proportional agreement with statements measuring choice agency (i.e., 'I was free to choose any item I wanted in this block.') and outcome agency (i.e., 'I was in control over the amount of money I gained in this block.'), plotted separately for free- and forced-choice blocks. Lines depict the mean difference in agency experience between free and forced choices for both choice (red) and outcome agency ratings (blue).

agency on the neuronal processing of affective action outcomes. This was achieved by manipulating freedom of choice within subjects in a reinforcement learning task, with monetary gains and losses as positive and negative feedback. Using EEG, we analyzed midfrontal oscillatory activity during feedback presentation and assessed differences between free and forced choices, as well as between positive and negative feedback. Explicit agency ratings, measuring perceived freedom of choice and outcome controllability, were obtained after each free- and forced-choice block.

Behavioral results show that participants quickly gained insight into the reward structure, with an increase in high-value item choices throughout free-choice blocks. Reported sense of agency was significantly higher during free- than forced-choice blocks, showing that our manipulation was effective in modifying agency experience during the task. The effect of choice was larger for perceived freedom of choice than the feeling of control over monetary gains. As hypothesized, negative compared to positive feedback elicited greater theta power in the region of interest. Also, we found an increase in midfrontal oscillatory activity in the theta range for free compared to forced choices during feedback presentation. Notably, our results reveal that freedom of choice amplifies the neuronal impact of feedback during the processing of both positive and negative action outcomes.

The present study substantiates the evidence on agency-related changes in the processing of affective action outcomes. Increased midfrontal theta power for negative compared to positive feedback, as well as for self-, rather than externally determined action outcomes mirrors results from previous studies focusing on the FRN (e.g., Bellebaum et al., 2010; Foti et al., 2015; Hassall et al., 2019; Weismüller et al., 2019; Yeung et al., 2005). By analyzing time-frequency oscillations, our findings complement previous ERP work and provide insight into the oscillatory dynamics underlying feedback processing during goal-directed tasks (Cavanagh et al., 2010; Luft, 2014).

Our paradigm was designed to manipulate freedom of choice, while maintaining a consistent level of personal motor involvement and an equal rate of positive and negative feedback across all conditions. To this end, participants performed motor actions in free- and forced-choice blocks and item selections and reward schemes were kept identical for both choice conditions. Importantly, behavioral analyses revealed that reaction times did not significantly differ between free and forced choices. This indicates that the observed differences in neural reactivity to feedback following participants' responses were due to differences in freedom of choice rather than discrepancies in the timing of motor reactions between conditions. Our results thus allow to draw conclusions about the distinct contribution of choice on affective feedback processing during goal-directed actions.

As suggested by theoretical accounts (Friston et al., 2013; Ly et al., 2019) and empirical evidence from previous studies (Barlas & Obhi, 2013; Haggard, 2017; Hassall et al., 2019), freedom of choice increases agency experience. By employing explicit measures that ask participants to report their perceived control over action outcomes, most previous studies have treated the sense of agency as a single construct. However, in our study, we utilized a self-report measure that explicitly differentiated between the perceived freedom of action choice (i.e., 'I was free to choose any item I wanted in this block.') and the ability to influence the outcome of that action (i.e., 'I was in control over the amount of money I gained in this block.'). It is important to note that having the freedom to make decisions does not guarantee the desired outcome, underscoring the importance of distinguishing between these components when assessing the sense of agency.

As apparent from agency ratings in the current study, freedom of choice is closely linked to the sense of control over the outcome. The decrease in perceived outcome controllability during forced-choice blocks is in line with previous work (Barlas et al., 2018). In addition, due to the substantial number of trials within each block and the inclusion of a non-corresponding block between two corresponding free-choice and forced-choice blocks, there was always a time gap of approximately 10 min between the start of two corresponding blocks. Considering our behavioral findings and the task structure, it is highly unlikely that participants were able to discern the match of their own choices and those made by the computer.

Importantly, the larger increase in choice than outcome agency ratings for free compared to forced choices shows that participants are sensitive to their variable influence on distinct task components. In the current study, items and outcomes were associated probabilistically, implying that outcomes could not always be predicted from item choices. A smaller increase in outcome than choice agency ratings during free choices thus shows that participants correctly determined that increased freedom of choice did not always guarantee positive feedback, illustrating the influence of various task elements on an individual's sense of agency.

Higher feedback-evoked theta activity for free-choice than forced-choice trials converges with insights from prior work (e.g., Weismüller et al., 2019; Zheng et al., 2020). Crucially, our study reveals that the augmented midfrontal theta power observed during feedback presentation following free choices extends to contexts of significant motivational value. By providing participants with a reinforcement learning task wherein they could maximize a performance-dependent bonus paid to them at the end of the experiment, we combined two aspects relevant to the motivational salience of actions and their outcomes (Ly et al.,

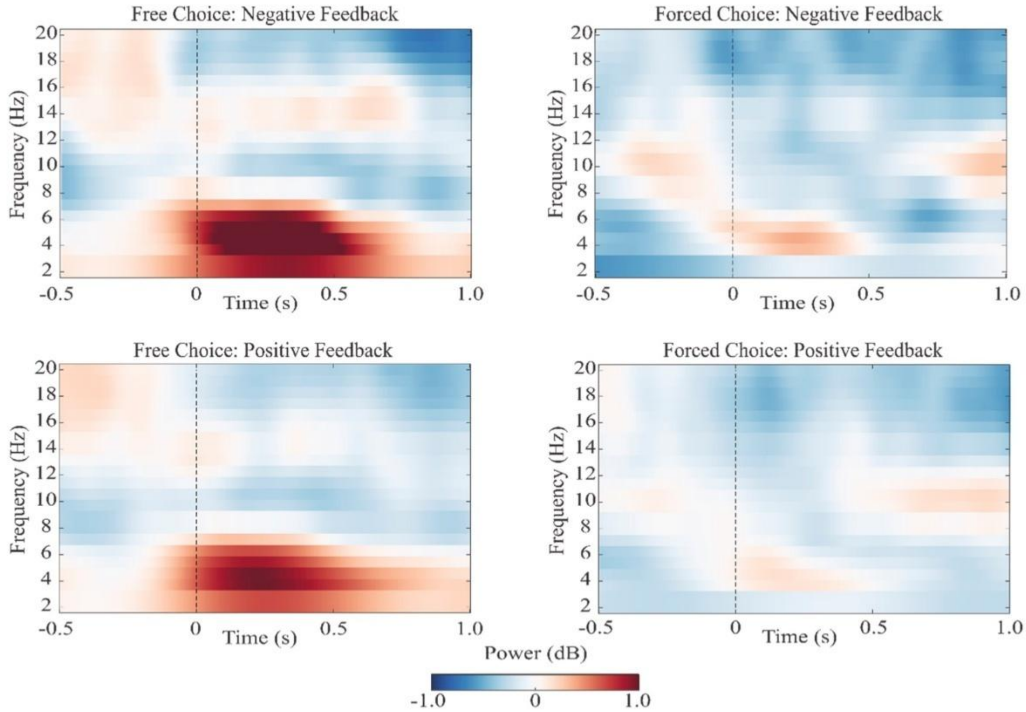

Fig. 5. Time-Frequency plots over midfrontal electrodes (Fz, FCz, FC1, FC2) for all choice-outcome conditions. Dashed line at Time = 0 marks the onset of feedback presentation.

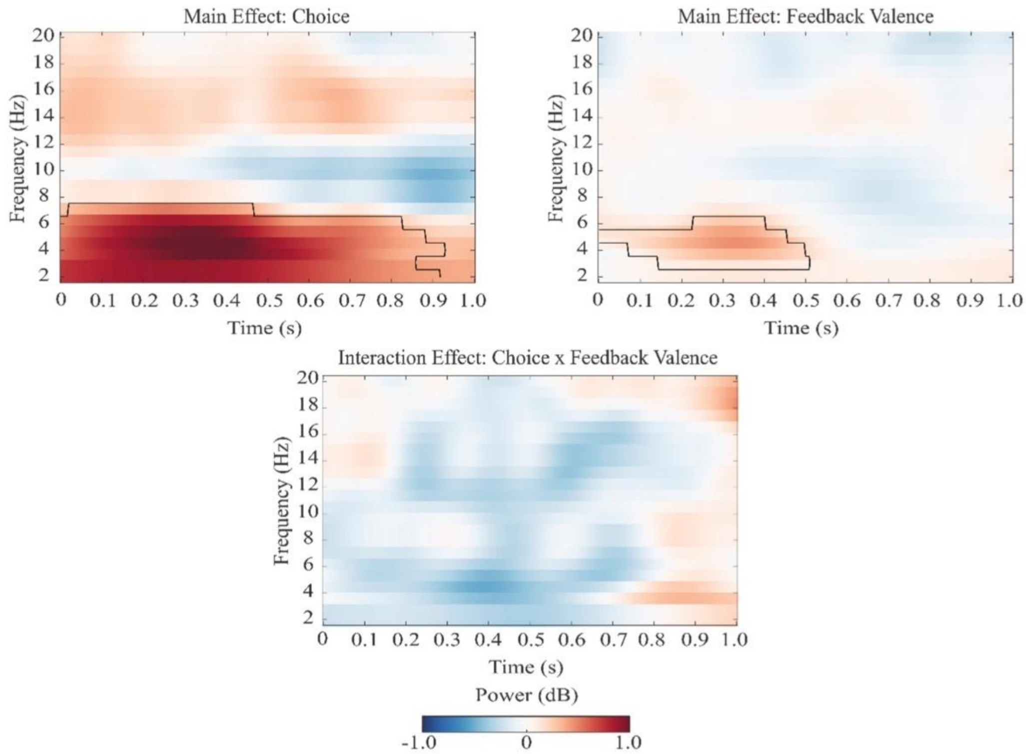

Fig. 6. Main and interaction effects of choice and feedback valence, averaged over midfrontal electrodes (Fz, FCz, FC1, FC2). Time = 0 indicates the onset of feedback presentation. Black contours mark the time and frequency range with significant differences between the examined conditions ($p < .05$).

2019; Mei et al., 2018). Sense of agency has been proposed to be particularly relevant in such contexts, allowing for effective regulation of behavior to attain desirable and avoid undesirable states (Kaiser et al., 2021; Ly et al., 2019; Murayama et al., 2015). Accounting for the goal-directedness of behavior therefore contributes to an understanding of how the sense of agency affects the processing of action outcomes in situations central to its functional role.

Midfrontal theta oscillations are suggested to play an important role for performance monitoring and the updating of task-relevant information (e.g., Cavanagh et al., 2010; Kaiser et al., 2021; Luft, 2014; Luft

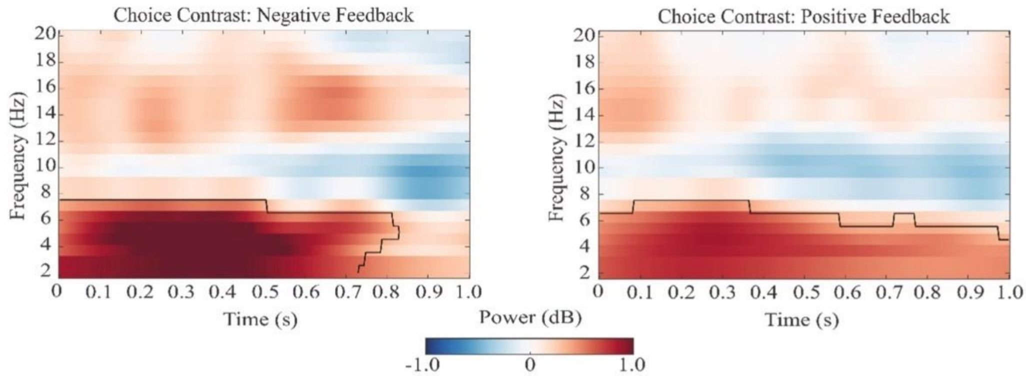

Fig. 7. Results of contrast analyses testing the effect of choice for negative (left) and positive (right) feedback, averaged over midfrontal electrodes (Fz, FCz, FC1, FC2). Time = 0 indicates the onset of feedback presentation. Black contours mark the time and frequency range with significant differences between the examined conditions ($p < .05$).

et al., 2013). With respect to these insights, the results from the present study might indicate that participants track affective feedback obtained for externally determined choices to a lesser extent than feedback obtained for self-determined choices, reflected in lower midfrontal theta power during forced- compared to free-choice trials. This choice-related decrease in theta power might reflect participants' perception of reduced personal responsibility for gains and losses resulting from externally determined actions. In line with this interpretation, diminished sense of agency has been associated with reduced outcome monitoring (Beyer et al., 2017). In addition, the motivation to learn from performance feedback might be decreased if it cannot be used to adjust behavior (Moscarello & Hartley, 2017). Both aspects signal a decrease in personal task involvement during forced choices, potentially explaining the reduced impact of affective feedback during task performance. It should be noted, however, that while our results clearly show that freedom of choice increases the neural impact of affective feedback, our study design does not allow to draw conclusions about potential behavioral and cognitive effects of agency-related changes in affective feedback processing.

Heightened midfrontal theta power for negative compared to positive feedback resonates with a large body of work on affective feedback processing in the context of reinforcement learning (see Luft, 2014). In the current task, action outcomes always affected participants' payout, meaning that feedback carried personal relevance during both free- and forced-choice blocks. Accordingly, our results suggest that midfrontal theta oscillations differentiate between positive and negative feedback for all self-relevant action outcomes, regardless of whether they result from self- or externally determined choices. Thus, whilst the main effect of choice indicates that being able to freely decide between response options increases personal task involvement, the mere presentation of adverse self-relevant feedback seems to be sufficient to elicit a surge in midfrontal theta power.

Notably, free compared to forced choices not only increased the neural impact of negative feedback, but also intensified the processing of positive feedback. While previous studies led to inconsistent conclusions regarding the question if agency selectively enhances the processing of positive or negative feedback (e.g., Kaiser et al., 2021; Weismüller et al., 2019; Zheng et al., 2020), our results clearly demonstrate midfrontal theta activity as a neurophysiological marker sensitive to within-subject differences in agency experience for both types of affective feedback. Thus, rather than exhibiting a positivity or negativity bias, the valence-independent increase in oscillatory power during free choices indicates midfrontal theta oscillations as a general mechanism for outcome monitoring during goal-directed actions.

The valence-independent increase in midfrontal theta power for feedback following free choices is inconsistent with Zheng et al. (2020), who found that the effect of choice was larger for negative than positive feedback. The origin of this divergence conceivably lies in the nature of the implemented tasks. Whereas Zheng et al. employed a pre-defined reward scheme with equiprobable gain and loss feedback, which did not allow participants to learn from feedback to optimize their behavior, the current study used a reinforcement learning task with informative, motivationally salient feedback. While free choices seem to increase the relevance of both positive and negative feedback in a reinforcement learning context, the processing of negative feedback appears to take precedence in non-learnable contexts. This indicates that the evaluation of trial-wise gains and losses for free and forced choices scales differently across affective contexts. In non-learnable environments, a selective increase in midfrontal theta power for negative feedback might reflect negative affect associated with the discrepancy between desired and actual state (Botvinick et al., 2001; Cavanagh et al., 2010). When agents are presented with learnable environments, however, performance monitoring becomes increasingly salient (Moscarello & Hartley, 2017), which might be reflected in a general enhancement of midfrontal theta activity during feedback presentation for free choices. Hence, by actively tracking both positive and negative action outcomes, agents not only ascertain what behavior to inhibit, but also learn to repeat rewarded actions.

Some limitations should be kept in mind when interpreting the current results. As all participants started with two free-choice blocks, we cannot exclude that order effects influenced the present results. To match reward rates between free and forced choices, while maintaining a certain degree of outcome controllability in free-choice trials, however, presenting free-, prior to forced-choice blocks was inevitable. Furthermore, as we provided participants with a relatively simple reinforcement learning task without explicit learning requirements in forced-choice blocks, the current study design was not suited for examining free-choice and forced-choice differences in learning per se. Thus, it is important to acknowledge that there are at least two potential explanations for the differences in feedback processing between free and forced choices in the current study. Firstly, the differences in theta power during feedback presentation might reflect variations in learning for self- compared to externally determined action outcomes. Secondly, participants may experience a heightened sense of personal responsibility for the consequences of their own choices compared to externally determined choices, which may not necessarily be linked to any learning effect. Future research is needed to disentangle these possibilities. In case participants exhibit agency-related differences in learning, midfrontal theta should be tested as a neuronal mechanism explaining this relation. When examining midfrontal theta activity as a mediator of agency and action regulation, it might additionally be useful to distinguish between effects pertaining to perceived freedom of choice on the one, and outcome controllability on the other hand. As agency ratings from the current study indicate, participants were able to differentiate between their ability to choose their action and their ability to influence the result of this action (i.e., whether they receive a monetary gain or loss). By investigating the influence of individual cognitive and motor factors on the neuronal processing of affective action outcomes, we can establish a valuable groundwork for comprehending the inconsistent findings observed in prior studies regarding the effects of agency on affective feedback processing (Kaiser et al., 2021).

Together, the current findings implicate midfrontal theta power as a neurophysiological marker sensitive to freedom of choice in a reinforcement learning task. Importantly, while previous studies found inconsistent results concerning the valence specificity of agency-related effects on feedback processing in goal-directed actions, the present study suggests that freedom of choice enhances the processing of both positive and negative performance feedback. Future work should assess the behavioral consequences of these neural effects and explore whether the enhanced processing of affective feedback during learning extends to other neurophysiological markers previously associated with the sense of agency.

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CRediT authorship contribution statement

Maren Giersiepen: Conceptualization, Methodology, Software, Formal analysis, Investigation, Writing - original draft, Project administration; Simone Schütz-Bosbach: Conceptualization, Writing - review and editing, Supervision, Funding acquisition; Jakob Kaiser: Conceptualization, Methodology, Software, Formal analysis, Writing - review and editing, Supervision, Funding acquisition.

Declaration of Generative AI and AI-assisted technologies in the writing process

The authors did not use generative AI technologies for preparation of this work.

Declaration of Competing Interest

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

Data Availability

Data and study materials can be found online at https://osf.io/nc945/?view_only= 94061c5c5e954c20b758cc3d479afe77.

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2.2 My Choice, my Actions: Self-Determination, not Instrumental Value of Outcomes Enhances Outcome Monitoring During Learning

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Maren Giersiepen conceptualized and administered the study, programmed the experiment, collected, analyzed, interpreted, and visualized the data, and wrote the manuscript. Simone Schütz-Bosbach acquired funding, commented on the manuscript, and contributed to study conceptualization and the interpretation of the results. Jakob Kaiser acquired funding, commented on the manuscript, and contributed to study conceptualization, formal analysis of the data, and the interpretation of the results.

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My choice, my actions: self-determination, not instrumental value of outcomes enhances outcome monitoring during learning

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Freedom of choice enhances our sense of agency. During goal-directed behavior, the freedom to choose between different response options increases the neural processing of positive and negative feedback, indicating enhanced outcome monitoring under conditions of high agency experience. However, it is unclear whether this enhancement is predominantly driven by an increased salience of self- compared to externally determined action outcomes or whether differences in the perceived instrumental value of outcomes contribute to outcome monitoring in goal-directed tasks. To test this, we recorded electroencephalography while participants performed a reinforcement learning task involving free choices, action-relevant forced choices, and action-irrelevant forced choices. We observed larger midfrontal theta power and N100 amplitudes for feedback following free choices compared with action-relevant and action-irrelevant forced choices. In addition, a Reward Positivity was only present for free but not forced choice outcomes. Crucially, our results indicate that enhanced outcome processing is not driven by the relevance of outcomes for future actions but rather stems from the association of outcomes with recent self-determined choice. Our findings highlight the pivotal role of self-determination in tracking the consequences of our actions and contribute to an understanding of the cognitive processes underlying the choice-induced facilitation in outcome monitoring.

Key words: electroencephalography; feedback processing; freedom of choice; outcome relevance; sense of agency.

Introduction

When interacting with the environment, we sometimes feel more or less in control over our actions and their effects. This experience of control reflects our sense of agency and serves as a cue to distinguish self- from externally determined actions (Haggard 2017). In conjunction with supporting a self–other differentiation, sense of agency facilitates an adaptive interaction with the environment (Ly et al. 2019; Studer et al. 2020). We can instrumentalize the knowledge that we are the agent of our actions to adopt behavioral strategies that promote goal attainment (Luo et al. 2022). Consequently, sense of agency is crucial for a coherent sense of self- and goal-directed behavior.

Agency experience is influenced by the integration of sensory, cognitive, and affective cues that operate prior (e.g. causal beliefs), during (e.g. sensorimotor signals), and after an action (e.g. contingency of action effects; Moore et al. 2009; Synofzik et al. 2013; Sidarus et al. 2017). A large body of work has focused on studying how the sense of agency affects the processing of action outcomes using electroencephalography (EEG; see Gentsch and Schütz-Bosbach 2015; Moore 2016; Giersiepen et al. 2023). In these studies, participants' sense of control over auditory or visual action effects is typically manipulated by varying their motor involvement or their degree of choice over response options and differences in outcome processing are examined. Results indicate a neural differentiation of self- and externally induced action effects already during early sensory stages of feedback processing, as reflected in the N100 component, a negativity in the event-related potential (ERP) waveform peaking around 100 ms after feedback onset (e.g. Martikainen et al. 2005; Gentsch and Schütz–Bosbach 2011; Weiss et al. 2011; Kaiser and Schütz-Bosbach 2018). Most of these studies report a reduction in N100 amplitude for action outcomes produced under conditions of high compared to low sense of agency, a phenomenon referred to as sensory attenuation (see Gentsch and Schütz-Bosbach 2015). Crucially, in the reported studies, action outcomes like visual stimuli or sounds typically serve as sensory confirmation of a completed action, without any instrumental value for future actions. Hence, they are not associated with instrumental positive or negative affective value indicative of participants' success or failure in attaining an action goal (see Haggard and Eitam 2015).

Interestingly, previous work indicates that the attenuation effect is reversed if action outcomes under conditions of high and low sense of agency are equally predictable (Kaiser and Schütz-Bosbach 2018). Furthermore, affective processing has been proposed to be intricately linked to the sense of agency (Synofzik et al. 2013; Gentsch and Synofzik 2014; Kaiser et al. 2021b; Majchrowicz and Wierzchoń 2021). Thus, early processing of action outcomes, as reflected in the visual N100, may be sensitive to both the affective context and the predictability of task-relevant action effects.

During goal-directed behavior, affective outcomes are informative cues that reinforce or inhibit previously performed actions.

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Thus, affective feedback carries practical significance, reflecting current task performance and serving as an instructive cue to optimize behavior. Despite the central role of the sense of agency in successful goal-directed behavior and the apparent importance of affective feedback for an adaptive interaction with the environment (Synofzik et al. 2013; Gentsch et al. 2015; Kaiser et al. 2021b), relatively little work has focused on studying how the experience of agency, particularly through self-determined choice, influences outcome processing in goal-directed and affective contexts. Using random reward schedules, involving equal occurrences of gains and losses, controls feedback processing differences that might result from frequency effects, such as those related to prediction errors (e.g. Holroyd et al. 2003). However, random reward schedules also preclude the study of how agency experience influences the processing of instrumental affective feedback during contexts, where participants can learn to optimize their behavior according to nonrandom reward contingencies.

Some studies have shown that affective context, in the sense of whether action outcomes carry positive or negative instrumental value, impacts how the sense of agency influences the processing of these outcomes (Gentsch et al. 2015; Christensen et al. 2016; Majchrowicz and Wierzchoń 2021). The results indicate a differentiation of positive and negative action outcomes as reflected in self-reports and implicit measures, such as the N100 component. Specifically, individuals are more inclined to experience agency over positive rather than negative action outcomes, which has been interpreted as a self-serving attribution bias (e.g. Gentsch et al. 2015; Chambon et al. 2020).

In addition to sensory processing, as reflected in the N100 component, affective contexts involve the evaluation of outcome value (Kaiser et al. 2021b). Negative compared to positive feedback is typically associated with greater midfrontal theta (MFθ; 4 to 7 Hz) power (Cavanagh et al. 2010; Van de Vijver et al. 2011; Kaiser et al. 2021a; Giersiepen et al. 2023). MFθ oscillations are assumed to reflect cognitive control and cognitive conflict during value-based decision-making (Cavanagh and Frank 2014; Weismüller et al. 2019; Kaiser et al. 2022). Conversely, positive feedback has been shown to elicit larger voltage deflections compared to negative feedback over similar midfrontal scalp sites, resulting in a Reward Positivity (RewP) that peaks 250 to 350 ms after feedback onset (Holroyd et al. 2008; Proudfit 2015; Zheng et al. 2020). Source analyses indicate that both feedback-induced MFθ oscillations and RewP originate from the anterior cingulate cortex (ACC; see Cavanagh and Frank 2014). The ACC is highly interconnected with other cortical and subcortical areas and is considered functionally relevant for behavioral monitoring and adaptation (Cavanagh and Frank 2014; Monosov et al. 2020; Kaiser et al. 2023; Qu et al. 2023). Importantly, valence-specific modulations of RewP and MFθ power seem to serve a functional role during feedback learning (Cohen and Donner 2013; Williams et al. 2018).

Studies investigating how action choice impacts affective outcome processing usually find an increased RewP amplitude and MFθ power for free choices (associated with high sense of agency) compared to forced choices (associated with low sense of agency; Hassall et al. 2019; Zheng et al. 2020; Giersiepen et al. 2023). Likewise, several studies indicate heightened outcome monitoring during active compared to observational learning (Bellebaum et al. 2010; Weismüller et al. 2019). Thus, self-determined actions may enhance the neurophysiological processes associated with outcome evaluation during goal-directed behavior. Importantly, freedom of choice seems to increase the monitoring of positive and negative action outcomes to a similar extent (Weismüller et al. 2019; Giersiepen et al. 2023), indicating the absence of a valence-specific (self-serving) bias during later stages of feedback processing (but see Zheng et al. 2020).

Crucially, the results from these studies do not unequivocally isolate the cognitive processes involved in the neural enhancement of outcomes during self-determined choice. On the one hand, high compared to low sense of agency during free compared to externally determined choices may be associated with a greater perceived *action-relevance* of affective feedback, meaning that participants monitor outcomes resulting from free compared to forced choices more strongly as they carry information with practical relevance for subsequent action selection decisions. For example, negative feedback during free-choice trials might inform participants not to repeat the same choice in subsequent trials. In this case, the *instrumental value*, i.e. the perceived capacity to use performance feedback to adjust behavior, would be the main factor leading to enhanced outcome processing. On the other hand, freedom of choice may induce a general increase in task engagement, independent of whether outcomes are *action-relevant* or *action-irrelevant* for future behavior, potentially reflecting a bias toward weighting self-induced action outcomes as more salient, even when outcomes of both free- and forced-choice conditions are equally informative of participants' goal achievement (Deci and Ryan 2012; Gentsch et al. 2015; Mühlberger et al. 2017; Chambon et al. 2020). For example, during reinforcement learning, humans may value negative feedback during free choices more than negative feedback during forced choices because they directly relate this value to a recent self-determined task choice.

With the goal of isolating the cognitive processes underlying the choice-induced enhancement in affective outcome monitoring observed in previous studies, the current study differentiates the neurocognitive effects of self-determined choice on the one hand and outcome relevance on the other hand in a motivationally salient, goal-directed task. To this end, we recorded EEG and manipulated participants' agency experience by varying their freedom of choice in a reinforcement learning task employing probabilistic item–outcome associations and monetary gains and losses as affective action effects. By monitoring action outcomes, participants could learn which of the two items constituted the high-value item (i.e. item choice likely results in a monetary gain) and which constituted the low-value item (i.e. item choice likely results in a monetary loss).

To examine how the sense of agency, operationalized as freedom of choice, influences different stages of outcome evaluation, we assessed both early and (N100) and later markers (RewP, MFθ) of feedback processing. We expected a significant increase in outcome monitoring for free choices compared with forced choices, reflected in larger ERP deflections and time–frequency power during feedback presentation. Furthermore, we predicted an RewP in response to positive feedback and a larger increase in MFθ power in response to negative feedback.

Crucially, unlike previous studies (e.g. Weismüller et al. 2019; Chang et al. 2020; Zheng et al. 2020; Giersiepen et al. 2023), we separated the impact of outcome relevance and choice autonomy by establishing three choice scenarios: (i) *free-choice* blocks, where participants could choose any of two items in each trial, (2) *action-irrelevant forced-choice* blocks, where participants confirmed a pre-set choice without using feedback for decision-making, and (3) *action-relevant forced-choice* blocks with forced choices initially, followed by free choices, allowing the initial feedback to inform later decisions. This approach tests whether the choice-induced increase in feedback processing is due to its perceived importance for future actions or a general bias beyond the immediate relevance of feedback for future action decisions.

We anticipated that these effects would be paralleled by higher self-reported agency experience when participants were given the freedom to choose between response options, compared to being confined to selecting a predetermined option.

Materials and methods

Participants

Inclusion criteria for this study were an age between 18 and 45 years, normal or corrected-to-normal visual acuity without color vision deficiencies, and the absence of an acute neurological or psychiatric disorder. We collected data from 40 participants. During data analysis, three participants were excluded (see Data Preprocessing). The final test set thus comprised 37 participants ($M_{age} = 25.5$ years, $SD = 4.9$, 20 female, 16 male, 1 gender not indicated, 33 right-handed). Power analysis and comparisons with previous EEG studies examining choice-induced within-subject differences in outcome processing (e.g. Mühlberger et al. 2017; Giersiepen et al. 2023) were conducted to ensure adequacy in detecting the effects of choice and outcome valence on feedback processing. Based on these insights, we concluded that our sample size is likely suitable to detect such effects. Further details are provided in the Supplementary Materials. Participants received a financial reimbursement of 9 Euro per hour or participation credit. Independent of compensation choice, participants received a performance-dependent monetary bonus at the end of the experiment ($M = 9.64$ Euro, $SD = 1.03$, range: 6.90 to 10.86; see Materials and Procedure). Study approval was obtained from the ethical board of the Department of Psychology at the Ludwig-Maximilians-University Munich. Participants voluntarily participated in the study, and written consent was obtained at the beginning of the experimental session.

Apparatus and measurement setup

We employed 64 active electrodes embedded in an elastic cap for EEG signal acquisition (actiCAP snap, Brain Products, Munich, Germany). The electrodes were placed in line with the extended version of the international 10-20 system. Electrode FCz served as an online reference, and a ground electrode was placed at location FPz. We employed a BrainAmp DC amplifier (BrainVision) for signal amplification, and the continuous signal was digitized at a sampling rate of 1000 Hz. The data were filtered online using a bandpass filter with half-amplitude cutoffs of 0.016 and 250 Hz. Electrode-to-skin impedances were kept below 20 kΩ.

Materials and procedure

Participants were seated approximately 70 cm from a 24-inch screen on which a reinforcement learning task was presented. MATLAB R2020B and Psychophysics Toolbox extensions (Psychtoolbox Version 3; Brainard and Vision 1997) were used to implement the task.

In the task, participants made binary item selections on each trial. Choice options comprised two differently colored squares presented horizontally aligned adjacent to the screen center. Unbeknown to participants, one of the two options was associated with a 75% probability of gaining 4 cents (high-value item), while the other option was associated with a 75% probability of losing 2 cents (low-value item; Tversky and Kahneman 1992). Whether an item choice resulted in a gain or loss of money was presented as affective action effect after item selection. The task was performed in separate blocks, each of which used two novel, differently colored squares as targets. Thus, each block necessitated the learning of novel stimulus–reward contingencies, and participants could learn from feedback after every trial which of the two items was more likely to lead to financial gain or loss.

To manipulate agency experience, choice context varied between three different types of blocks: free-choice blocks, action-irrelevant forced-choice blocks, and action-relevant forced-choice blocks. During free-choice blocks, participants were free to choose either of the two stimuli presented on the screen by pressing the left or right arrow keys on the keyboard. During action-irrelevant forced-choice blocks, item selections were determined by the computer throughout the entire block, thereby withdrawing participants' control over item choices and their ensuing gains and losses. In action-relevant forced-choice blocks, participants were instructed to first complete 54 (75%) forced-choice trials, followed by 18 free choices during the final quarter of trials. Thus, during action-relevant forced-choice blocks, but not during action-irrelevant forced-choice blocks, feedback during forced-choice trials was informative for participants' future behavior. Prior to each block, participants were informed if during the upcoming block they would always (free-choice blocks), never (action-irrelevant forced-choice blocks), or only in the latter part of the block (action-relevant forced-choice blocks) be free to choose which item to select. To match motor involvement during free- and forced-choice trials, participants confirmed computer choices with button presses during forced choices (see also Chambon et al. 2020).

Trials of all conditions started with a fixation cross presented in the screen center (jittered for 1.5 to 1.8 s). Next, participants performed item selections (1 s), followed by a choice confirmation period (1 s). Finally, "+4" or "−2" were presented as affective action effect during the feedback period (1 s; Fig. 1). All stimuli were presented on a gray background with a visual angle of 1.2°. Participants were instructed to use their right index finger for item selection. In cases where participants did not respond during the choice period, the screen did not display gain or loss feedback, but instead a message prompting them to respond faster appeared. If they tried to select the item not chosen by the computer, participants were informed that they had pressed the wrong key. Trial durations ranged from 3.5 to 4.8 s.

The task comprised four blocks per choice condition (12 blocks in total), each consisting of 72 trials (864 trials total; 288 trials per choice condition). The 24 targets (two target colors per block) were determined to be maximally perceptually distinct from each other and the background according to the CIELAB color space (Holy 2022; Giersiepen et al. 2023). Which of the two items corresponded to the high- and low-value item was determined randomly at the beginning of each block. Stimuli appeared equally often and in random order on the left and right side of the screen center. Item selections during forced choices from action-irrelevant and action-relevant forced-choice blocks were yoked to participants' responses during previous free-choice blocks. Consequently, all participants started in the free-choice condition, followed by the action-irrelevant and the action-relevant forced-choice condition. This was necessary to allow for an equivalent sequence and frequency of high- and low-value item choices in all three choice conditions. Participants were informed about their block-wise monetary gain at the end of each block. Importantly, as participants were informed prior to the experiment, they received the money gained during their two best blocks of each condition after the experiment, making choice-related gains and losses relevant to participants in all choice conditions.

To measure the effect of our choice manipulation on agency experience, we obtained participants' agency ratings at the end of each block. In line with previous work (Giersiepen et al. 2023),

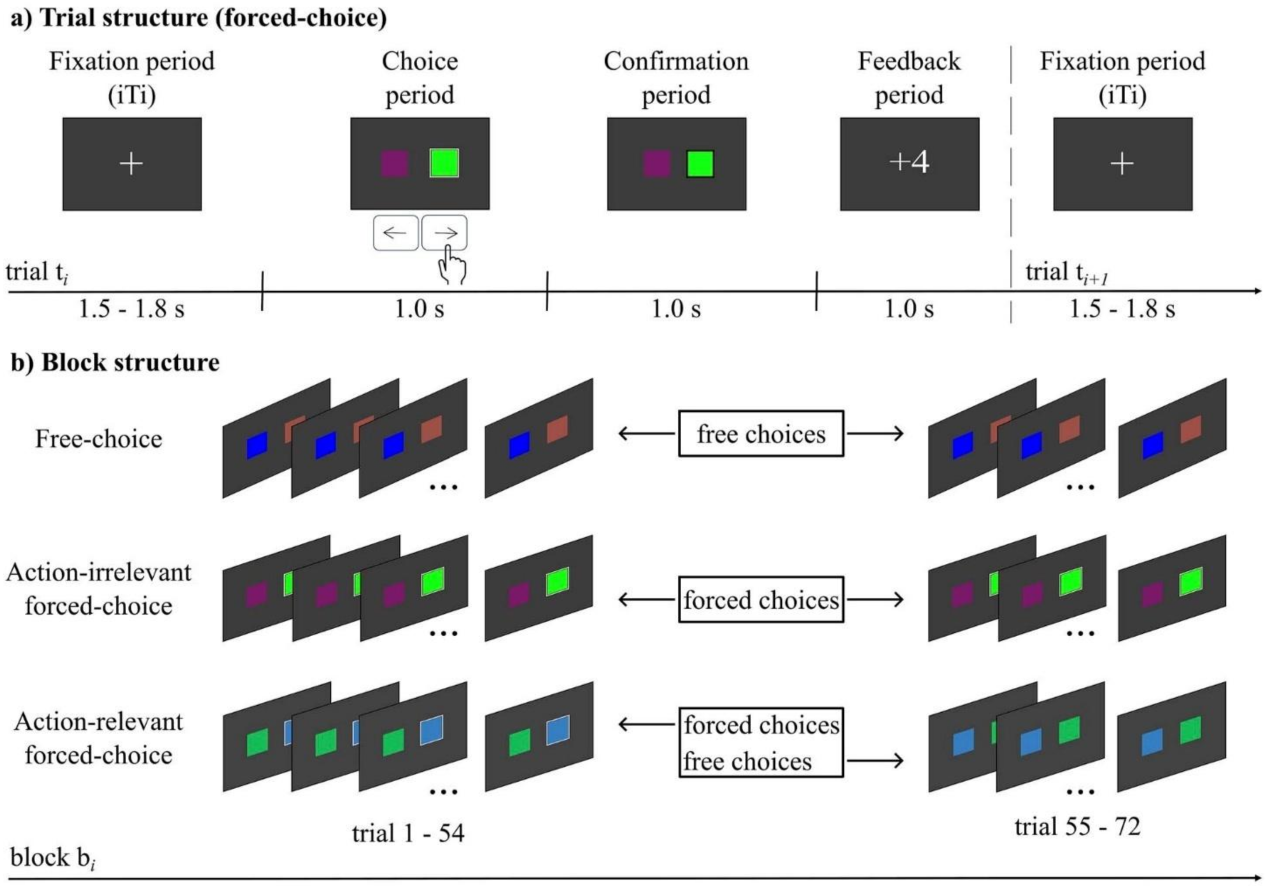

Fig. 1. Schematic representation of the experimental task. a) Trial structure exemplified by a forced-choice trial. Each trial comprised an item choice followed by a black rectangle around the selected item to confirm participants' key presses. Probabilistic affective feedback was presented as action effect. Trials were separated by a white fixation cross presented at the screen center. b) Block structure depicting examples of free-choice (upper row), action-irrelevant forced-choice (middle row), and action-relevant forced-choice (bottom row) blocks. During free-choice blocks, participants freely selected one of the two items. During action-irrelevant forced-choice blocks, the computer selected one item in all trials, signaled by a white frame around the selected stimulus. Item choices had to be confirmed by participants. During action-relevant forced-choice blocks, participants performed forced-choices during the first 75% of trials (trial 1 to 54) and could freely choose between items during the final 25% of trials (trial 55 to 72). Each block employed a novel pair of colored squares as targets.

participants were asked to indicate their agreement with two statements (item 1: "I was free to choose any item I wanted in this block."; item 2: "I was in control over the amount of money I gained in this block.") on a bipolar quasi-continuous scale, ranging from *Strongly Disagree* to *Strongly Agree*. As highlighted in theoretical work (Pacherie 2008) and empirical evidence from previous studies (Sidarus et al. 2017; Giersiepen et al. 2023), the sense of agency is a multidimensional construct influenced by different aspects related to an action. Consequently, we separately evaluated individuals' perceived control over their item choices (item 1: choice agency) and the outcomes of these choices (item 2: outcome agency; Kaiser et al. 2021b). After agency ratings, participants could advance to the next block at their own pace.

Participants completed a practice session of blocks of 10 free-choice, action-irrelevant forced-choice, and action-relevant forced-choice trials to familiarize themselves with the task. The entire experimental session took approximately 2.5 hours per participant.

Data analysis

Behavioral analysis

MATLAB R2020B and RStudio (Version 2023 June 1) were used for behavioral data analyses. To evaluate participants' learning performance, we tested whether the proportion of high-value item choices was significantly higher than chance level during free choices performed during free-choice and action-relevant forced-choice blocks using a one-sample t-test (two-tailed). Performance was examined by plotting participants' cumulative proportion of high-value item choices over bins of four trials (19 bins) during free-choice blocks, action-relevant forced-choice blocks, and action-irrelevant forced-choice blocks.

We also tested whether participants exhibited different reaction times for high-value item choices in free-choice blocks, forced-choice trials from action-relevant forced-choice blocks, and forced-choice trials from action-irrelevant forced-choice blocks using paired samples t-tests (two-sided).

Repeated-measures ANOVAs with the factors CHOICE (free-choice/action-relevant forced-choice/action-irrelevant forced-choice) and RATING (choice agency/outcome agency) were conducted to assess whether our freedom of choice manipulation influenced participants' postblock agency ratings. To examine the interaction of CHOICE and RATING, follow-up contrasts (t-test, two-sided) were performed, testing whether the effect of choice was larger for choice agency or outcome agency ratings. We quantified participants' judgments as percentage agreement with statements 1 and 2 (Strongly Disagree = 0%, Strongly Agree = 100%; Giersiepen et al. 2023). One participant did not provide agency ratings for the last action-relevant forced-choice block. Here, agency experience was quantified using the mean values of the remaining three action-relevant forced-choice blocks. Agency judgments revealed eight extreme outliers (i.e. values < [1st quartile—3 ∗ interquartile range] or values > [3rd quartile +3 ∗ interquartile range]). Because the outliers did not change the direction or significance of the results, the reported statistics are based on the dataset including extreme values. Follow-up test results were corrected for multiple comparisons using Holm's (1979) method. In cases where Mauchly's test indicated violation of sphericity, we performed Greenhouse–Geisser corrections (uncorrected *df*s are reported for all tests).

Effect sizes for condition-wise differences are reported as Cohen's *d* (small effect: $d = 0.20$; medium effect: $d = 0.50$; large effect: $d = 0.80$), partial eta-squared (small effect: $\eta_p^2 = 0.01$; medium effect: $\eta_p^2 = 0.06$; large effect: $\eta_p^2 = 0.14$; Cohen 1988). Bayes factors (*BF*) are presented to quantify the evidence for the null (H_0), as well as the alternative hypothesis (H_1; weak evidence for H_1: $BF_{10} = 1$ to 3; positive evidence for H_1: $BF_{10} = 3$ to 20; strong evidence for H_1: $BF_{10} = 20$ to 150; very strong evidence for H_1: $BF_{10} > 150$; Raftery 1995).

Data preprocessing

Offline analyses were performed in MATLAB R2020B using Field-Trip software toolbox (Oostenveld et al. 2011). First, a Butterworth Infinite Impulse response two-pass filter (roll-off: 6 db/octave), using 1.0 and 40 Hz as low and high cut-offs, was applied to the raw data. Next, the average of all active electrodes was defined as offline reference (Kaiser et al. 2021a; Giersiepen et al. 2023). Epochs were created from 3,500 ms prior to and 2,500 ms after feedback onset. Next, the data were downsampled to 250 Hz and artifacts resulting from eyeblinks and saccadic eye movements were identified using independent component analysis (logistic infomax ICA algorithm *runica* as implemented in FieldTrip). An average of 2.9 components (*SD* = 0.9, range: 1 to 4) were removed, and the remaining components were projected back to the data. Activation patterns were baseline corrected by subtracting the grand average activity of 200 ms before feedback onset for every trial.

Trials with substantial noise influence (i.e. voltage deflections greater than ±100 μV) were subsequently removed from each dataset, leading to the exclusion of 6.0% trials (*SD* = 5.1, range: 0 to 17.4). We further removed the data of one to three noisy electrodes for 21 participants (*M* = 1.1 electrodes, *SD* = 0.5). Activity at the channel level was reconstructed using spherical spline interpolation (see also Perrin et al. 1989). For condition-wise statistical analyses, only valid trials, defined as trials in which one of the two items was selected during the choice period of free-choice trials or trials in which participants confirmed computer choices during forced-choice trials, were retained, leading to a mean removal of 18.6 invalid trials (*SD* = 22.3, range: 3 to 139) per participant. Note that action-relevant forced-choice blocks ended with a small number of free-choice trials. These were only included to allow us to investigate whether the anticipation of free choices would modulate the processing of feedback presented in response to preceding forced-choice trials. Accordingly, only forced-choice trials of action-relevant forced-choice blocks were included in statistical analyses. Finally, because reinforcement learning is associated with a strong decrease in low-value item choices over time (cf. Fig. 2), we focused our analysis on high-value item choices. Specifically, unlike designs with random reward schedules, learnable tasks with relatively stable reward contingencies, as in the current study, contain very few low-value item choices, especially those with positive feedback, making the analysis of these trials potentially unreliable and highly noisy.

Table 1. Mean number of trials (and standard deviations) for all choice-outcome conditions relevant to electrophysiological statistical analyses.

Trial type	**Feedback valence**	
	Negative	**Positive**
Free-choice	58.6 trials (8.3)	172.1 trials (23.1)
Action-irrelevant forced-choice	59.6 trials (6.2)	172.8 trials (20.1)
Action-relevant forced-choice	42.3 trials (6.9)	125.9 (17.8)

Owing to noncompliance with the task (i.e. selecting the item not chosen by the computer > 2.5 SD more often than average during forced choices), absence of learning (i.e. selecting the low-value item > 2.5 SD more often than average during free choices), or fewer than 25 trials in at least one of the experimental conditions after preprocessing, we excluded three participants from the dataset, resulting in a final sample of 37 participants. In the final dataset, no significant differences in the number of errors could be detected between the free-choice condition (*M* = 5.80, *SD* = 3.67), the action-relevant forced-choice condition (*M* = 3.84, *SD* = 4.25), and the action-irrelevant forced-choice condition ($M = 5.22$, $SD = 4.25$, $F(2, 72) = 2.82$, $P = 0.080$, $\eta_p^2 = 0.07$, $BF_{10} = 0.82$). Participants completed an average of 631.35 trials (*SD* = 73.2, range: 480 to 750; Table 1).

Time–frequency analysis

We used a Surface Laplacian filter (polynomial degree: 10; Perrin et al. 1989; Cohen 2014) to increase the topographical specificity of our time–frequency results. To identify the frequency power over time, we subsequently performed Morlet wavelet convolution. During convolution, the number of cycles linearly increased from three to eight in 19 steps, encompassing frequencies from 2 to 20 Hz (Cohen 2014; Giersiepen et al. 2023). Epochs for statistical analyses were cut from −1,500 to 1,000 ms around feedback onset. The time window from −300 to −100 ms was used for time–frequency-specific baseline normalization. To this end, we converted the data to decibel scale ($dB = 10 * \log10[power/baseline]$) and corrected all time–frequency points by the average oscillatory power over all trials.

Event-related potentials

We employed a time window ranging from −200 to 1,000 ms relative to feedback onset to visualize ERP waveforms during feedback presentation.

Statistical analyses

In line with previous studies, the effect of CHOICE (free-choice/action-relevant forced-choice/action-irrelevant forced-choice) and feedback VALENCE (negative feedback/positive feedback) on MFθ power was expected to be most pronounced from 200 to 600 ms after feedback onset (e.g. Zheng et al. 2020; Kaiser et al. 2022; Giersiepen et al. 2023). To account for temporal smoothing inherent to time–frequency data (Cohen 2014), significant condition differences in midfrontal oscillatory activity were examined from 0 to 1,000 ms relative to feedback onset. We expected the N100 and RewP components to peak around 100 and 300 ms postfeedback onset, respectively (Weiss

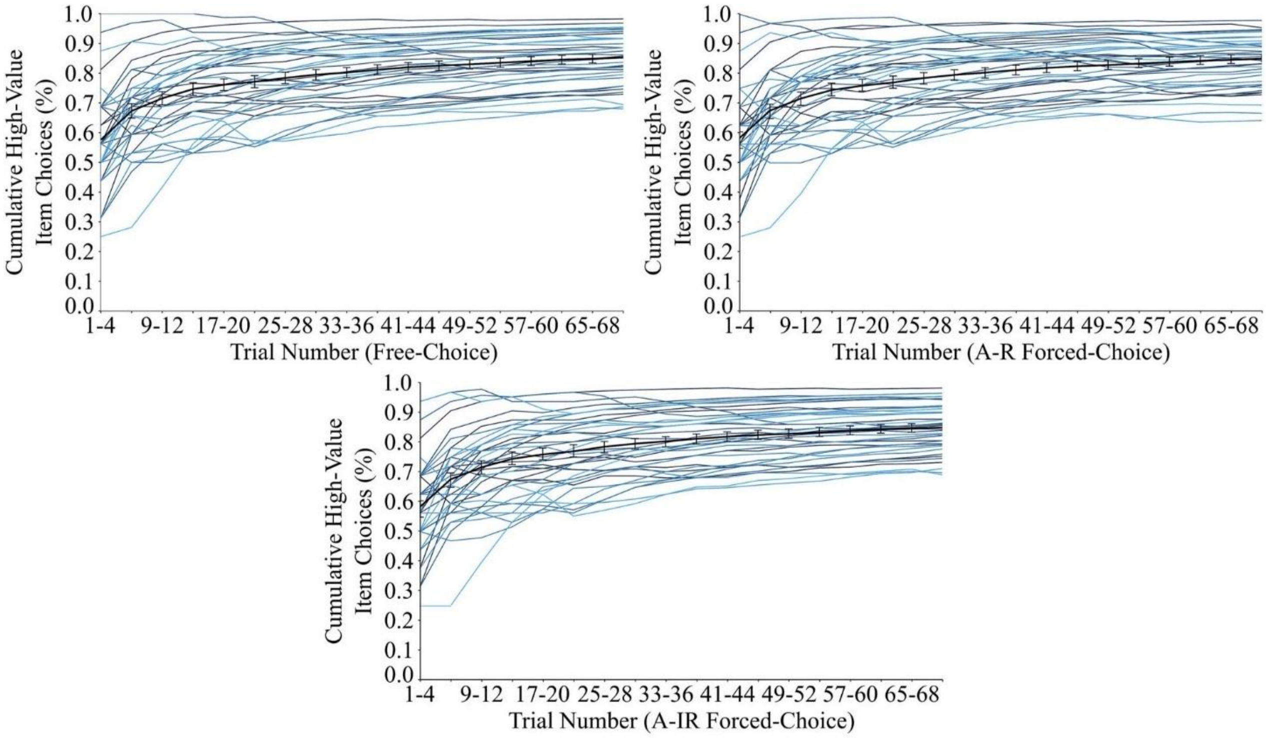

Fig. 2. Behavioral results depicting participant performance as the cumulative proportion of high-value item choices for free-choice blocks (upper left), action-relevant (A-R) forced-choice blocks (upper right), and action-irrelevant (A-IR) forced-choice blocks (lower middle). Black lines show participants' grand average performance, including standard errors. Note that forced-choice item selections were manipulated to mirror participants' free choices.

et al. 2011; Proudfit 2015; Kaiser and Schütz-Bosbach 2018; Zheng et al. 2020). We thus examined differences associated with CHOICE and VALENCE during the first 500 ms of feedback presentation, encompassing both ERP components of interest.

Both theta oscillations and the RewP were previously shown to be most pronounced over midfrontal scalp sites. In addition, agency experience has consistently been found to modulate the N100 component across frontal, central, and parietal scalp sites (e.g. Gentsch and Schütz-Bosbach 2011; Hughes and Waszak 2011; Gentsch et al. 2015; Weismüller et al. 2019). To allow for direct comparison, we therefore employed the same midfrontal electrodes for time–frequency and ERP data and averaged activity for statistical analyses over the midfrontal electrodes Fz, FCz, FC1, and FC2.

We tested the effect of the factors CHOICE and VALENCE on midfrontal oscillatory activity and feedback-locked ERPs using cluster-based permutation *F*-tests and *t*-tests (two-sided, $\alpha = 0.05$) as implemented in FieldTrip (Oostenveld et al. 2011). This approach circumvents the multiple comparison problem inherent to the analysis of multidimensional EEG data (Maris and Oostenveld 2007). During permutation analyses, significant differences of individual data points are evaluated against a predefined alpha level and data points adjacent in time and frequency are summarized into clusters. Cluster size, defined as the sum of test statistics (i.e. *F*- or *t*-values) of all significantly different adjacent data points, is used to determine whether significant differences between conditions exist. Random permutations of the original data are drawn to evaluate whether the probability of finding a cluster of the observed size is greater than would be expected by chance.

We applied the Monte Carlo Method to the largest of the clusters and performed 1,000 random permutations to evaluate whether the data of our experimental conditions stem from the same probability distributions (Maris and Oostenveld 2007). During each permutation, the condition labels, indicating to which condition each data point belongs, were shuffled randomly, while keeping the data points themselves fixed. This process created a null distribution of the test statistic by breaking any systematic relationship between the conditions and the observed data, allowing for the computation of a *P*-value that reflects the likelihood of observing the test statistic if no significant condition differences exist.

Crucially, while the resulting clusters can indicate statistically significant differences between conditions, they do not specify the exact time windows, frequencies, and electrodes where these differences occur (Sassenhagen and Draschkow 2019). Therefore, we confined our analyses to the prespecified time windows and regions of interest (Maris and Oostenveld 2007) and report statistical inferences from cluster-based permutation results along with descriptive information about the cluster's features.

To test whether freedom of choice differentially affects the processing of negative and positive feedback (CHOICE × VALENCE interaction), we subtracted the mean power values during positive feedback presentation from the mean power values of negative feedback for MFθ analyses, as well as mean voltage deflections during negative feedback from the activity observed during the presentation of positive feedback for the N100 and RewP. The resulting condition-wise differences were entered in a repeated-measures ANOVA. To extract the RewP from other ERP components, the resulting difference waveform (positive − negative feedback) was plotted (Proudfit 2015).

Cohen's *d* is reported as a measure of effect size. Effect sizes for significant differences between conditions were determined based on the time (and frequency) characteristics of the clusters detected in the data.

Results

Behavioral results

Participant performance depicting the cumulative proportion of high-value item choices throughout free-choice blocks, action-relevant forced-choice blocks, and action-irrelevant forced-choice blocks is displayed in Fig. 2.

The high-value item was selected significantly more often than chance level during free-choice blocks ($M = 86.9\%$, $SD = 8.5$, range: 69.9 to 99.0), $t(36) = 24.74$, $P < 0.001$, CI 95% [237.2, 253.8], Cohen's $d = 9.83$, $BF_{10} > 10^6$. Participants also selected the high-value item significantly more often than chance level ($M = 86.9\%$, $SD = 10.6$, range: 59.7 to 1.0) in free-choice trials of action-relevant forced-choice blocks, $t(36) = 18.98$, $P < 0.001$, CI 95% [58.3, 63.7], Cohen's $d = 7.62$, $BF_{10} > 10^6$. Thus, participants successfully learned item-reward contingencies in free-choice, and action-relevant forced-choice blocks.

Reaction times of trials during free-choice blocks were significantly higher ($M = 519.67$ ms, $SD = 62.54$, range: 409.63 to 681.26) than reaction times of trials during action-irrelevant forced-choice blocks ($M = 508.22$ ms, $SD = 68.10$, range: 392.84 to 690.22), $t(36) = 2.84$, $P = 0.007$, CI 95% [3.27, 19.64], Cohen's $d = 0.17$, $BF_{10} = 5.41$. Also, reaction times during free-choice blocks were significantly higher than reaction times in action-relevant forced-choice blocks ($M = 508.85$ ms, $SD = 62.92$, range: 420.70 to 691.37), $t(36) = 2.31$, $P = 0.027$, CI 95% [1.32, 20.32], Cohen's $d = 0.17$, $BF_{10} = 1.83$. No significant differences in reaction times were detected for action-relevant forced-choice blocks and action-irrelevant forced-choice blocks, $t(36) = 0.20$, $P = 0.841$, CI 95% [−5.74, 7.02], Cohen's $d = 0.01$, $BF_{10} = 0.18$. Thus, item selections during free choices involved longer response times than those requiring the execution of predetermined responses. This might be because, during forced-choice trials, participants could immediately confirm the preselected item choices without the need to consider the optimal choice. Supporting this interpretation, we also found that forced choices compared to free choices, were associated with higher motor readiness potentials (see Supplementary Materials).

Regarding participants' self-reported agency experience, a two-way ANOVA with the factors CHOICE (free-choice/action-relevant forced-choice/action-irrelevant forced-choice) and RATING (choice/outcome) showed a main effect of CHOICE, with highest judgments for free-choice blocks ($M = 71.5\%$, $SD = 19.3$), followed by action-relevant forced-choice blocks ($M = 41.4\%$, $SD = 8.7$) and action-irrelevant forced-choice blocks, $M = 12.3\%$, $SD = 12.3$, $F(2, 72) = 191.22$, $P < 0.001$, $\eta_p^2 = 0.84$, $BF_{10} > 10^6$ (Fig. 3). In addition, a main effect of RATING was observed, with higher scores for the statement pertaining to freedom of choice ("I was free to choose any item I wanted in this block."; $M = 46.4\%$, $SD = 12.4$) than outcome controllability ("I was in control over the amount of money I gained in this block."), $M = 37.1\%$, $SD = 13.3$, $F(1, 36) = 17.25$, $P < 0.001$, $\eta_p^2 = 0.32$, $BF_{10} = 1.52$. A significant CHOICE × RATING interaction indicated that the effect of choice depended on rating item, meaning that choice condition differentially affected participants' ratings pertaining to choice agency and outcome agency, $F(2, 72) = 29.11$, $P < 0.001$, $\eta_p^2 = 0.45$, $BF_{10} > 10^6$. Post-hoc contrasts revealed that free-choice blocks led to significantly higher choice agency ratings and outcome agency ratings than action-relevant forced-choice blocks (choice agency: $\Delta M = 42.8\%$, $t(36) = 13.58$, $P < 0.001$, CI 95% [36.73, 49.15], Cohen's $d = 2.56$, $BF_{10} > 10^6$; outcome agency: $\Delta M = 17.4\%$, $t(36) = 4.41$, $P < 0.001$, CI 95% [9.39, 25.34], Cohen's $d = 0.74$, $BF_{10} = 276.66$), and action-irrelevant forced-choice blocks

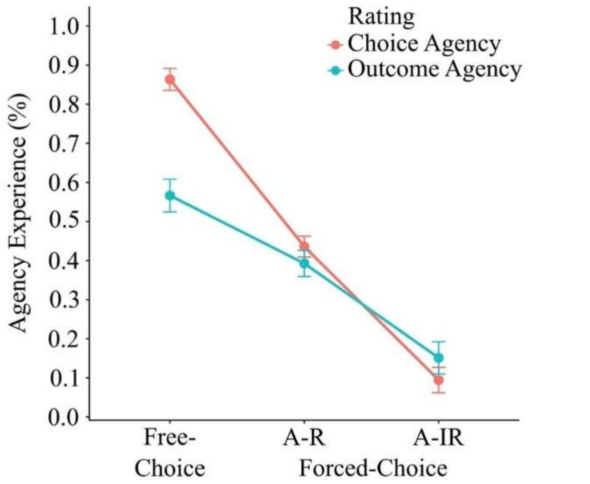

Fig. 3. Mean agency experience (including standard errors) in the three choice conditions (free-choice/action-relevant [A-R] forced-choice/action-irrelevant [A-IR] forced-choice), averaged over participants and blocks. Mean values and lines separately depict participants' agreement with statements relating to freedom of choice (choice agency: "I was free to choose any item I wanted in this block.") and outcome controllability (outcome agency: "I was in control over the amount of money I gained in this block.").

(choice agency: $\Delta M = 76.9\%$, $t(36) = 18.31$, $P < 0.001$, CI 95% [68.37, 85.41], Cohen's $d = 4.16$, $BF_{10} > 10^6$; outcome agency: $\Delta M = 41.5\%$, $t(36) = 7.39$, $P < 0.001$, CI 95% [30.13, 52.90], Cohen's $d = 1.64$, $BF_{10} > 10^6$). Furthermore, action-relevant forced-choice blocks were associated with significantly higher choice and outcome agency ratings than action-irrelevant forced-choice blocks (choice agency: $\Delta M = 34.1\%$, $t(36) = 14.88$, $P < 0.001$, CI 95% [29.48, 38.78], Cohen's $d = 1.85$, $BF_{10} > 10^6$; outcome agency: $\Delta M = 24.1\%$; $t(36) = 7.85$, $P < 0.001$, CI 95% [17.91, 30.39], Cohen's $d = 1.03$, $BF_{10} > 10^6$). Our results indicate that the effect of choice condition is larger for choice agency ratings than outcome agency ratings and show that agency experience decreases with a reduction in the freedom to choose between different response options.

Electrophysiological results

Feedback-induced time-frequency oscillations

Topographical plots depict the scalp distribution of theta power 200 to 600 ms after feedback onset (Fig. 4).

Time-frequency maps with midfrontal oscillatory activity during feedback presentation are shown in Fig. 5. Cluster-based permutation analyses revealed a main effect of CHOICE (free-choice/action-relevant forced-choice/action-irrelevant forced-choice) on feedback processing, $P < 0.001$, Cohen's $d = 0.79$. This cluster encompassed the delta and theta range for the entire duration of feedback presentation.

Post-hoc t-tests (two-sided) revealed a significant enhancement in feedback processing for the free-choice condition compared with the action-relevant forced-choice condition (cluster difference: $\Delta M = 0.63$ dB, $SD = 0.25$, $P = 0.001$, Cohen's $d = 0.72$) and for the free-choice condition compared with the action-irrelevant forced-choice condition (cluster difference: $\Delta M = 0.66$ dB, $SD = 0.33$, $P = 0.001$, Cohen's $d = 0.81$; Fig. 6). No significant differences in feedback processing between the action-relevant forced-choice condition and the action-irrelevant forced-choice conditions were detected (largest cluster: $t_{cluster} = 222.41$, $P = 0.235$). Thus, freedom of choice, but not action relevance, was associated with enhanced neural feedback processing.

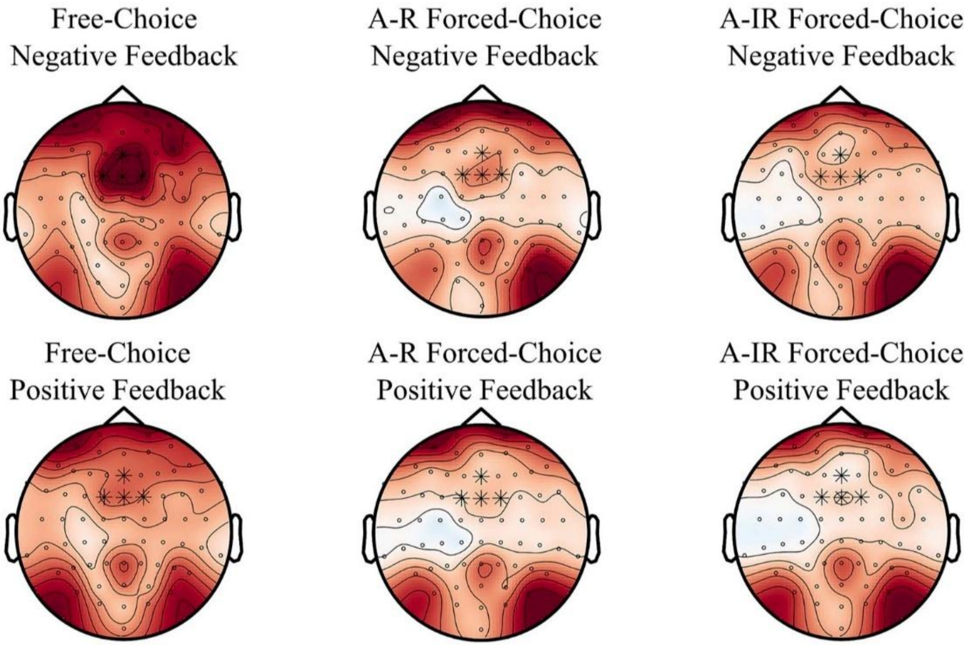

Fig. 4. Topographical plots show the scalp distribution of oscillatory power in the theta range (4 to 7 Hz) between 200 and 600 ms postfeedback onset. Electrodes used for statistical analyses (FC1, FC2, FCz, Fz) are marked as black stars.

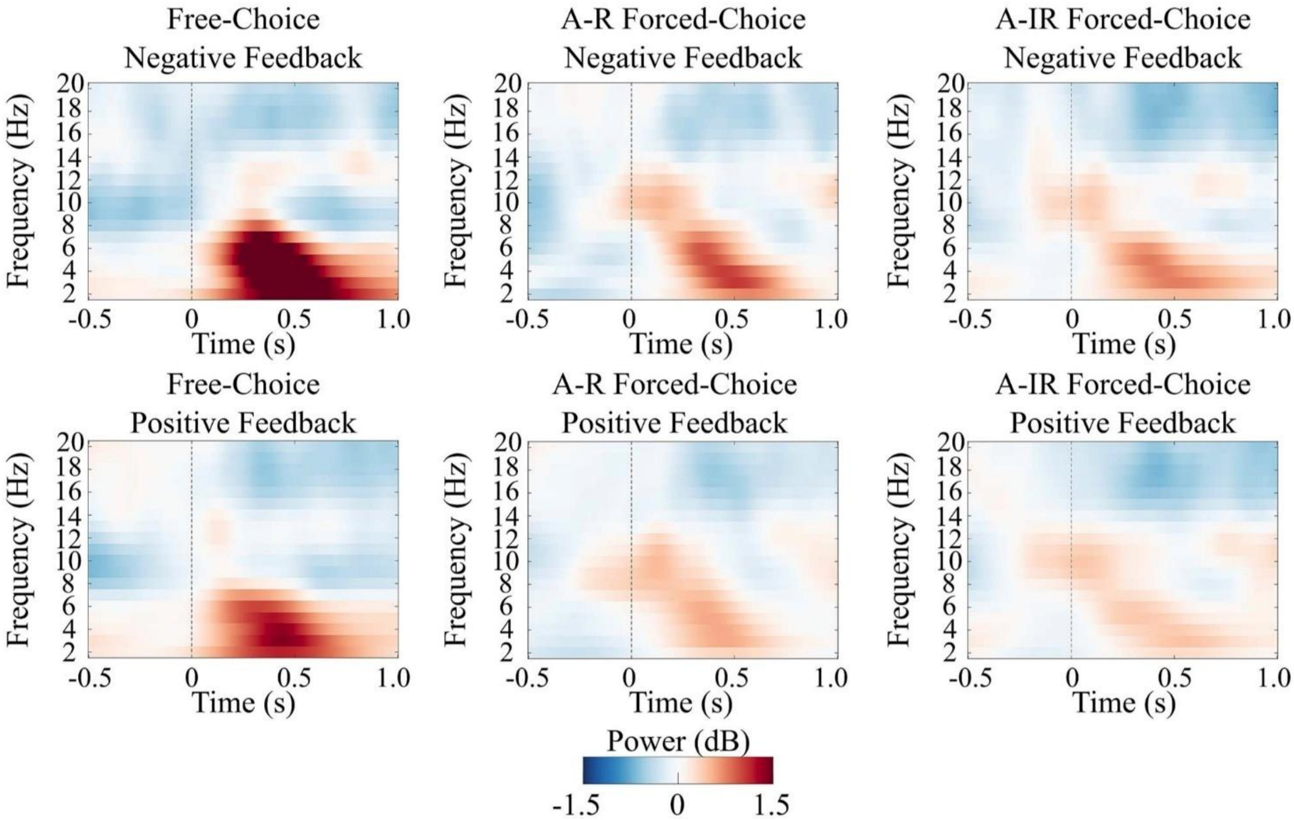

Fig. 5. Time–frequency maps depicting oscillatory power averaged over midfrontal electrodes FC1, FC2, FCz, and Fz for all choice–outcome conditions. Dashed line at time (s) = 0 indicates feedback onset.

We further found a significant effect of VALENCE (negative feedback/positive feedback) on feedback processing, encompassing a cluster from 160 ms until the end of feedback presentation, $P = 0.001$, Cohen's $d = 0.73$. The results indicate that negative feedback led to a significantly larger neural impact than positive feedback (cluster difference: $\Delta M = 0.36$ dB, $SD = 0.16$). As indicated by follow-up t-tests (two-sided), negative compared to positive feedback led to significantly higher midfrontal oscillatory activity in the free-choice condition (150 to 1,000 ms, Cluster difference: $\Delta M = 0.62$ dB, $SD = 0.29$, $P = 0.001$, Cohen's $d = 0.67$), the action-relevant forced-choice condition (260 to 880 ms, cluster difference: $\Delta M = 0.38$ dB, $SD = 0.08$, $P = 0.004$, Cohen's $d = 0.48$), and the

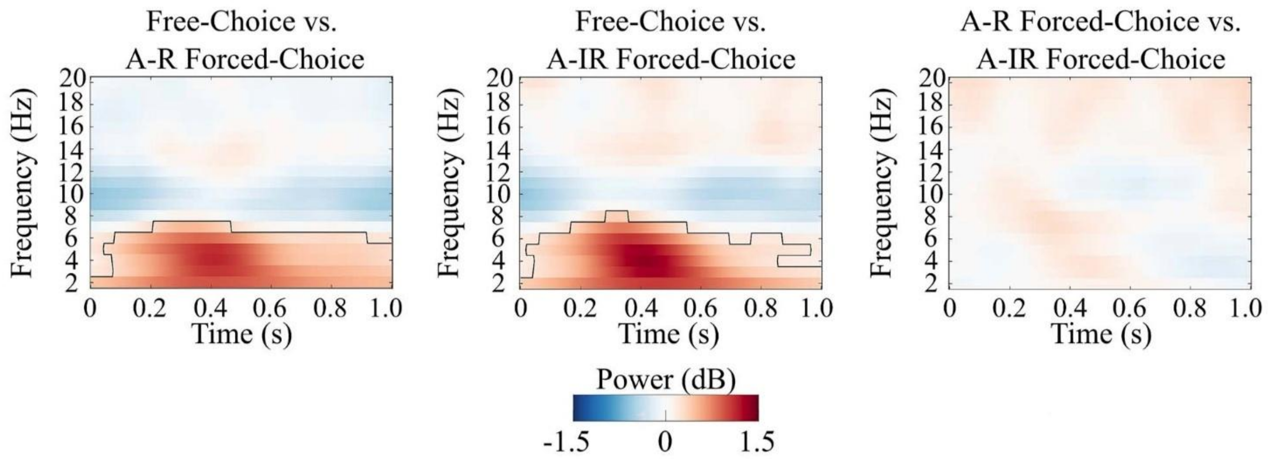

Fig. 6. Results of cluster-based permutation tests, showing the effect of CHOICE (free-choice/action-relevant [A-R] forced-choice/action-irrelevant [A-IR] forced-choice) on feedback processing. Time–frequency points with significant differences between conditions ($P < 0.05$) are marked in black.

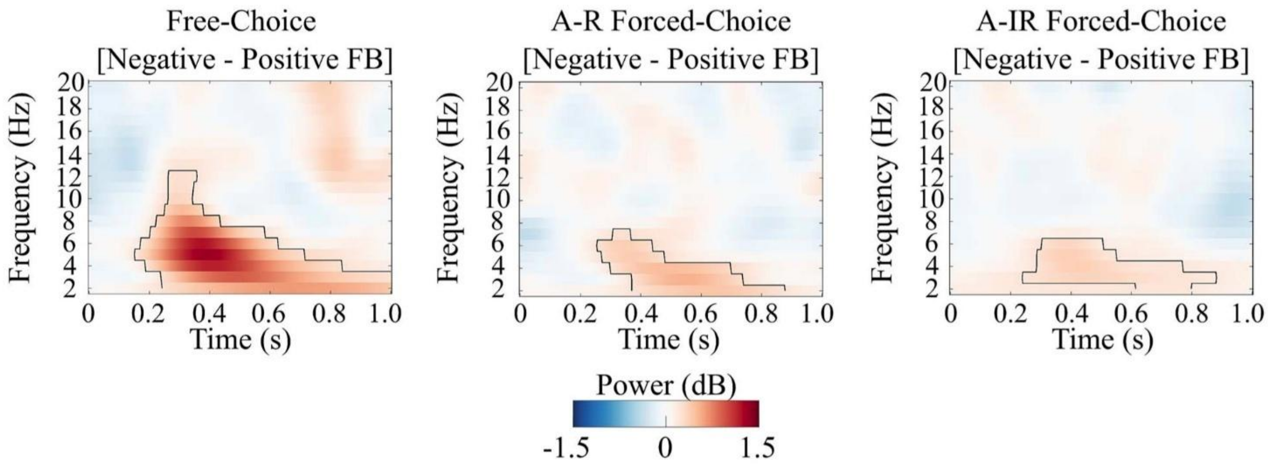

Fig. 7. Results of cluster-based permutation tests, showing the effect VALENCE (negative feedback [FB]/positive feedback [FB]) on feedback processing for free-choice blocks (left), action-relevant [A-R] forced-choice blocks (middle), and action-irrelevant [A-IR] forced-choice blocks (right). Time–frequency points with significant differences between conditions ($P < 0.05$) are marked in black.

action-irrelevant forced-choice condition, 240 to 880 ms, Cluster difference: $\Delta M = 0.28$ dB, $SD = 0.05$, $P = 0.018$, Cohen's $d = 0.41$ (Fig. 7).

A significant 3 × 2 interaction of the factors CHOICE and VALENCE additionally indicated that the effect of choice on midfrontal oscillatory power differed for negative and positive feedback, encompassing a cluster from 200 to 600 ms after feedback onset, $P = 0.002$, Cohen's $d = 0.53$. Follow-up t-tests (two-sided) showed that the difference between negative and positive feedback processing was more pronounced for the free-choice condition than for the action-relevant forced-choice condition (180 to 610 ms, cluster difference: $\Delta M = 0.60$ dB, $SD = 0.16$, $P = 0.004$, Cohen's $d = 0.54$; Fig. 8). In addition, free choices, compared to action-irrelevant forced choices elicited significantly larger oscillatory power for negative compared to positive feedback (cluster difference: $\Delta M = 0.54$ dB, $SD = 0.19$, $P = 0.002$, Cohen's $d = 0.48$). In the observed data, this cluster ranged from 200 to 870 ms post feedback onset and encompassed frequencies in the theta and alpha band. No significant differences in feedback-induced midfrontal oscillatory activity were detected for negative and positive feedback in the action-relevant forced-choice condition compared with the action-irrelevant forced-choice condition (largest cluster: $t_{cluster} = 140.02$. $P = 0.470$).

In summary, the freedom to choose between different response options enhanced affective feedback processing, as observed in midfrontal low-frequency oscillations in our data, both in comparison to action-relevant and action-irrelevant forced choices. This effect was larger for negative feedback than for positive feedback, indicating a neuronal processing bias for negative feedback. No neural differentiation between action-relevant and action-irrelevant outcomes following forced choices could be observed.

Feedback-evoked event-related potentials

Figure 9 displays individual midfrontal ERP waveforms of all choice-outcome conditions as well as difference waves (positive – negative feedback) of the free-choice condition, action-relevant forced-choice condition, and action-irrelevant forced-choice condition. Scalp distributions of the N100, the RewP nondifference waves, and the RewP difference waves are depicted in Fig. 10.

Cluster-based permutation analyses indicated a significant effect of CHOICE (free-choice/action-relevant forced-choice/action-irrelevant forced-choice) on feedback processing during the first 500 ms of feedback processing, $P < 0.001$, Cohen's $d = 0.75$. T-tests (two-sided) revealed significantly more negative amplitudes during free-choice blocks than action-relevant forced-choice blocks, with a cluster extending from 100 to 140 ms post

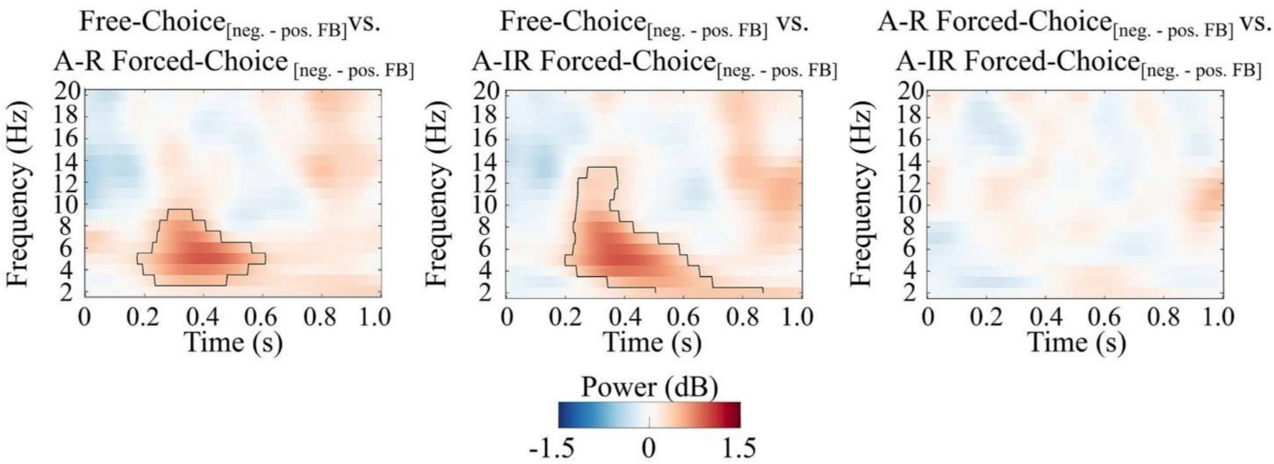

Fig. 8. Results of cluster-based permutation tests, showing the interaction of CHOICE (free-choice/action-relevant [A-R] forced-choice/action-irrelevant [A-IR] forced-choice) and VALENCE (positive feedback [pos. FB]/negative feedback [neg. FB]) over midfrontal electrodes during feedback presentation. Time-frequency points with significant differences ($P < 0.05$) are marked in black.

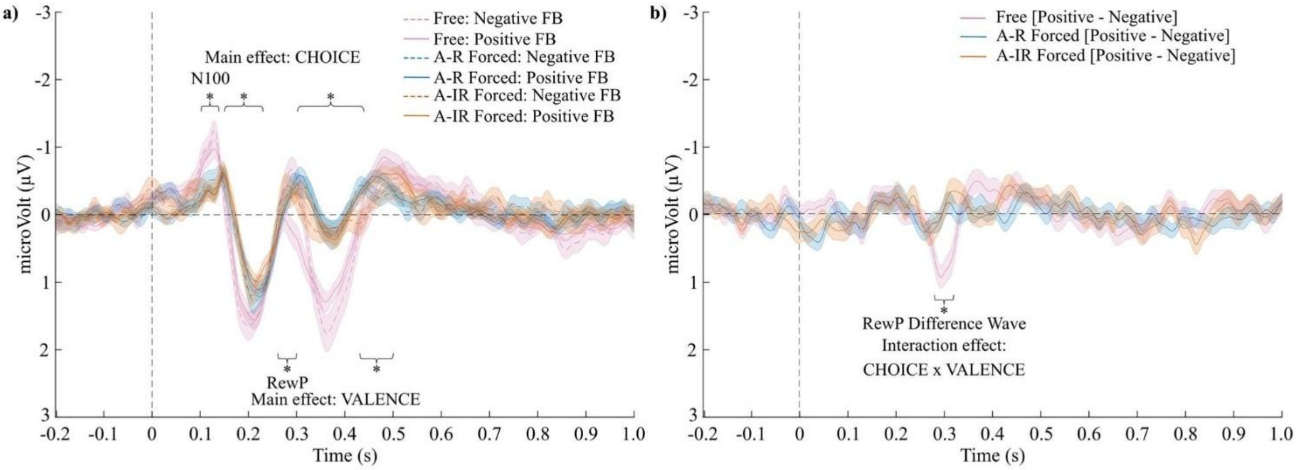

Fig. 9. ERP waveforms over midfrontal scalp sites (FC1, FC2, FCz, Fz). a) Waveforms of all choice (CHOICE: free-choice/action-relevant [A-R] forced-choice/action-irrelevant [A-IR] forced-choice) and outcome (VALENCE: positive feedback/negative feedback [FB]) conditions. Braces with stars above the waveforms indicate time windows for which permutation analyses indicated significantly larger amplitudes in the free-choice compared to the action-relevant and action-irrelevant forced-choice condition. Braces with stars below the waveforms indicate time windows for which permutation analyses indicated significant processing differences for positive and negative feedback. ERP components N100 and RewP are marked. b) Difference waveforms (positive − negative feedback) for the free-choice, the A-R forced-choice, and the A-IR forced-choice condition. The brace with star below the waveforms marks the time window for which a cluster with significant differences was observed in the data. RewP isolated from the difference wave analysis is marked.

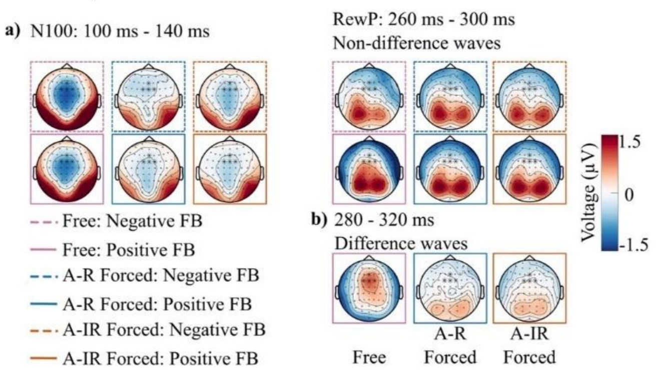

Fig. 10. Topographical plots depicting condition wise scalp distributions of the N100 component (100 to 140 ms), as well as the RewP non-difference (260 to 300 ms) and difference waves (280 to 320 ms) relative to feedback onset. a) Dashed squares around the topographical plots mark negative feedback and solid squares mark positive feedback for the free-choice condition, the action-relevant [A-R] forced-choice condition, and the action-irrelevant [A-IR] forced-choice condition. b) Solid lines are used to mark topographical plots of difference waveforms for the free-choice condition, the A-R forced-choice condition, and the A-IR forced-choice condition.

feedback onset (Cluster difference: $\Delta M = -0.56$ μV, $SD = 0.17$, $P = 0.017$, Cohen's $d = 0.70$), indicating an enhanced N100 amplitude for feedback resulting from free choices compared to action-relevant forced choices. We further observed clusters from 150 to 250 ms and 310 to 420 ms postfeedback onset, with permutation tests indicating significantly larger P200 (cluster difference: $\Delta M = 0.60$ μV, $SD = 0.18$, $P = 0.002$, Cohen's $d = 0.62$) and P300 amplitudes (cluster difference: $\Delta M = 0.89$ μV, $SD = 0.24$, $P < 0.001$, Cohen's $d = 0.83$) in the free-choice condition than the action-relevant forced choice condition during feedback presentation. Free choices also elicited significantly larger amplitudes than action-irrelevant forced choices, with clusters extending over similar time windows (N100: 80 to 140 ms, cluster difference: $\Delta M = -0.44$ μV, $SD = 0.15$, $P = 0.012$, Cohen's $d = 0.61$; P200: 150 to 220 ms, cluster difference: $\Delta M = 0.57$ μV, $SD = 0.21$, $P = 0.010$, Cohen's $d = 0.60$; P300: 300 to 440 ms, cluster difference: $\Delta M = 0.92$ μV, $SD = 0.31$, $P < 0.001$, Cohen's $d = 0.82$). No significant differences in feedback processing could be found for action-relevant and action-irrelevant forced choices during the examined time window (largest cluster: $t_{cluster} = 17.84$, $P = 0.097$). Thus, the freedom to choose between different response options enhances outcome monitoring, as reflected in larger feedback-evoked N100 amplitudes, as well as later ERPs, compared to both the action-relevant and action-irrelevant forced choices.

Cluster-based permutation tests did not reveal a significant effect of VALENCE (positive feedback/negative feedback) on N100 amplitude (largest cluster: $t_{cluster} = 6.92$, $P = 0.345$). A cluster with less negative amplitudes for positive compared to negative feedback was observed from 260 to 300 ms post feedback onset (cluster difference: $\Delta M = 0.31$ μV, $SD = 0.06$, $P = 0.025$, Cohen's $d = 0.47$), indicating the presence of an RewP during this time window. In addition, positive feedback elicited significantly more negative amplitudes during later stages of feedback processing (cluster difference: $\Delta M = -0.26$ μV, $SD = 0.05$, $P = 0.002$, Cohen's $d = 0.48$). The observed cluster ranged from 430 to 500 ms after feedback onset.

Finally, a CHOICE × VALENCE interaction indicated significant differences in RewP amplitude, reflecting processing differences between gain and loss feedback, across choice conditions during the examined time window ($P = 0.001$, Cohen's $d = 0.61$). The detected cluster ranged from 280 to 320 ms after feedback onset. Positive compared to negative feedback elicited significantly larger positive amplitudes in free-choice blocks than in action-relevant forced-choice blocks (cluster difference: $\Delta M = 0.85$ μV, $SD = 0.19$, $P < 0.001$, Cohen's $d = 0.59$) as well as in free-choice blocks than in action-irrelevant forced-choice blocks (cluster difference: $\Delta M = 0.82$ μV, $SD = 0.15$, $P = 0.005$, Cohen's $d = 0.61$). In addition, positive compared to negative feedback evoked significantly more negative amplitudes following free choices than action-irrelevant forced choices, $P = 0.010$, Cohen's $d = 0.53$. This cluster could be observed from 20 to 60 ms after feedback onset (cluster difference: $\Delta M = -0.42$ μV, $SD = 0.08$). No differences in neural processing for positive and negative feedback could be found for action-relevant and action-irrelevant forced-choice blocks (largest cluster: $t_{cluster} = -19.85$, $P = 0.061$). Post-hoc t-tests (two-sided) confirmed that a RewP was only present for free-choice blocks (cluster difference: $\Delta M = 0.74$ μV, $SD = 0.17$, $P < 0.001$, Cohen's $d = 0.68$), whereas no RewP was observed for either action-relevant (largest cluster: $t_{cluster} = 0$, $P = 1.0$) or action-irrelevant (largest cluster: $t_{cluster} = 0$, $P = 1.0$) forced-choice blocks. Additionally, cluster-based permutation analyses for a cluster observed from 420 to 470 ms postfeedback onset indicated a significantly larger negative deflection for negative compared to positive feedback in the action-relevant forced-choice condition (cluster difference: $\Delta M = -0.39$ μV, $SD = 0.05$, $P = 0.014$, Cohen's $d = 0.38$). Also, significantly larger ERP amplitudes could be observed in response to positive compared to negative feedback in the action-irrelevant forced-choice condition, $P = 0.022$, Cohen's $d = 0.45$. In the observed data, this cluster started 10 ms post feedback onset and lasted for 40 ms (cluster difference: $\Delta M = 0.36$ μV, $SD = 0.05$).

In conclusion, freedom of choice enhanced both early and late stages of event-related feedback processing for both positive and negative feedback. While no evidence for an early processing bias for positive or negative feedback could be found (N100), the presence of a RewP during free-choice blocks indicates a processing bias for positive feedback when being endowed with the freedom to choose between different response options.

In response to one reviewer's suggestion to use a less exploratory statistical approach for analyzing the established neurophysiological markers of feedback processing, we also conducted traditional parametric 3 × 2 ANOVAs and post-hoc t-tests (two-sided) across the time windows, regions, and frequencies of interest. The results from these analyses fully corroborate the findings obtained through cluster-based permutations. Detailed results of these tests can be found in the Supplementary Materials.

Discussion

We typically perform actions to attain desired outcomes or to prevent the occurrence of undesired ones. The sense of agency influences the ability to adaptively adjust our behavior in accordance with these objectives. To examine how the brain differentiates self- and externally determined actions during goal-directed behavior, the present study examined how choice autonomy influences the processing of affective action outcomes during reinforcement learning. To this end, we recorded EEG while participants completed a computer-based learning task involving free and forced choices.

As intended in reinforcement learning tasks, participants increasingly chose the high-value item throughout block progression during free-choice blocks, thereby maximizing their final payout. Successful learning of item–outcome associations could also be observed in action-relevant forced-choice blocks, reflected in participants' item selections during free choices of this block. Corroborating previous work examining the influence of freedom of choice on learning performance (Chambon et al. 2020), our results therefore indicate similar feedback learning during free-choice blocks and action-relevant forced-choice blocks, suggesting that participants learned from feedback both during free-choice and forced-choice trials. Furthermore, our results resonate with findings from studies examining learning from action versus observation, showing similar learning rates in both contexts (Bellebaum et al. 2010; Kobza and Bellebaum 2015; Weismüller et al. 2019). Slower reaction times during free compared to forced choices may further reflect the selective involvement of decision-related processes during self-determined but not externally determined item selections. Supplementary analyses of response-evoked neural processing indicate that this may be reflected in a reduced amplitude of the readiness potential during free compared to forced choices.

Our neurophysiological results show that the freedom to choose between response options enhances both sensory and evaluative markers of feedback processing, reflected in greater N100 amplitudes, larger midfrontal low-frequency power, and a selective RewP during free-choice compared to action-relevant and action-irrelevant forced-choice blocks, respectively. Crucially, prior results showing heightened outcome monitoring for free choices over forced ones (e.g. Weismüller et al. 2019; Chang et al. 2020; Zheng et al. 2020; Giersiepen et al. 2023) could be attributed to two distinct mechanisms: (i) the association of outcomes with recent self-determined choice, highlighting agency-specific influences on outcome processing, and (ii) the enhanced relevance of outcomes for participants' future decisions, indicating variations in the informational value of feedback across choice conditions. Differing from these studies, our current research discriminates between action-relevant forced-choices (where outcomes are informative for future action decisions) and action-irrelevant forced choices (where outcomes do not inform future decisions), thus enabling a clearer separation of these explanations. If neural feedback processing was sensitive to the relevance of outcomes for future actions, we would have expected enhanced outcome processing for action-relevant compared to action-irrelevant forced choices. Yet, the results from the current study reveal similar feedback-induced outcome monitoring for action-relevant and action-irrelevant forced choices, reflected in both midfrontal oscillatory activity and feedback-evoked potentials, indicating that these markers do not track the relevance of affective action outcomes for subsequent behavior. Instead, freedom of choice enhances the processing of affective action outcomes, even if forced choice outcomes are relevant for future actions. By demonstrating that free choices enhance outcome monitoring compared to forced choices, our findings corroborate prior research, on observational learning, suggesting that midfrontal outcome processing, signified in MFθ activity, N100, and RewP, may play a predominant role for learning from self- but not externally determined actions (Bellebaum et al. 2012; Kobza et al. 2012; Kobza and Bellebaum 2015). Importantly, by distinguishing between action-relevant and action-irrelevant forced choices, our results indicate that heightened outcome processing during free-choice blocks is driven by the association of outcomes with recent self-determined choice rather than the practical significance of outcomes for future actions. In other words, the enhanced processing of outcomes is more about the psychological impact of making one's own choices, rather than how informative the outcome is for what the individual decides to do next.

Notably, the choice-induced enhancement in outcome processing was not specific to the N100 and RewP but could also be observed in feedback-locked P200 and P300 amplitudes, potentially reflecting increased attentional engagement associated with higher levels of perceived control during free compared to forced choices (e.g. Yeung et al. 2005; Mühlberger et al. 2017; Han et al. 2021). Our results therefore indicate that agency experience, in the form of self-determined choice, leads to a general enhancement in affective outcome monitoring.

At first glance, the enhanced N100 amplitude during self-determined choice may seem contradictory to a large body of work linking agency experience to sensory attenuation (see Gentsch and Schütz-Bosbach 2015). However, considering the functional role of action outcomes, we believe that our findings are consistent with these studies. In studies of sensory attenuation, outcomes typically do not carry instrumental affective value. In contrast, the current study employed motivationally salient action outcomes that inform participants whether item choices were correct (i.e. are likely to result in a gain of money) or incorrect (i.e. are likely to result in a loss of money). Thus, depending on the task context, self-determined choice may selectively increase or decrease the neural impact of action outcomes. In line with this prediction, previous work suggests that N100 amplitude is sensitive to more general processes, including attentional processes and task context (Kaiser and Schütz-Bosbach 2018). Accordingly, our results indicate a greater deployment of attentional resources, reflected in enhanced N100 amplitudes for free- compared to action-relevant and action-irrelevant forced choices.

In line with research associating MFθ activity with conflict monitoring and cognitive control during learning (e.g. Cavanagh et al. 2010), our results showed increased MFθ power for negative feedback compared with positive feedback. Differentiation of gain and loss feedback was observed for all three choice conditions (free-choice/action-relevant forced-choice/action-irrelevant forced-choice), indicating that oscillatory activity in the theta range tracks outcome valence for all self-relevant action outcomes. Yet, this effect was most pronounced in the free-choice condition (see also Zheng et al. 2020), potentially reflecting that negative outcomes are perceived as more aversive when they are self- rather than externally controlled (Majchrowicz and Wierzchoń 2021). Negative outcomes under conditions of high agency experience (i.e. free-choice) may consequently induce greater cognitive conflict and elicit more cognitive control to prevent negative outcomes in the future. Our findings extend previous research comparing active to observational learning (e.g. Weismüller et al. 2019) by suggesting that this cognitive conflict is not solely driven by the instrumental value of the outcomes but rather the self-determination associated with them.

Conversely, analyses of ERP waveforms indicate a valence-specific processing bias for positive feedback. Our results show that an RewP, reflecting increased neural responses for positive compared to negative feedback, was only present in the free-choice condition. Thus, whereas MFθ power was increased for negative feedback compared with positive feedback in both free- and forced-choice conditions, an RewP was present only for self-determined action outcomes. The RewP has been associated with reward evaluation (Becker et al. 2014), reward prediction error (Zheng et al. 2020), motivational intensity, and the informational value of outcomes for subsequent action (Mühlberger et al. 2017). Given similar performance during free-choice blocks and action-relevant forced-choice blocks as well as the implementation of identical item–outcome associations in all choice conditions, differences in the instrumental value of feedback or outcome predictability unlikely account for the selective presence of a RewP during free-choice blocks. Rather, the motivational salience or subjective value of outcomes seems to be increased when actions are self- rather than externally determined (see also Mei et al. 2018). Accordingly, recent behavioral results indicate that only free choices are associated with differential weighting of positive and negative feedback during reinforcement learning, whereas outcomes of forced choices are treated impartially, meaning valence-neutral, regardless of their positive or negative affective value (Chambon et al. 2019, 2020).

Interestingly, while many previous studies have observed a diminished RewP for positive outcomes after forced choices compared to free choices (e.g. Yeung et al. 2005; Mühlberger et al. 2017; Mei et al. 2018; Hassall et al. 2019; Zheng et al. 2020), these studies typically employed gambling tasks with random reward schedules. Consequently, while participants may use the outcomes of their actions to influence their subsequent choices, the randomness limits their ability to establish consistent item–outcome associations for reliable outcome prediction over time. In contrast, the reinforcement learning task of the current study enabled participants to develop concrete outcome expectations, thereby diminishing the element of surprise (i.e. prediction error) associated with receiving feedback. Considering that RewP amplitude is known to decrease with increasing outcome predictability (Krigolson et al. 2014; Williams et al. 2020; Weber and Bellebaum 2024), the absence of a RewP in both action-relevant and action-irrelevant forced choices in the current experiment suggests that this neural marker differentiates between positive and negative outcomes based on their predictability from prior actions, but only when those outcomes were self-, not externally, controlled. In the current experiment, successful learning was only established based on free choices in the free-choice and action-relevant forced-choice blocks. This approach was necessary, since including an assessment of learning in the action-irrelevant forced-choice blocks would have made the feedback automatically action-relevant. Nevertheless, we cannot fully exclude the possibility that differences in learning-related reward prediction errors between free choices, action-relevant forced-choices, and action-irrelevant forced choices influenced the observed differences in outcome processing. If outcome processing in the current study was modulated by reward prediction error, the absence of significant processing differences between the action-relevant and action-irrelevant forced-choice condition could be interpreted as an indicator of comparable learning in both conditions. However, this possibility needs to be further tested in future studies.

Taken together, both the increased impact of negative feedback on MFθ oscillations and positive feedback on RewP during free choices may be reconciled within the reward-based framework of perceived control (Leotti et al. 2015; Murayama et al. 2015; Ly et al. 2019; Wang et al. 2021). The framework builds on theories of perceived control and empirical evidence that both highlight the fundamental drive of humans to exert control when interacting with the environment. More specifically, the opportunity to choose is thought to be inherently rewarding and to elicit activity in reward-related dopaminergic cortico-striatal circuits (Fujiwara et al. 2013). In addition, activity in the medial prefrontal cortex (including the ACC) in response to aversive events has been found be modulated by perceived control (Kolling et al. 2016), pointing toward improved coping with aversive events when endowed with the opportunity to exert control through choice. Consequently, freedom of choice is suggested to increase motivational and affective processing in response to both positive and negative feedback. The choice-induced enhancement in MFθ power and RewP amplitude in response to negative and positive feedback, respectively, therefore plausibly reflects an increase in the motivational salience and subjective value of affective action outcomes when they are self-compared to externally determined (see also Gentsch et al. 2015; Majchrowicz and Wierzchoń 2021; Wang et al. 2021). In contrast to MFθ oscillations and the RewP, N100 amplitude was unaffected by feedback valence. The N100 reflects early stages of feedback processing, and its amplitude has been shown to be modulated by selective attention and the predictability of action outcomes (Hillyard et al. 1998; Kaiser and Schütz-Bosbach 2018). In line with the interpretation that freedom of choice increases motivational processing, the increase in N100 amplitude for free compared to forced choices might reflect an increased deployment of attentional resources to monitor affective action outcomes. In a similar vein, sense of agency over action outcomes has previously been reported to increase N100 amplitude in response to auditory effects without affective valence, if outcomes under conditions of high and low agency experience are equally predictable (Kaiser and Schütz-Bosbach 2018).

To examine whether our freedom of choice manipulation also affected participants agency judgments, we complemented our neurophysiological measures with self-reported agency ratings after each block. As expected, participants reported highest choice agency ("I was free to choose any item I wanted in this block.") during free-choice blocks, followed by action-relevant forced-choice blocks and action-irrelevant forced-choice blocks. A similar albeit smaller decrease from free-choice to action-irrelevant forced-choice blocks could be observed for outcome agency ("I was in control over the amount of money I gained in this block.") ratings. Thus, participants' agency experience increased when they were endowed with the freedom to choose between different response options. These findings highlight that enhanced outcome processing during self-determined choice is paralleled by greater perceived control during reinforcement learning. When experiencing control, we may be more inclined to monitor the opportunities for interaction available in our environment, resulting in greater sensitivity, especially for motivationally salient stimuli that indicate our success or failure of achieving a desired goal. Increased outcome monitoring in situations of high perceived control may consequently reflect an increased investment of cognitive resources, such as cognitive control and conflict monitoring (Frömer et al. 2021).

Retrospective agency ratings after each block were in line with the ratio of free-choice trials of that block, with lowest agency ratings for blocks with only forced-choice trials (action-irrelevant forced choice), higher agency ratings with blocks containing some free-choice trials (action-relevant forced choice), and highest agency ratings for blocks with only free choices (free choice).

Notably, the differential effect of block type on choice and outcome agency ratings highlights the multifaceted nature of the sense of agency, shaped by distinct cues to agency experience (e.g. Synofzik et al. 2013; Sidarus et al. 2017; Hassall et al. 2019). Whereas choice comprised a reliable, deterministic cue to the sense of agency in the current experiment, outcomes were probabilistically associated with item choices. Accordingly, our agency manipulation more strongly affected participants' freedom of choice judgments than their perceived control over action outcomes. These results are in line with predictions from optimal cue integration accounts of the sense of agency (Synofzik et al. 2013) and support previous findings that illustrate the influence of distinct task components on the sense of agency (Giersiepen et al. 2023).

As self-reported agency experience was assessed after participants completed individual blocks of trials, it should be noted that their ratings may be strongly shaped by retrospective processes, including the predictability of action outcomes and a higher rate of positive compared to negative feedback during learning blocks (Synofzik et al. 2013). Consequently, agency ratings are inclined to reflect higher-level beliefs rather than moment-to-moment changes in agency experience, precluding the assessment of immediate, lower-level changes in the sense of agency such as the influence of outcome valence. Likewise, future studies could investigate the relation between subjective agency ratings and neural reactivity during feedback presentation more closely by having participants rate their agency after each trial. Including trial-wise agency judgments in future studies using motivationally salient positive and negative feedback would advance our understanding of how affective processes influence agency experience and outcome evaluation.

Conclusion

In conclusion, our finding that freedom of choice during reinforcement learning enhances MFθ oscillations as well as early (N100) and late (RewP) event-related markers of feedback processing, irrespective of the relevance of forced-choice outcomes for subsequent actions, suggests that linking outcomes to self-determined decisions heightens their motivational importance and perceived value. However, further research concerning the functional role of choice-induced effects on affective outcome processing is needed to develop a comprehensive understanding of the practical significance of these results. During everyday behavior, the affective valence of outcomes is central for assessing actions as successful or not. In a recent review, Kaiser et al. (2021b) proposed that outcome processing functionally mediates agency-related improvements in action regulation. Whether increased outcome monitoring under conditions of self-determined choice leads to improved behavioral adaptation should therefore be directly tested in future studies. In a similar vein, further studies are needed to systematically test whether increased MFθ power and RewP amplitudes during free choices are predominantly driven by the motivational salience of action outcomes, by an increase in the subjective value of self-determined action outcomes, irrespective of motivational involvement, or whether these two processes interact in the neural enhancement of self-determined action outcomes.

To summarize, our study shows that the sense of agency, operationalized as freedom of choice, enhances the neural impact of positive and negative feedback during reinforcement learning, as reflected in an enhanced N100 and RewP amplitude as well as increased MFθ power for free compared to forced choices. Crucially, we show that this choice-related enhancement in outcome processing is not driven by the relevance of outcomes for future actions but rather stems from the association of outcomes with self-determined choice. Taking into consideration the reward-based framework of perceived control, we interpret more pronounced theta power for negative feedback and the selective expression of an RewP during free choices as indicative of increased motivational salience and subjective value of self-compared to externally induced action outcomes. Future research is required to further disentangle motivational processes and agency-related differences in subjective value and test the functional significance of enhanced outcome processing during self-determined choice.

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Author contributions

Maren Giersiepen (Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Project administration, Software, Visualization, Writing—original draft), Simone Schütz-Bosbach (Conceptualization, Funding acquisition, Supervision, Writing—review & editing), and Jakob Kaiser (Conceptualization, Funding acquisition, Methodology, Software, Supervision, Writing—review & editing).

Supplementary material

Supplementary material is available at *Cerebral Cortex* online.

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Data availability

Data and study materials can be found online at https://osf.io/6tsxv/?view_only=fd79377cfcb548e29155337e665a4ff5.

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Supplementary Materials

Power Analysis

G*Power (Version 3.1.9.7; Faul et al. 2007) was used for power calculation in the current study. Previous studies have reported medium to large effects of freedom of choice and outcome valence on outcome processing, specifically the RewP (Mühlberger et al. 2017; Hassall et al. 2019; Zheng et al. 2020) and MFθ (Wang et al. 2016; Zheng et al. 2020). Furthermore, medium to large effects are reported for the effect of agency on N100 amplitude (Kaiser and Schütz-Bosbach 2018). Based on these findings, we determined the required sample size for finding a medium effect with a desired power of 80% ($\alpha = .05$), a correlation among repeated measures of $r = .5$ and a non-sphericity correction $\varepsilon = 1$ for a repeated-measures ANOVA. Given that G*Power's functionality does not provide a straightforward solution for power analyses for two-way ANOVAs (Brysbaert 2019), we approximated the required sample size using a one-way ANOVA with a single three-level factor. This analysis indicated that a sample size of 28 is required to detect a medium effect size. Recognizing that the examination of interactions in our study might require a larger sample, we complemented our power analysis with comparisons to previous studies that also examined interactions. Based on these insights, we concluded that our sample size is likely suitable to find effects of choice and outcome valence on outcome processing.

Neurophysiological Correlates of Movement Preparation: The Readiness Potential

Analysis of high- and low-value item choices suggests similar learning of item-outcome associations in free-choice and action-relevant forced-choice blocks. Furthermore, previous research indicates larger amplitudes of the readiness potential (RP), an ERP component time-locked to movement onset, when experiencing a high compared to a low sense of agency, potentially reflecting differences in the degree to which the movement is experienced as voluntary (Jo et al. 2014). In exploratory analyses, we therefore examined how freedom of choice and item-outcome learning influenced RP amplitude.

To examine the influence of CHOICE on electrophysiological activity prior to movement onset, we tested whether the amplitude of RP differed between free-choice, action-relevant forced-choice and action-irrelevant forced-choice blocks using cluster-based permutation F-tests and t-tests (two-sided). To additionally examine whether learning (i.e., block progression) was associated with an increase or decrease in RP amplitude, we examined correlations of block progression (TRIAL; indexing learning) and RP amplitude (AMPLITUDE).

The RP is characterized by a slow, gradual increase in negativity prior to movement onset thought to index voluntary movement preparation (Schurger et al. 2021). It is most pronounced over central electrodes and peaks contralateral to the moving limb. To analyze the RP, epochs ranging from 1500 ms prior to 1000 ms post movement onset were created, and baseline corrected to the average of the time window -1500 ms to -1300 ms prior to action. As all participants responded using their right-hand index finger, activity of electrode C3 was analyzed to examine the RP.

The ERP waveforms and topographical plots of all three choice conditions are depicted in Figure 1. Cluster-based permutation F-tests indicate a significant effect of CHOICE on RP amplitude from 210 ms to 140 ms prior to feedback onset, p = .003, Cohen's d = 0.43. Topographical plots confirm that activity during this time window was maximally negative over electrode C3. Pairwise t-tests indicated significantly more negative RP amplitudes in the action-relevant forced-choice condition compared to the free-choice condition (-180 ms – -140 ms, p = .032, Cohen's d = 0.48) and in the action-irrelevant forced-choice condition compared to the free-choice condition (-220 ms – -140 ms, p = .002, Cohen's d = 0.49) during this time window. No significant differences in RP amplitude could be observed for the action-relevant and the action-irrelevant forced-choice condition (largest cluster: $t_{cluster}$ = 9.68, p = .450).

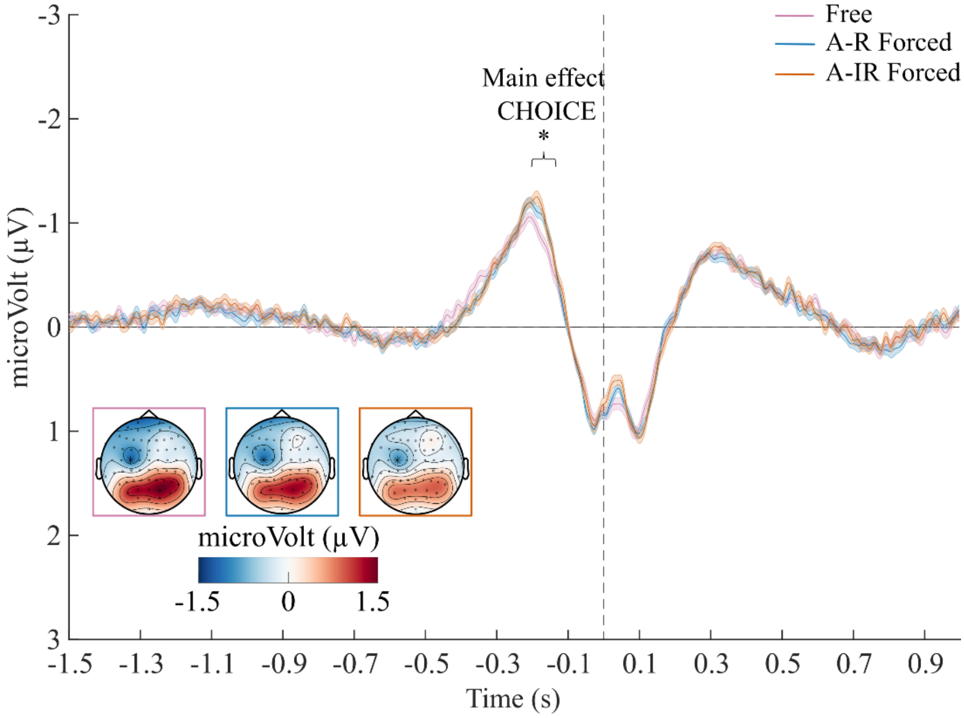

Figure 1. Movement-locked ERP waveforms over electrode C3. The plot depicts waveforms for the free-choice (purple), action-relevant [A-R] forced-choice (blue), and action-irrelevant [A-IR] forced-choice (orange) condition. Braces with stars above the waveforms indicate the main effect of CHOICE on RP amplitude. The dashed vertical line at Time = 0 indicates movement onset.

Our results therefore suggest a reduction in RP when participants are endowed with freedom of choice, indicating that cognitive aspects of choice-induced agency experience are reflected in reduced RP amplitudes. Typically, a larger RP indicates movement planning and preparation associated with initiating a voluntary movement compared to an externally instructed one (e.g., Khalighinejad et al. 2019; Schurger et al. 2021; Travers et al. 2021). In most of these studies, instructed actions differ from voluntary ones in the timing at which participants perform the action. The diverging results in the current study compared to previous ones might therefore lie in how voluntary actions are operationalized. Notably, in the current task, both free- and forced-choice actions were constrained to a one-second time window. Thus, although the action target could be either freely chosen or externally determined, both scenarios involved cued responses, indicated by the onset of stimulus presentation during the choice period. Additionally, free-choice trials involved both decision-related processing and motor preparation. In contrast, forced-choice trials required participants only to react to a pre-determined response option, potentially augmenting the neural processes associated with motor preparation during externally determined actions.

Figure 2 displays trial-wise movement-locked ERP voltage as a function of time. To examine whether block progression was associated with a decrease or increase in RP amplitude, as observed at electrode C3, we determined RP peak amplitude across all (t_{peak} = - 204 ms) and for the individual choice conditions ($t_{peak\_free\text{-}choice}$ = - 208 ms; $t_{peak\_AR\_forced\text{-}choice}$ = - 188 ms; $t_{peak\_A\text{-}IR\_forced\text{-}choice}$ = - 208 ms) and correlated the average activity $\pm$ 50 ms relative to the RP peak (AMPLITUDE) with trial number (TRIAL). After correcting for multiple comparisons using Holm's method (1979), correlation analyses indicate a negative but non-significant association of RP amplitude and task progression across choice conditions (r = - .27, p = .082) or for the individual choice conditions (free-choice: r = - .16, p = .191; action-relevant forced-choice: r = - .22, p = .222; action-irrelevant forced-choice: r = - .26, p = .074). Thus, movement preparatory processes, as reflected in the RP, did not change with learning of item-outcome associations, potentially reflecting a predominant influence of action- but not decision-related processes on RP during reinforcement learning.

A reduced RP during free choices compared to action-relevant and action-irrelevant forced choices complements the results observed during feedback presentation and indicates that the freedom to choose, not the action relevance of outcomes, alters neural processing during free compared to forced choices.

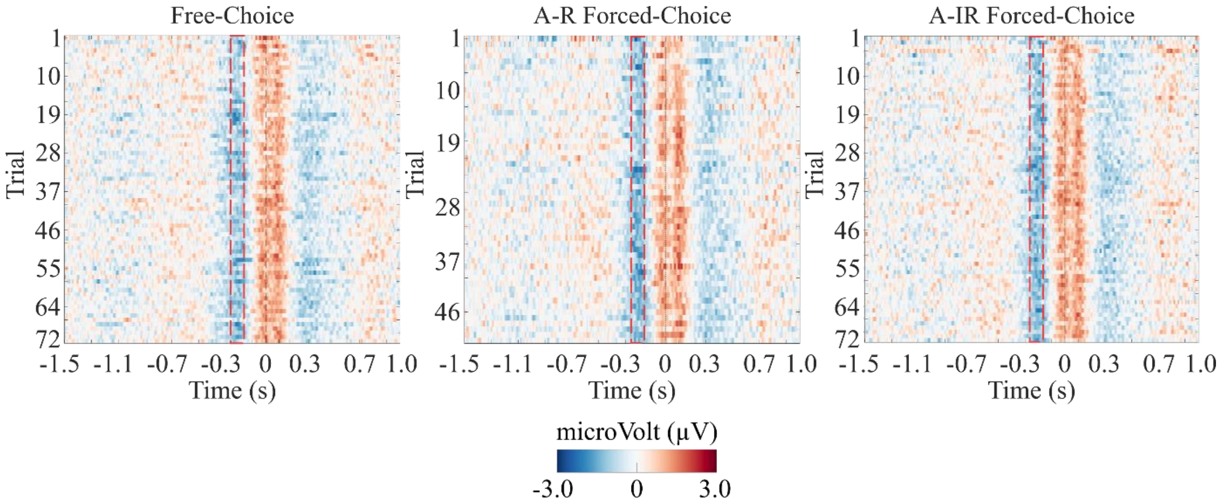

Figure 2. Trial-wise ERP amplitude over electrode C3, averaged over blocks of free choices (left), action-relevant [A-R] forced-choices (middle), and action-irrelevant [A-IR] forced-choices (right). Time = 0 indicates movement onset of each trial. The red dashed lines highlight the time windows used for correlation analyses, including ± 50 ms around the peak of RP amplitude in each condition.

Parametric Analysis of Neurophysiological Data

Methods

To examine the influence of choice and outcome valence on midfrontal theta power, we averaged midfrontal theta (4 – 7 Hz) activity of each condition from 200 ms to 600 ms after feedback onset over midfrontal electrodes (FC1, FC2, FCz, Fz; Luft et al. 2013; Zheng et al. 2020; Giersiepen et al. 2023).

To examine choice and valence-evoked differences in ERP amplitudes, we averaged midfrontal activity (FC1, FC2, FCz, Fz) from 50 ms to 150 ms post feedback onset for the N100 component and, in accordance with previous literature (Yeung et al. 2005; Bellebaum et al. 2010; Mühlberger et al. 2017), analyzed the RewP using the average activity from 250 ms to 350 ms post feedback onset. To extract the RewP, we further calculated the difference in mean amplitude for positive compared to negative feedback (positive – negative) during this time window.

The preprocessed data were submitted to a repeated measures ANOVA with the factors CHOICE (free-choice/action-relevant forced-choice/action-irrelevant forced-choice) and VALENCE (negative/positive). Greenhouse Geiser corrections were applied if sphericity was violated (uncorrected *df*s are reported for all tests).

To follow-up CHOICE x VALENCE interactions, post-hoc contrasts were calculated using the difference score of feedback-induced neural activity in response to negative compared to positive feedback for each choice condition (Kaiser et al. 2019). Post-hoc comparisons were corrected for multiple testing using Holm's method (1979). Statistical analyses were performed in RStudio (Version 2023.06.1).

Results

Midfrontal Theta Power. The ANOVA revealed a significant effect of CHOICE on feedback-induced midfrontal theta power, $F(2, 72) = 28.79$, $p < .001$, $\eta_p^2 = .44$, $BF_{10} > 10^6$. Pairwise comparisons revealed significantly larger theta power during free-choice blocks than during action-relevant forced-choice blocks, $\Delta M = 0.72$ dB ($SD = 0.47$), $t(36) = 5.41$, $p < .001$, CI 95% [0.45, 0.99], Cohen's $d = 1.04$, $BF_{10} = 4497.40$. Similarly, free-choice blocks were associated with significantly larger MFθ power than action-irrelevant forced-choice blocks, $\Delta M = 0.86$ dB ($SD = 0.48$), $t(36) = 6.29$, $p < .001$, CI 95% [0.59, 1.14], Cohen's $d = 1.25$, $BF_{10} =$

55817.28. No significant processing differences in theta power could be detected between action-relevant and action-irrelevant forced choices, *ΔM* = 0.14 dB (*SD* = 0.01), $t(36) = 1.58$, $p = .124$, CI 95% [-0.04, 0.03], Cohen's $d = 0.31$, $BF_{10} = 0.55$. The ANOVA also revealed a main effect of VALENCE, with higher MFθ power in response to negative compared to positive feedback, *ΔM* = 0.43 dB (*SD* = 0.41), $F(1, 36) = 41.90$, $p < .001$, $\eta_p^2 = .54$, $BF_{10} > 10^6$.

Lastly, the ANOVA revealed a significant CHOICE x VALENCE interaction, indicating that the effect of choice on outcome processing depends on whether feedback was positive or negative, $F(2, 72) = 13.39$, $p < .001$, $\eta_p^2 = .27$, $BF_{10} > 10^6$. The stronger increase in MFθ power in response to negative compared to positive feedback was significantly larger in the free-choice compared to the action-relevant forced-choice condition ($t(36) = 4.39$, $p < .001$, CI 95% [0.31, 0.83], Cohen's $d = 0.83$, $BF_{10} = 258.34$), as well as in the free-choice compared to the action-irrelevant forced-choice condition, $t(36) = 3.96$, $p < .001$, CI 95% [0.30, 0.92], Cohen's $d = 0.92$, $BF_{10} = 82.10$. Action-relevant compared to action-irrelevant forced-choices did not differentially affect MFθ power for positive and negative feedback, $t(36) = 0.38$, $p = .706$, CI 95% [-0.18, 0.26], Cohen's $d = 0.08$, $BF_{10} = 0.19$.

N100. The ANOVA indicated a significant effect of CHOICE on N100 amplitude, $F(2, 72) = 10.58$, $p < .001$, $\eta_p^2 = .23$, $BF_{10} = 85.35$. Post-hoc tests indicated significantly more negative N100 amplitudes during free-choice blocks than during action-relevant forced-choice blocks, *ΔM* = -0.33 µV (*SD* = 0.11), $t(36) = -3.59$, $p = .002$, CI 95% [-0.52, -0.14], Cohen's $d = -0.64$, $BF_{10} = 32.25$. Furthermore, free-choice blocks elicited significantly larger N100 amplitudes than action-irrelevant forced-choice blocks, *ΔM* = -0.32 µV (*SD* = 0.16), $t(36) = -3.69$, $p = .002$, CI 95% [-0.50, -0.15], Cohen's $d = -0.64$, $BF_{10} = 40.58$. No significant differences in N100 amplitude for action-relevant and action-irrelevant forced choices could be observed, *ΔM* = 0.01 µV (*SD* = 0.05), $t(36) = 0.15$, $p = .884$, CI 95% [-0.12, 0.14], Cohen's $d = 0.02$, $BF_{10} = 0.18$.

No significant effect of outcome valence on N100 amplitude could be detected, *ΔM* = 0.09 µV (*SD* = 0.11), $F(1, 36) = 2.57$, $p = .118$, $\eta_p^2 = .07$, $BF_{10} = 0.27$. Furthermore, no significant interaction of the factors CHOICE and VALENCE could be observed during this early time window of feedback processing, $F(2, 72) = 0.29$, $p = .751$, $\eta_p^2 = .01$, $BF_{10} = 2.16$.

Reward Positivity. The results from the repeated measures ANOVA suggested a significant effect of VALENCE on RewP amplitude, with significantly more positive amplitudes following reward feedback than following loss feedback, *ΔM* = 0.13 µV (*SD* = 0.01), $F(1, 36) = 4.36$, $p = .044$, $\eta_p^2 = .11$, $BF_{10} = 0.22$. Furthermore, we observed a significant effect of CHOICE on RewP amplitude, $F(2, 72) = 9.88$, $p < .001$, $\eta_p^2 = .22$, $BF_{10} = 4.81$. More positive amplitudes were observed the free-choice condition compared to the action-relevant forced-choice condition (*ΔM* = 0.41 µV, *SD* = 0.40, $t(36) = 2.95$, $p = .011$, CI 95% [0.13, 0.70], Cohen's $d = 0.36$, $BF_{10} = 6.88$) and in the free-choice condition compared to the action-irrelevant forced-choice condition, *ΔM* = 0.51 µV (*SD* = 0.44), $t(36) = 3.77$, $p = .002$, CI 95% [0.24, 0.79], Cohen's $d = 0.44$, $BF_{10} = 49.87$. No significant processing differences could be observed for action-relevant and action irrelevant forced-choices, *ΔM* = 0.10 µV (*SD* = 0.04), $t(36) = 1.21$, $p = .233$, CI 95% [-0.07, 0.26], Cohen's $d = 0.12$, $BF_{10} = 0.35$.

A significant CHOICE x VALENCE interaction further indicated significant differences in RewP across choice conditions, $F(2, 72) = 4.70$, $p = .013$, $\eta_p^2 = .12$, $BF_{10} = 0.21$. Post-hoc contrasts of the difference wave for each choice condition indicated a significantly larger RewP in the free-choice compared to the action-relevant forced-choice (*ΔM* = 0.43 µV, *SD* = 0.96, $t(36) = 2.73$, $p = .030$, CI 95% [0.11, 0.75], Cohen's $d = 0.66$, $BF_{10} = 4.25$) and the free-choice compared to the action-irrelevant forced-choice condition, *ΔM* = 0.34 µV (*SD* = 0.88), $t(36) = 2.37$, $p = .047$, CI 95% [0.05, 0.63], Cohen's $d = 0.52$, $BF_{10} = 2.05$. No significant differences in RewP difference waves could be observed for the action-relevant forced-choice compared to the action-irrelevant forced-choice condition, *ΔM* = -0.09 µV (*SD* = 0.87), *t*(36) = -0.64, *p* = .529, CI 95% [-0.38, 0.20], Cohen's *d* = -0.15, BF_{10} = 0.21. Follow-up analyses confirmed that positive feedback elicited larger RewP amplitudes compared to negative feedback only in the free-choice condition (*ΔM* = 0.39 µV, *SD* = 0.69, *t*(36) = 3.42, *p* = .004, CI 95% [0.16, 0.62], Cohen's *d* = 0.31, BF_{10} = 30.97), but not in the action-relevant forced-choice (*ΔM* = -0.04 µV, *SD* = 0.62, *t*(36) = -0.43, *p* = 1.000, CI 95% [-0.25, 0.16], Cohen's *d* = -0.05, BF_{10} = 0.19) or the action-irrelevant forced-choice condition, *ΔM* = 0.05 µV (*SD* = 0.63), *t*(36) = 0.46, *p* = 1.000, CI 95% [-0.16, 0.26], Cohen's *d* = 0.06, BF_{10} = 0.19.

In summary, results obtained from parametric statistical testing mirror the findings observed based on cluster-based permutation tests performed on the time-frequency and feedback-locked data of the current study.

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2.3 Am I in Control? The Dynamics of Sensory Information, Performance Feedback, and Personality in Shaping the Sense of Control

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Author Contributions:

Maren Giersiepen (M.G.) conceptualized and administered the study, collected and interpreted the data, and wrote the original manuscript draft. She contributed to formal data analysis and visualization. Nils Wendel Heinrich (N.W.H.) programmed the experiment, analyzed and visualized the data, and commented on the manuscript. He contributed to study conceptualization and data interpretation. Annika Österdiekhoff (A.Ö.) programmed the experiment, commented on the manuscript, and contributed to study conceptualization. Stefan Kopp, Nele Russwinkel, Simone Schütz-Bosbach, and Jakob Kaiser acquired funding, commented on the manuscript, supervised the work of A.Ö., N.W.H., and M.G., and contributed to study conceptualization.

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Full Length Article

Am I in control? The dynamics of sensory information, performance feedback, and personality in shaping the sense of control

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ABSTRACT

Sense of control (SoC) over our actions is crucial for regulating our behavior. SoC arises from low-level processes, such as immediate sensory feedback, and high-level processes, such as performance evaluation. Studies using simple action-effect tasks suggest that people rely more on low-level sensory than on high-level cues of control. Yet, it remains unclear how these cues interact to shape the SoC in complex, goal-directed environments that require continuous behavioral adaptation. To investigate this, 50 participants performed a challenging motor control task akin to a video game, steering a spaceship along a continuously changing path. Sensorimotor control was manipulated by varying task difficulty via input noise across experimental blocks. After each trial, participants received negative, neutral, or positive feedback, followed by rating of their SoC. Linear mixed model analyses revealed that both sensory and evaluative feedback influenced the SoC. SoC decreased with increasing task difficulty. Furthermore, independent of difficulty, negative feedback reduced the SoC whereas positive feedback enhanced it, with a stronger effect for negative feedback. Notably, the effects of task difficulty and negative feedback were influenced by participants' depressive symptoms and their external locus of control, suggesting that generalized control beliefs modulate task-specific control experience. These findings indicate that SoC is informed by both low-level sensorimotor cues and high-level affective feedback, suggesting an integration of multiple types of information to assess control in dynamic task contexts where action-effect contingencies are extended over time. Crucially, these effects depend on trait-like control beliefs, highlighting the need to account for individual differences when investigating situated control experience.

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1. Introduction

Sense of control (SoC), the subjective feeling of control over a specific action (Pacherie, 2007), contributes to agency experience and a coherent sense of self. It allows us to assess our ability to bring about change in our environment, form intentions, and ultimately act upon them (Gentsch & Schütz-Bosbach, 2015; Kaiser et al., 2021; Luo et al., 2022). In well-practiced tasks, the SoC typically operates unconsciously and only reaches awareness when disrupted. For example, when riding our bicycle, we can directly relate our manipulations of the handlebar to the bicycles' movements. Yet, when a strong wind hits the bicycle from the side, control experience is disrupted, affording corrective actions to regain control.

Recent theories propose that SoC is influenced by different levels of processing, namely a lower sensorimotor level and a higher cognitive level (see Badre & Nee, 2018; Heinrich et al., 2024; Kahl et al., 2022). The sensorimotor level relies on real-time, proprioceptive and visual feedback to maintain control, while the cognitive level integrates external information, such as social or contextual cues, to evaluate performance and guide future actions. For instance, in the example of steering a bicycle, changes in driving conditions may lead to discrepancies between our manipulation of the handlebar and the bicycles' movement, diminishing our experience of control at the sensorimotor level. Furthermore, other cyclists or honking cars may provide external feedback, warning us when we deviate from the designated bike lane, thereby reducing our experience of control at the cognitive level. To reestablish perceived control, we may consequently increase our attention and focused effort to realign the bicycles' trajectory on the road.

Accordingly, various studies indicate that both low-level and higher-level manipulations influence self-reported SoC (Desantis et al., 2011; Giersiepen et al., 2024; Metcalfe et al., 2012; Österdiekhoff et al., 2024). At the sensorimotor level, changes in visual or proprioceptive feedback, such as spatially offsetting visual action effects, have been found to significantly reduce the SoC (Österdiekhoff et al., 2024). Beyond these sensorimotor influences, SoC is shaped by high-level feedback, which provides external information about performance. This type of feedback is typically categorized as positive (e.g., rewards or reinforcement), negative (e.g., error signals or penalties), or neutral. Self-reports indicate that action-congruent and positive feedback, such as rewards for executed actions, are associated with higher control compared to action-incongruent and negative feedback, demonstrating an influence of outcome valence on the cognitive layer of perceived control (Barlas et al., 2017; Barlas & Kopp, 2018; Gentsch et al., 2015; Oishi et al., 2018). Notably, most studies have examined the influence of low- and high-level cues of control in isolation, leaving their interaction in shaping the SoC unresolved.

Some theoretical and empirical work suggests a greater reliance on sensorimotor than higher-level or external cues when control can be reliably inferred from the former (Gentsch et al., 2012; Moore et al., 2009; Synofzik et al., 2013). For instance, Moore and colleagues (2009) showed that implicit measures of control were more strongly modulated by outcome primes when participants performed involuntary movements (i.e., internal predictive signals were absent) compared to voluntary ones (i.e., internal predictive signals were present). Importantly, though, the vast majority of studies investigated control experience in highly simplified task contexts, where, for example, trial-wise feedback was related to a single button press. This contrasts with real-life tasks, where high-level evaluative feedback typically occurs only after completing multi-step actions in a continuous environment, in which sensorimotor cues are arising all the time. Thus, it remains unclear how low-level and high-level cues interact to shape the SoC in dynamic, goal-directed tasks involving continuous change (Heinrich et al., 2024). Dynamic task environments require sustained action monitoring, providing a continuous stream of sensorimotor information that can be used to estimate one's SoC. At the same time, positive and negative feedback serve as salient external cues for evaluating task performance, potentially outweighing sensorimotor signals in shaping control judgments during goal-directed tasks.

Studies employing dynamic task environments present a mixed picture of the influence of sensorimotor cues and evaluative feedback on the SoC. While a recent study found that performance feedback in a dynamic visuomotor task influenced SoC more strongly when it was valid, reflecting actual performance (Dewey, 2023), other studies suggest that task instructions and performance feedback shape the SoC even when not reliably reflecting actual control over the action or its outcome (Oishi et al., 2018; Wen et al., 2015). Furthermore, their results suggest that the impact of evaluative feedback on SoC judgments increases with task difficulty. Thus, our understanding of how sensorimotor control and evaluative feedback interact to shape the SoC may be advanced by varying task difficulty during continuous, goal-directed tasks. Additionally, using rating items that precisely distinguish between participants' perceived motor control and their ability to successfully complete the task can help disentangle how distinct aspects of an action influence their SoC.

To better understand how evaluative feedback influences the SoC during continuous action, it is further necessary to examine the role of feedback valence more closely. Studies employing affective (i.e., positive and negative) feedback typically report a higher SoC for positive compared to negative feedback (see Gentsch & Synofzik, 2014). However, since most studies in this field do not employ a neutral feedback condition for comparison, it is unclear whether this effect reflects a positive-related increase or a negative-related decrease in perceived control. On the one hand, participants may exhibit a self-serving bias, wherein positive outcomes are weighted more strongly than negative ones (see Chambon et al., 2020; Villa et al., 2022). On the other hand, feedback-related changes in self-reported SoC may primarily be driven by negative feedback, as this feedback provides salient cues for behavioral adaptations in continuous task environments.

A previous study examined the relative influence of positive and negative feedback on perceived control in a task setting where participants made single key presses, each resulting in a positive (e.g., amusement), neutral (i.e., pure tones), or negative (e.g., disgust) auditory outcome (Yoshie & Haggard, 2013). The authors found that negative feedback had a stronger impact on the SoC than positive feedback, suggesting that the difference in SoC between feedback types is primarily driven by a decrease in control experience in response to negative feedback rather than an increase in perceived control in response to positive feedback. This asymmetry aligns with models of loss aversion and predictive coding (Friston, 2010; Kahneman & Tversky, 1979) which suggest that the brain prioritizes unexpected or threatening information over confirming positive signals. Negative feedback generates a prediction error, signaling a mismatch between intended and actual outcomes, which likely results in stronger adjustments in perceived control. However, it is important to note that their task did not involve continuous or goal-directed actions. Specifically, negative, neutral, and positive feedback were presented in separate blocks following single button presses, making the feedback primarily sensory in nature. Thus, it remains unclear whether positive and negative feedback are weighted equally in shaping participants' SoC in goal-directed dynamic environments (Kaiser et al., 2021).

Finally, it should be noted that long-term individual differences in the experience of control exist, shaped by dispositional traits and life experiences (Carstensen, 2024; Dewez et al., 2019). These differences manifest in various ways, such as trait-like locus of control (LoC), chronic stress exposure, and learned helplessness, which can influence how individuals perceive and respond to control-related situations. For example, individuals with a high internal LoC tend to attribute outcomes to their own actions and exhibit greater resilience in the face of negative feedback, whereas those with high external LoC may feel more dependent on external factors, leading to reduced SoC in unpredictable environments. Additionally, long-term exposure to uncontrollable negative events such as early life adversity, can lead to diminished agency perceptions and an increasing risk of developing depressive symptoms (Maier & Seligman, 2016). Conversely, individuals who have repeatedly experienced high contingency between actions and outcomes may develop an inflated SoC which has been linked to risk-taking behaviors such as problem gambling (Carstensen, 2024; Orgaz et al., 2013). These long-term differences suggest that SoC is not only influenced by immediate task conditions but is also shaped by broader personality and life history factors that may determine how individuals integrate feedback into their control judgements (see Dewey, 2023). However, the extent to which these dispositional factors interact with task-specific aspects in shaping the SoC remains poorly understood.

The goal of the current experiment was to investigate how sensorimotor cues of control interact with evaluative feedback and generalized, personality-specific control assumptions in shaping the SoC in a dynamic task environment. To this end, we utilized a modified version of the Dodge Asteroids task (Abalakin et al., 2024; Heinrich et al., 2024; Österdiekhoff et al., 2024), a visuospatial motor control task. In this task, participants steered a spaceship along a predefined path in a continuously changing environment using a computer keyboard. Control over the spaceship's movement was manipulated by two levels of input noise, amplifying movement distortion in response to keyboard inputs. After each trial, participants received either negative, positive, or neutral feedback. Unbeknown to participants, feedback type was counterbalanced, with an equal number of trials for all types of feedback within each block. Following feedback presentation, participants rated their SoC, assessing their experienced control over the spaceship steering during the preceding trial.

We hypothesized a reduction in SoC ratings (H1) in high compared to low input noise blocks (Oishi et al., 2018; Österdiekhoff et al., 2024). Additionally, we expected highest SoC ratings for positive feedback, followed by neutral, and then negative feedback (H2; Gentsch et al., 2015; Yoshie & Haggard, 2013). By directly comparing positive and negative feedback with neutral feedback, we aimed to determine whether the influence of feedback valence on SoC is primarily driven by an increase in SoC following positive feedback or a decrease in response to negative feedback. We further predicted that participants' SoC ratings would increase as their error rates decrease (H3; Oishi et al., 2018; Österdiekhoff et al., 2024). Crucially, we anticipated that feedback valence would have a stronger impact on SoC ratings in high input noise trials compared to low input noise trials, reflecting a stronger reliance on high-level affective feedback when sensorimotor noise increases (H4; see also framework of optimal cue integration, Synofzik et al., 2013). Following a reviewer's suggestion, we additionally examined whether the influence of evaluative feedback changed over the course of the experiment.

To investigate whether the effects of input noise, error rates, and outcome value on SoC are moderated by between-subject differences in control experience, we further examined the influence of participant's depression scores, as measured by the Center for Epidemiologic Studies Depression Scale Revised (CESD-R; Eaton et al., 2004; Van Dam & Earleywine, 2011), as well as their locus of control (LoC), as assessed by the Internal-External Locus of Control Short Scale (IE-4; Kovaleva et al., 2014; Nießen et al., 2022), on trial-wise SoC ratings. By including these trait measures, we could directly test whether task-specific variations in SoC were general phenomena or depended on the personalities of the participants. As previous research has associated depression with diminished control experience (Disner et al., 2011; Yu & Fan, 2016), we expected that participants with higher CESD-R scores would report a decreased SoC (H5). Additionally, as the LoC is an established measure of an individual's general tendency to attribute events to internal factors (i.e., assuming personal control) or external ones (i.e., assuming events are influenced by fate, chance, or other factors outside of one's personal control), we anticipated a reduced reliance on feedback to inform SoC ratings for participants with higher internal LoC scores (H6). Conversely, those with higher external LoC scores were expected to show an increased reliance on evaluative feedback to inform their SoC ratings (H7). Finally, in response to a reviewer's suggestion and recent findings that highlight the role of individual differences in weighting immediate sensorimotor information versus high-level feedback (Chang & Wen, 2025), we additionally explored whether participants' questionnaire scores modulated the effects of input noise on SoC ratings.

To summarize, while previous studies often focused on the influence of individual aspects on the SoC in simple task contexts, the current study examined the interaction of both low-level (i.e., sensorimotor) and high-level (i.e., affective feedback and trait-like beliefs) cues on SoC in a complex, goal-directed task environment.

2. Methods

2.1. Participants

Fifty healthy adult participants with a mean age of 24.14 years ($SD = 3.46$) participated in this study. All participants had normal or corrected to normal vision without color vision deficiencies. Due to above average error rates (see 2.4 Data analysis), two datasets were excluded during preprocessing. The final sample thus comprised 48 participants ($n_{\text{female}} = 32$, $n_{\text{male}} = 16$ indicated via self-report about their identified gender; $n_{\text{righthanded}} = 43$) with a mean age of 25.08 years (*SD* = 3.44). A power analysis in G*Power (Faul et al., 2007), following the procedure of Österdiekhoff et al. (2024), who examined how different cues affect the SoC in a dynamic multitasking environment, indicated that a sample of 23 participants would be large enough to detect medium-sized within-subject main effects with a power of 0.95 and an alpha level of 0.05. This estimate aligns with previous studies examining within-subject effects during continuous action (e.g., Heinrich et al., 2024; Oishi et al., 2018). Because detecting within-subject interactions and between-subject effects requires larger samples (Brysbaert & Stevens, 2018), we complemented our power analysis with and increased the sample size based on a literature review (Carstensen, 2024; Dewey, 2023). Participants could choose to be compensated with course credit or 9 Euro/hour. In addition, all participants received 2.10 Euro bonus they earned during the task at the end of the experiment. All participants provided written informed consent and were informed that the data of this study would be anonymized and processed confidentially. The study was approved by the ethical board of the Department of Psychology at the LMU Munich (date of approval: 29.03.2021) and was conducted in accordance with the Declaration of Helsinki.

2.2. Experimental design

To examine the influence of low- and high-level cues on participants' SoC, we used a modified version of the Dodge Asteroids spaceship-steering task (Heinrich et al., 2024; Österdiekhoff et al., 2024). In this computer-based task, participants navigate a spaceship through a dynamically changing environment using a standard computer keyboard. Task difficulty was varied across blocks by introducing either low or high sensorimotor noise to participants' keyboard input. Each trial was followed by high-level feedback that was either negative, neutral, or positive, with feedback type counterbalanced within blocks. After receiving feedback, participants rated their SoC for the current trial. The CESD-R and IE-4 questionnaires were administered at the end of the experimental session. A schematic task overview is presented in Fig. 1.

2.3. Procedure

We implemented the experiment in Python (Version 3.10; Rossum, 1995) using PyCharm, an integrated development environment (JetBrains Community Edition; Version 2019.3.5). Participants were seated approximately 70 cm from a 24-inch monitor (1920 x 1080 px; FPS: 60) on which the experimental task was presented on a black background.

Each trial started with the presentation of a white fixation cross (1° visual angle) on the screen center for 1.5 s. After the fixation cross disappeared, participants navigated a spaceship, an inverted, blue-colored triangle (1° visual angle), along a navigation path (with a thickness of 1° visual angle) that required dynamically adjusting its trajectory using button presses throughout each trial. Line trajectories were randomly generated while fulfilling the following conditions: First, every line contained vertical segments adding up to a total of 602 pixels. Second, 1330 pixels were dedicated to creating left and right turns in the path. Turns were constrained to have a size of 70 to 140 pixels to the left or right side, respectively. These settings guaranteed that each path was wide enough for effective

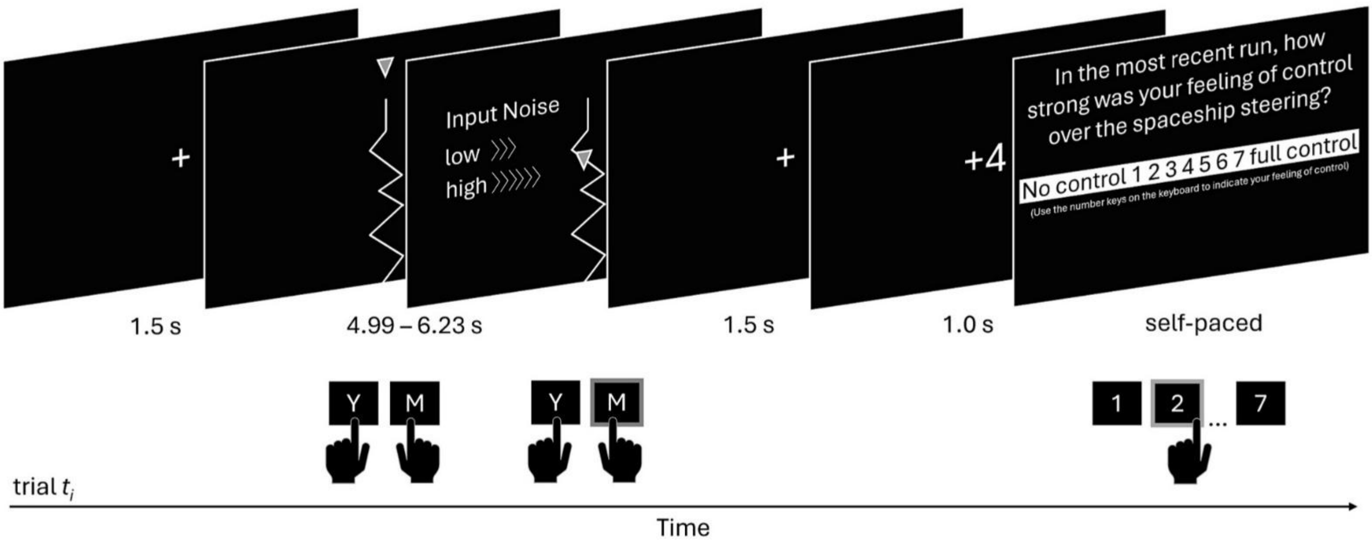

Fig. 1. Schematic task overview. Trials started with a fixation cross presented in the screen center. The spaceship, an inverted blue rectangle, entered the screen from the top at the start of the navigation task. Using the Y- and M−keys, participants steered the continuously moving spaceship along the white path as accurately as possible. Task difficulty was varied by changing input noise (low/high; condition not visible to participants) across blocks. The navigation task was followed by a white fixation cross at the screen center and the presentation of either positive (+4), neutral (*grey circle*), or negative (−2) evaluative feedback. Participants indicated their SoC over the spaceship steering at the end of each trial, using keys from '1′ (no control) to '7′ (full control). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

spaceship maneuvering while still requiring frequent adjustments to maintain optimal steering, keeping the task dynamic. To allow participants to prepare for navigation, the spaceship entered the screen 100 pixels below the top edge center and descended to the screen center (pixel 520). Participants could begin with steering as soon as the spaceship reached the center (i.e., 124 pixels prior to reaching the start of the navigation path at pixel 644).

Participants' goal was to steer the spaceship as accurately as possible along the paths' trajectory by pressing the Y-key (left) and M−Key (right) on the computers' keyboard using their left- and right-hand index finger, respectively. We opted for the Y- and M−key to avoid giving an advantage to right-handers, who might find it easier to use the arrow keys traditionally placed on the right side of a standard keyboard (see Österdiekhoff et al., 2024). Response keys registered inputs of sequential and continuous button presses. Once the spaceship reached the screen center, its position remained fixed. A dynamic task environment was created by continuously introducing new path segments at the bottom of the screen and moving the existing segments upward until they exit the screen at its top edge. Each navigation trial took between 4.99 and 6.23 s ($M = 5.12$, $SD = 0.07$) to complete.

Crucially, participants were instructed that the ease of spaceship navigation may vary across blocks of trials. In both 'low input noise' and 'high input noise' blocks, keyboard input was distorted by adding noise to participants' key presses, thereby introducing sensorimotor disturbance to spaceship navigation. The distortion followed a normal distribution, with a mean of 0 (i.e., no distortion) and a standard deviation of 0.5 for low input noise blocks and a standard deviation of 2.0 for high input noise blocks. As a result, high input noise blocks were expected to make accurate performance more difficult compared to low input noise blocks.

After navigation, negative (i.e., monetary loss of 2 cents), neutral (i.e. a grey circle), or positive (i.e., monetary gain of 4 cents) feedback was centrally presented for 1 s (1° visual angle). Gains were set to be twice as large as losses, as individuals typically perceive losses to be approximately twice as impactful as equivalent gains (Tversky & Kahneman, 1992). This also ensured that participants would end the experiment with a net gain rather than a net-zero outcome (Proudfit, 2015). At the end of each trial, participants indicated their perceived control over the spaceship, answering the question 'In the most recent run, how strong was your feeling of control over the spaceship steering?' in a self-paced manner on a seven-point Likert-scale, ranging from '1' (i.e., no control) to '7' (i.e., full control).

Unbeknown to participants, post-navigation feedback was not performance dependent but counterbalanced within blocks. Thus, participants received an equal number of negative, neural, and positive feedback in each block of trials. To create the impression that feedback reflected performance, participants were told that accurate steering of the spaceship would result in positive feedback, while substantial deviations from the target path would lead to negative feedback. They were also informed that, on some trials, no performance feedback would be given and that a grey colored circle would appear as feedback in the screen center. Finally, participants were told that they would receive a bonus based on the net gain from their best blocks at each difficulty level. Presenting neutral as well as performance-independent feedback allowed us to examine the influence of task difficulty and feedback valence on participants' SoC. Importantly, our study design allowed us to examine a) whether positive feedback is associated with higher perceived control than negative feedback and b) whether this difference is differentially driven by a decrease in control experience for negative feedback, an increase in the SoC for positive feedback, or whether both types of feedback equally influence participants control ratings. Furthermore, by manipulating both sensorimotor noise and evaluative feedback, this task setup allowed us to test how low-level and high-level information interact in shaping the SoC.

Participants started with four practice trials, followed by 8 blocks consisting of 30 trials each (240 trials in total, 40 trials for each input-noise-feedback condition). Participants were informed about their block-wise gains at the end of each block. To prevent participants from recognizing that payout was pre-determined to add up to 20 cents per block, their block-wise balance was randomly adjusted to a margin of 20 %, resulting in five different possible outcome values (16 ct, 18 ct, 20 ct, 22 ct, 24 ct).

To explore whether individual differences in perceived control influence state-dependent SoC ratings, participants completed the IE-4 (Kovaleva et al., 2014; Nießen et al., 2022) and CESD-R (Eaton et al., 2004; Radloff, 1977) on SoSci Survey (Leiner, 2024) at the end of the experiment. The IE-4 scale assumes that internality and externality comprise two dimensions of control, each measured with two items. For each item, participants were asked to indicate the extent to which they think it applies to them personally on a five-point Likert scale, ranging from '1' (i.e., does not apply at all) to '5' (i.e., applies completely). The scale has been validated and is recommended as a self-report tool for research purposes (Nießen et al., 2022). The CESD-R contains 20 items that assess symptoms of a major depressive episode as defined by the American Psychiatric Association and the Diagnostic and Statistical Manual of Mental Disorders, Fifth Edition, including an assessment of depressed mood, feelings of guilt or worthlessness, fatigue, sleep disturbances, changes in appetite, and difficulty concentrating. For each item, participants were asked to indicate how often they have felt this way recently on a five-point Likert-Scale (0 = 'not at all or less than 1 day last week', 1 = '1–2 days last week', 2 = '3–4 days last week', 3 = '5–7 days last week', 4 = 'nearly every day for 2 weeks'). The CESD-R is recommended to assess depressive symptomatology in the general population (Van Dam & Earleywine, 2011).

2.4. Data analysis

RStudio 2023.06.1 was used for preprocessing and statistical analyses of the experimental data. We examined the average trial-wise distance (in pixels) between spaceship and the navigation path to evaluate participants' task performance. Due to above-average error rates (i.e., spaceship deviations exceeding three times the interquartile range from the mean) two participants were excluded from the data during preprocessing (André, 2022).

Questionnaire scores were calculated based on the standard recommendations of the corresponding scoring instructions. To examine between-subject differences in control experience, subscale scores for internal and external LoC (IE-4) were calculated for each participant using the unweighted mean of both subscale items, resulting in a range of possible scores from 1 to 5 for both the internal and the external subscale. Depression scores were calculated as the sum of response values to all items of the CESD-R. Consequently, CESD-R scores could vary between 0 and 60, with higher scores indicating more severe depressive symptoms.

Multilevel mixed modelling was used to analyze the data, with the goal to build mathematical models that reflect the influence and interplay of low-level and high-level cues on participants' error rates (Model 1) and SoC (Model 2). Both models were estimated using the *lme4* package (Bates et al., 2014) and fitted using the Maximum Likelihood method, which estimates both fixed effects and their variance.

In both models, Participant was included as a random intercept to account for the repeated-measures structure of the data. This approach allows for the estimation of both within- and between- participant effects while preserving trial-level variability and avoiding the loss of information associated with averaging responses per condition (Meteyard & Davies, 2020). Likelihood ratio tests were used to determine the fixed effects structure of the model. Finally, we explored the models' maximal random effects structure, the most comprehensive set of random effects that could be included in the models while maintaining model stability and improving model fit, as indicated by the Bayesian Information Criterion (Barr et al., 2013; Chakrabarti & Ghosh, 2011). Including random slopes allows the model to account for individual differences in the size of within-subject effects by estimating participant-specific deviations from the average effect (Bates et al., 2015). This approach helps avoid underestimating the variability of fixed effects and reduces the risk of misattributing subject-level variance to fixed effects.

To investigate potential transformations of the predicted variables, error rates and SoC, we conducted Box-Cox distributional analyses, which yield a lambda value indicating the most appropriate power transformation (no transformation: $\lambda = 1$, logarithmic transformation: $\lambda = 0$, square root transformation: $0 < \lambda < 1$; Box & Cox, 1964). The suggested transformations result in an approximation of a normal distribution for the predicted variables and their residuals, thereby allowing for more reliable estimates of fixed and random effects than would be obtained without applying the indicated transformations.

Model 1 examined whether high input noise increased task difficulty compared to low input noise and whether error rates decreased with task practice. The final model predicting participants' Error Rates (line deviation in pixel) is displayed in Eq. (1) and included the fixed effects Input Noise (β_1; low/high) and Block Number (β_2; 1–8), as well as their interaction (β_3). The final model also featured a random slope for Input Noise ($\mu_{1,j[i]}$) within the random intercept for Participant ($\mu_{0,j[i]}$). ϵ_i denotes the residual error term. The Box-Cox distributional analysis implied a logarithmic transformation of participants' error rates ($\lambda = 0.10$; Box & Cox, 1964).

$$\log(ErrorRates_i) = \beta_0 + \beta_1 InputNoise_i + \beta_2 BlockNumber_i + \beta_3 (InputNoise_i {*} BlockNumber_i) + \mu_{0,j[i]} + \mu_{1,j[i]} {*} InputNoise_i + \epsilon_i \quad (1)$$

Model 2 examined how sensorimotor information, and higher-level feedback interact in shaping participants' SoC. The final model is displayed in Eq. (2). Model selection indicated the inclusion of the fixed effects Input Noise (β_1; low/high; H1), Feedback (β_2; negative/neutral/positive; H2), Error Rate (β_3; line deviation in pixel; H3), Block Number (β_4, 1–8), CESD-R scores (β_5; 0–60), and External LoC scores (β_6; 1–5) for a model predicting trial-wise SoC ratings. In addition, the model included an interaction of Feedback and CESD-R scores (β_7), Input Noise and CESD-R scores (β_8), Input Noise and External LoC (β_9), Feedback and Block Number (β_{10}), as well as of Input Noise and Block Number (β_{11}). It further featured a random slope effect for Input Noise ($\mu_{1,j[i]}$) within the random intercept for Participant ($\mu_{0,j[i]}$). ϵ_i denotes the residual error term. The Box-Cox distributional analysis implied a square root transformation of SoC ratings ($\lambda = 0.71$; Box & Cox, 1964). Post-hoc t-tests (two-sided) were performed to compare the relative influence of positive and negative feedback as well as sensorimotor (i.e., input noise) and high-level (i.e., evaluative feedback) control cues on the SoC.

$$\begin{aligned}\sqrt{SoC_i} = {} & \beta_0 + \beta_1 InputNoise_i + \beta_2 Feedback_i + \beta_3 ErrorRate_i + \beta_4 BlockNumber_i + \beta_5 CESDR_i + \beta_6 ExternalLoC_i \\ & + \beta_7 (Feedback_i {*} CESDR_i) + \beta_8 (InputNoise_i {*} CESDR_i) + \beta_9 (InputNoise_i {*} ExternalLoC_i) + \beta_{10} (Feedback_i {*} BlockNumber_i) \\ & + \beta_{11} (InputNoise_i {*} BlockNumber_i) + \mu_{0,j[i]} + \mu_{1,j[i]} {*} InputNoise_i + \epsilon_i\end{aligned} \quad (2)$$

For each of the fixed effects, we report β-estimates, standard errors, and *p*-values. Significance was evaluated against $\alpha = 0.05$. In addition, we report 95 % confidence intervals (CIs) as effect size indicators. CIs were obtained by a parametric bootstrap with 10,000 iterations. To precisely recover the results, we used a random seed (36).

3. Results

3.1. IE-4 scores

Participants reported a mean internal LoC of 3.68 ($SD = 0.82$, range: 1.5–5) and a mean external LoC of 2.11 ($SD = 0.75$, range = 1–5). Similar to the German reference sample (males and females aged 18 to 29 years; $N = 105$, Nießen et al., 2022), internal LoC scores were slightly negatively skewed (skewness = −0.73) and external LoC scores displayed a positive skewness (skewness = 1.42). Both internal and external LoC scores were lower in the current sample than in the reference sample (internal: $M = 4.13$, $SD = 0.69$; external: $M = 2.57$, $SD = 0.93$). No extreme outliers could be detected (i.e., questionnaire scores deviating more than three times the inter-quartile range from the mean).

3.2. CESD-R scores

Average depression scores in the current study were positively skewed (skewness = 1.28) and ranged from 0 to 44, with a mean score of 11.90 ($SD = 9.46$). Ten (20.83 %) participants exhibited critical depression scores (i.e., scores > 15). All other participants (*N*

= 38) scored lower, indicating no clinical significance of depressive symptomatology. No extreme outliers could be detected.

3.3. Model estimates

3.3.1. Error rates

The null model predicting error rates indicated an average trial-wise error, measured as distance between spaceship and target path, of 32.56 pixels ($\sigma = 1.03$, $p < 0.001$). Participant-specific individual differences explained 14.38 % of total variance observed in the data.

The model revealed significantly higher error rates in the high compared to the low input noise condition, confirming that spaceship steering became more difficult as input noise increased, $\beta = 1.79$, $\sigma = 1.03$, 95 % CI [1.70, 1.89], $p < 0.001$. Furthermore, a significant effect of Block Number revealed a reduction in error rates with block progression, indicating improved performance with task practice, $\beta = -1.02$, $\sigma = 1.00$, 95 % CI [−1.024, −1.018], $p < 0.001$ (Fig. 2A). Finally, a significant interaction indicated that the effect of Block Number differed for high and low input noise blocks, with the reduction in error rates being more pronounced in the low input noise condition compared to the high input noise condition, $\beta = 1.01$, $\sigma = 1.00$, 95 % CI [1.01, 1.02], $p < 0.001$ (Fig. 2B).

3.3.2. Trial-Wise SoC

The null model predicting SoC ratings indicated an average control of 3.75 ($\sigma < 0.01$, $p < 0.001$). Participant-specific individual differences explained 16.53 % of the total variance observed in the data. Distribution plots of all main effects are displayed in Fig. 3A.

Participants reported a decreased SoC when input noise changed from low to high, $\beta = -0.13$, $\sigma = 0.01$, 95 % CI [−0.35, −0.01], $p = 0.005$ (H1). While self-reported SoC in the low input noise condition increased with task practice ($\beta = 4.78*10^{-5}$, $\sigma = 2.61*10^{-6}$, 95 % CI [$1.44*10^{-5}$, $1.01*10^{-4}$], $p < 0.001$), a significant negative interaction of Input Noise and Block Number indicated that high input noise blocks were associated with a gradual decrease in SoC, $\beta = -3.71*10^{-4}$, $\sigma = 5.11*10^{-6}$, 95 % CI [$-5.62*10^{-4}$, $-2.23*10^{-4}$], $p < 0.001$ (Fig. 3B). Furthermore, error rates were negatively associated with SoC ratings, indicating that participants' SoC changed with actual efficiency in motor control, $\beta = -8.03*10^{-5}$, $\sigma = 5.14*10^{-8}$, 95 % CI [$-8.85*10^{-5}$, $-7.27*10^{-5}$], $p < 0.001$ (H3).

In contrast to neutral feedback, negative feedback significantly decreased SoC ratings, $\beta = -8.44*10^{-3}$, $\sigma = 2.23*10^{-4}$, 95 % CI [-0.01, $-3.90*10^{-3}$], $p < 0.001$. Conversely, in contrast to neutral feedback, positive feedback significantly increased SoC ratings, $\beta = 7.84*10^{-3}$, $\sigma = 2.23*10^{-4}$, 95 % CI [$3.44*10^{-3}$, 0.01], $p < 0.001$ (H2). The final model also featured a significant interaction of Feedback and Block Number, indicating that the influence of positive feedback on SoC ratings decreased over time, $\beta = -1.14*10^{-4}$, σ

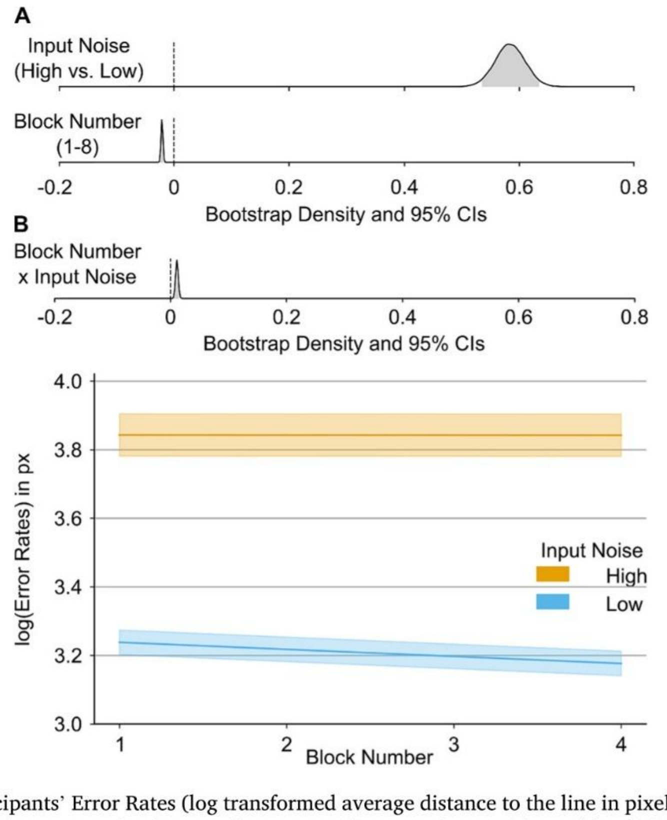

Fig. 2. Model results predicting participants' Error Rates (log transformed average distance to the line in pixels). **A)** Distribution of significant main effects, obtained through a parametric bootstrap. The data was bootstrapped 10,000 times, with model refitting for each iteration. The distributions represent the resulting model parameters, and the grey-shaded areas indicate the 95 % CIs. Increasing input noise significantly increased participants' error rates, whereas advancing block number significantly decreased them. **B)** Bootstrapped distribution of the interaction between Input Noise (low/high) and Block Number (1–4 for each the high and the low input noise condition), characterized by a stronger decrease in error rates for blocks with low compared to high input noise. The colored areas around the estimated mean values in the graph indicate standard errors.

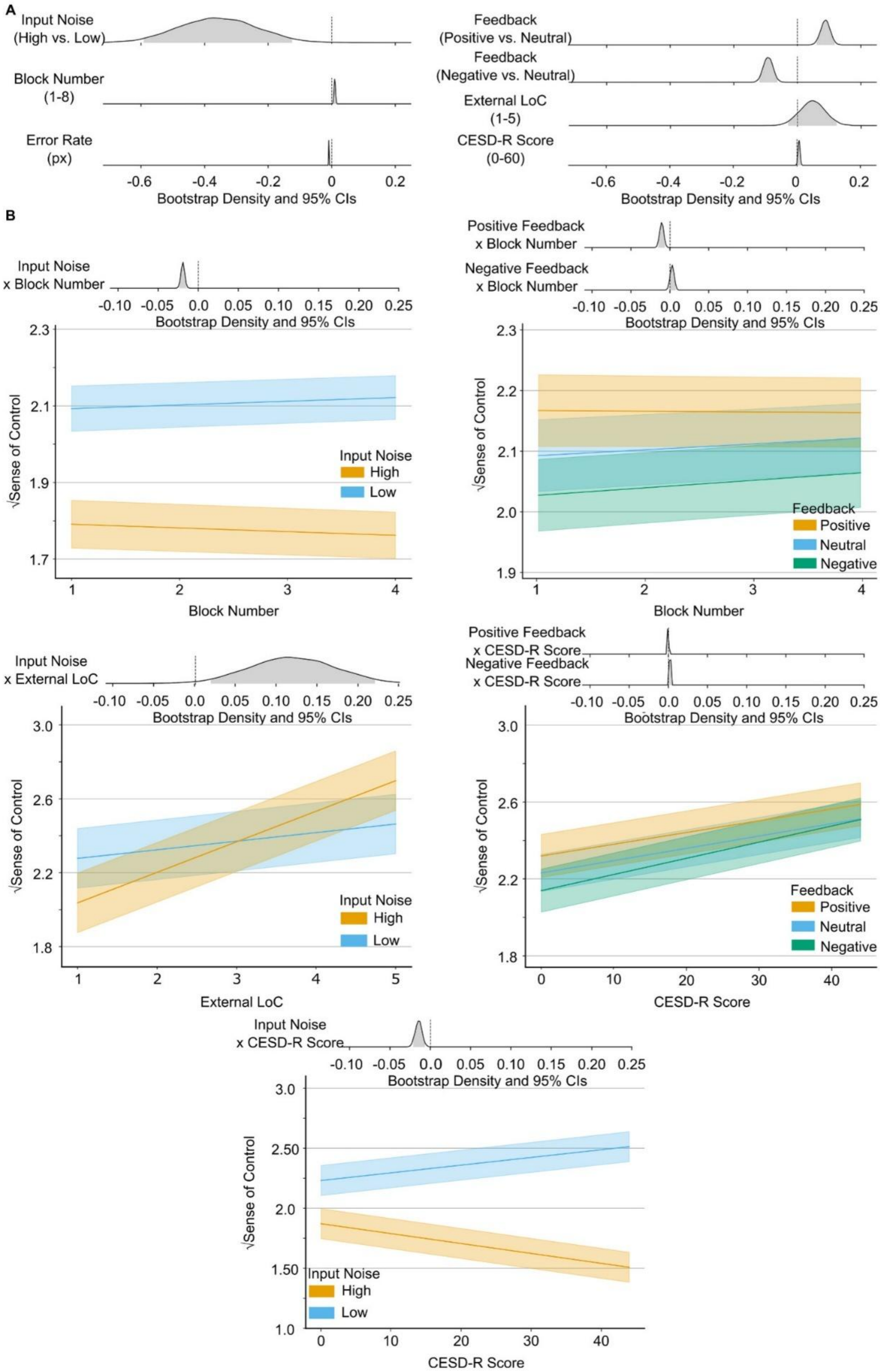

Fig. 3. Model results predicting trial-wise SoC (measured on a 7-point Likert scale; mean square root transformed). Distributions of the main effects (**A**) and interaction effects (**B**) included in the final model, derived from a parametric bootstrap. The data was bootstrapped 10,000 times, with model refitting for each iteration. The distributions represent the resulting model parameters, and the grey-shaded areas indicate 95 % CIs. The colored areas around the estimated mean values in the graph indicate standard errors.

$= 6.58*10^{-6}$, 95 % CI [$-2.46*10^{-4}$, $-3.12*10^{-5}$], $p < 0.001$ (Fig. 3B). The effect of negative feedback on SoC did not significantly change with task progression, $\beta = 7.31*10^{-6}$, $\sigma = 6.57*10^{-6}$, 95 % CI [$-5.53*10^{-6}$, $5.98*10^{-5}$], $p = 0.291$. Post-hoc t-tests (two-sided) of the bootstrapped CIs revealed a significant difference in means of positive and negative feedback, with the mean of the paired difference being significantly greater than zero, $\Delta M = 3.32*10^{-3}$, $t(9999) = 12.86$, 95 % CI [$2.28*10^{-3}$, $3.83*10^{-3}$], $p < 0.001$. Thus, while both positive and negative feedback affected SoC ratings, the impact of negative feedback was significantly stronger.

Contrasting our expectations (H4), the final model featured no interaction between Input Noise and Feedback ($p > 0.05$), indicating that low-level sensorimotor information and higher-level feedback independently contribute to the SoC during goal-directed dynamic tasks. To compare whether Input Noise or Feedback had a stronger effect on participants' SoC ratings, we computed a paired *t*-test (two-sided) on the bootstrapped β-values. The test revealed a significant difference, with the mean of the paired differences being significantly greater than zero for both negative feedback ($\Delta M = 0.27$, $t(9999) = 217.69$, 95 % CI [0.26, 0.27], $p < 0.001$) and positive feedback, $\Delta M = 0.27$, $t(9999) = 220.58$, 95 % CI [0.268, 0.272], $p < 0.001$. These results indicate that input noise had a stronger impact on self-reported SoC than post-trial affective feedback.

In addition to task-specific effects, individual differences in control experience significantly affected participants' SoC ratings. Whereas the main effect of External LoC on SoC was not significant ($\beta = 2.16*10^{-3}$, $\sigma = 1.55*10^{-3}$, 95 % CI [$-8.61*10^{-4}$, 0.02], $p = 0.244$; H7), External LoC positively interacted with Input Noise, $\beta = 0.01$, $\sigma = 2.70*10^{-3}$, 95 % CI [$3.08*10^{-4}$, 0.05], $p = 0.027$. While in the low input noise condition, SoC did not vary with external LoC, SoC ratings increased with external LoC scores in the high input noise condition (Fig. 3B).

A significant main effect of CESD-R further indicated that depressive symptomatology positively influenced SoC ratings, $\beta = 4.10*10^{-5}$, $\sigma = 9.77*10^{-6}$, 95 % CI [$3.31*10^{-9}$, $1.56*10^{-4}$], $p = 0.047$ (H5). Crucially, CESD-R score interacted with Negative Feedback, indicating a weaker influence of negative feedback on SoC with increasing depression scores, $\beta = 4.00*10^{-6}$, $\sigma = 3.94*10^{-7}$, 95 % CI [$6.07*10^{-7}$, $1.04*10^{-5}$], $p = 0.001$ (Fig. 3B). Follow-up correlational analyses confirmed that the reduction in perceived control for negative compared to neutral feedback (i.e., the difference in ratings between neutral and negative conditions) was less pronounced in individuals with higher depression scores, $r_{pearson} = -0.33$, $t(46) = -2.33$, 95 % CI [-0.56, -0.05], $p = 0.024$. No significant interaction of Positive Feedback and CESD-R score could be observed, $\beta = -9.14*10^{-8}$, $\sigma = 3.94*10^{-7}$, 95 % CI [$-2.29*10^{-6}$, $8.52*10^{-7}$], $p = 0.630$.

Finally, we observed a significant negative interaction of Input Noise and CESD-R scores, $\beta = -2.14*10^{-4}$, $\sigma = 1.68*10^{-5}$, 95 % CI [$-5.19*10^{-4}$, $-4.31*10^{-5}$], $p < 0.001$. This interaction revealed that individuals with higher depression scores experienced increased SoC under low input noise, but a diminished SoC under high input noise (Fig. 3B). Follow-up participant-level correlations confirmed that the difference in perceived control between low and high input noise blocks was greater among individuals with higher CESD-R scores, $r_{pearson} = 0.42$, $t(46) = 3.14$, 95 % CI [0.15, 0.63], $p = 0.003$.

To examine whether depressive symptoms more strongly affected the influence of low-level or high-level cues on perceived control, we performed follow-up t-tests (two-sided) on the bootstrapped β-values of the interaction terms of CESD-R scores with Input Noise and CESD-R scores with Feedback. The test indicated that depressive symptoms more strongly modulated the impact of low-level sensorimotor feedback than of high-level evaluative feedback on participants' SoC, $\Delta M = 0.01$, $t(9999) = 304.92$, 95 % CI [0.0125, 0.0127], $p < 0.001$.

Overall, the results showed that sensorimotor information and evaluative feedback independently influenced the SoC during a dynamic, goal-directed motor control task. Notably, negative feedback more strongly influenced SoC ratings than positive feedback, potentially reflecting a reduced influence of positive feedback on SoC over time. Furthermore, the impact of both evaluative feedback and sensorimotor information was moderated by individual differences. A higher external LoC was associated with greater perceived control under conditions of increased sensorimotor noise, while higher levels of depressive symptoms diminished the impact of negative feedback on control experience and increased the reliance on sensorimotor cues.

4. Discussion

This study aimed to investigate how low-level sensorimotor control and high-level factors, including feedback valence and trait-like differences in control experience, interact to shape the SoC in a dynamic task environment. Using a modified version of the Dodge Asteroids task (Heinrich et al., 2024; Österdiekhoff et al., 2024), we manipulated sensorimotor control through input noise and provided participants with post-trial feedback (positive, negative, or neutral) to assess their impact on trial-wise SoC. Additionally, we examined how trait-like differences in LoC (IE-4 scores) and depressive symptoms (CESD-R scores) modulated these effects.

Our results revealed that sensorimotor control strongly influences SoC, as participants reported significantly lower control in the high input noise condition than in the low input noise condition (H1). Additionally, performance improvements (i.e., decreasing error rates) were associated with increased SoC (H3). This supports the idea that motor coordination dynamically informs control perception. Notably, task practice selectively enhanced perceived control in the low input noise condition, while being associated with a gradual decrease in the high input noise condition. This suggests that sensorimotor disruptions impair the ability to establish a stable control estimate over time. By introducing a continuous manipulation of motor control during action execution, this finding extends previous research on the SoC in dynamic task environments that shows a reduction of SoC by introducing action-effect delays (Inoue et al., 2017; Oishi et al., 2018; Wen et al., 2015). Furthermore, as our post-trial questions directly assessed perceived control over spaceship steering, our inferences directly relate to participants' motor control. This distinction helps separate motor control, which lies at the core of the SoC, from the perceived ability to successfully complete the task, two aspects not consistently dissociated in previous studies (see Oishi et al., 2018).

Furthermore, in line with our expectations (H2), affective feedback modulated the SoC, with positive feedback increasing and negative feedback decreasing perceived control. The significant interaction of positive feedback and block number additionally revealed that the influence of positive feedback diminished over time. This may suggest that, while the psychological impact of negative feedback remained stable, participants gradually habituated to positive feedback, leading to a reduced effect on self-reported control experience. Crucially, negative feedback exerted a stronger influence on SoC than positive feedback, indicating a negativity bias in control judgments. This finding aligns with models of error monitoring and the utilization of prediction errors during reinforcement learning, which suggest that negative feedback is more salient and promotes behavioral adaptation more effectively than positive reinforcement (Cavanagh et al., 2010; Yoshie & Haggard, 2013).

Importantly, this result contrasts with self-serving bias theories, which posit that individuals preferentially integrate positive feedback while disregarding negative feedback (e.g., Chambon et al., 2020). Our results suggest that whether a valence-specific bias towards positive or negative feedback exists may likely depend on the task demands: In performance-driven contexts, negative feedback may be more important due to its greater corrective utility. In fact, insights from neuroscience indicate that feedback-induced theta oscillations originating from the anterior cingulate cortex likely constitute a neural mechanism translating negative, but not positive, feedback to behavioral adaptations by increasing cognitive control (Cavanagh & Frank, 2014; Cavanagh et al., 2010; Giersiepen et al., 2023, 2024). In the current experiment, participants were instructed to maximize their performance-dependent bonus. Although we did not directly assess whether participants believed that the feedback was contingent on their performance, the modulation of perceived control by feedback type suggests that participants did associate the feedback with their steering performance. In this context, negative feedback may have been more salient, serving as an instructive cue to adapt behavior on subsequent trials. Alternatively, the increased salience of negative compared to positive feedback may not have been driven by its informative value for subsequent action but rather relate to participants' surprise at receiving it (Noordewier & Breugelmans, 2013; Wurm et al., 2022). More specifically, although participants were informed that feedback was performance-dependent, we ensured an equal frequency of negative, neutral, and positive feedback to evaluate the relative impact of positive and negative feedback on self-reported SoC. Thus, while positive feedback may have reinforced participants' perceived control, negative feedback might have conflicted with their expectations, thereby more strongly diminishing their SoC over spaceship navigation.

It should be noted that, in contrast to our prediction, feedback effects on SoC were not moderated by task difficulty (i.e., input noise; H4), suggesting that low-level and high-level cues independently contribute to control perception. This hypothesis was based on studies using non-dynamic task environments, showing an increased reliance on externally provided feedback when immediate sensorimotor feedback was unreliable (Gentsch et al., 2012; Moore et al., 2009; Synofzik et al., 2013). In the current study, input noise was employed to disrupt the relation between participants' keyboard input and the spaceships' movement. Given that this distortion was enhanced in high compared to low input noise blocks, we hypothesized that participants would display an increased reliance on positive and negative feedback to infer their SoC in blocks with high input noise. In contrast to that assumption, and consistent with a recent study on self-reported control during continuous action (Dewey, 2023), our findings indicate that the influence of evaluative feedback on the SoC did not depend on the reliability of sensorimotor signals. Rather, our results suggest that dynamic, goal-directed tasks provide a continuous stream of sensorimotor information that remains influential even under high uncertainty. Our findings also contribute to the discussion on whether invalid feedback affects self-reported SoC. While some studies suggest that external feedback primarily influences participants' SoC when it reliably reflects performance (e.g., Dewey, 2023), others indicate that feedback shapes SoC ratings even when unrelated to behavior (e.g., Wen et al., 2015). Consistent with Wen et al., our results show that both positive and negative feedback significantly modulate perceived control, despite being entirely independent of actual performance.

Our results further indicate that trait-like control beliefs shape task specific SoC. First, while there was no significant main effect of external LoC on SoC ratings, a significant interaction between external LoC and input noise emerged. Specifically, individuals with a higher external LoC reported greater SoC under high input noise compared to those with a lower external LoC. This finding does not provide evidence for the assumption that individuals with a high external LoC, who attribute events to external factors such as fate or luck (Kovaleva et al., 2014; Nießen et al., 2022), would show an increased reliance on performance feedback (H7). It instead suggests that externalizing the causes of events changes how sensorimotor reliability influences perceived control during dynamic, goal-directed tasks.

Second, our results revealed that participants with higher scores on the CESD-R were less strongly affected by negative feedback than participants with lower scores, indicating a reduced negativity bias in individuals with a higher expression of depressive symptoms (H5). This unexpected finding contrasts with research on depression-related cognitive and perceptual biases, where negative information is processed more strongly than positive information (see e.g., Disner et al., 2011; Roiser et al., 2012). In the current context, participants with higher depression scores seem to have been less emotionally reactive to negative trial-wise feedback. This may reflect blunted outcome processing associated with depression, where the ability to adequately incorporate negative feedback to adjust behavior is impaired (Steele et al., 2007). Crucially, while depressive tendencies were associated with a reduced sensitivity to negative feedback, they more strongly impacted the influence of input noise on perceived control. Specifically, individuals with higher CESD-R scores showed a stronger influence of input noise on SoC ratings. This suggests that elevated depressive tendencies may enhance the sensitivity to the loss of control conveyed through low-level sensorimotor feedback.

Taken together, these findings underscore the importance of considering individual differences in how low-level and high-level feedback is processed when studying control perception. The modulation of perceived control by both depressive symptoms and external LoC partly aligns with recent work showing that individuals differ in how they weight different cues of control (Chang & Wen, 2025). Importantly, the current study identifies two trait-like factors, depressive symptoms and external LoC, that shape this integration process.

The findings of the current study align with the hierarchical framework of situated action control proposed by Kahl et al. (2022). According to this framework, input noise affects a low-level SoC by generating a mismatch between expected and observed spaceship behavior. In contrast, post-trial feedback would be predicted to directly target a high-level SoC by providing explicit information to evaluate task performance. While, according to the model, participants' SoC ratings would not explicitly differentiate between low-level and high-level information, ratings are assumed to reflect an integration of cues at both levels. Future work should test these propositions by directly scrutinizing the mechanisms underlying the emergence of SoC in dynamic tasks. To this end, studies should examine the neural and computational signatures underlying the integration of sensorimotor and affective feedback in signaling control. This approach would allow us to also directly relate the influence of positive and negative feedback on SoC ratings to neural measures of feedback processing, such as the reward positivity or midfrontal theta oscillations (see Giersiepen et al., 2024). Moreover, it has been shown that cognitive load during task execution decreases perceived control (Dewey, 2023). Future studies could therefore examine whether the weighting of low- and high-level cues shifts with task proficiency, for example, by comparing cue integration in well-practiced versus novel tasks.

Some limitations should be considered when interpreting the results of the current study. First, our sample consisted of a non-clinical population with generally low depression scores. To draw robust inferences on the influence of psychiatric disorders on the task-specific SoC, future studies should consider a more heterogeneous sample, including individuals diagnosed with a depressive disorder. Additionally, our sample size may have been insufficient to detect all within-subject interactions and between-subject differences in self-reported SoC. Specifically, our power analysis was conducted based on within-subject main effect hypotheses and did not account for higher-order effects or between-subject differences. As a result, our study may have been underpowered to detect smaller effects.

The current study focused on the effect of low-level and high-level cues on explicit, self-reported SoC. Even though SoC ratings were influenced by feedback type, we did not explicitly assess whether participants believed that the feedback was contingent on their performance. Thus, the current results do not allow us to determine whether the reduced influence of positive feedback on perceived control over time reflects a habituation to positive outcomes or growing skepticism about the feedback's validity. Furthermore, while our results suggest a stronger impact of negative compared to positive feedback on SoC, using gains twice as large as losses introduces a methodological confound that may have influenced the strength of the effects. However, the pattern of results, characterized by a stronger influence of negative compared to positive feedback, suggests that outcome magnitude alone is unlikely to account for this asymmetry. Future studies could address these limitations by directly assessing participants' belief in the performance-feedback contingency and by including a control condition that accounts for the asymmetry in outcome magnitude. Finally, further insight may be gained from assessing implicit measures of control. This is especially relevant, considering that not all aspects related to situated control may be subject to reflective, conscious experience (Pacherie, 2007).

5. Conclusion

Using a dynamic motor control task, the current study provides new insights into the interplay of low-level sensorimotor cues and high-level evaluative feedback in shaping the SoC during continuous, goal-directed action. Employing a complex task design, our results provide insight to the emergence of SoC under dynamic conditions that resemble everyday behavior, thereby extending previous work that predominantly examined the SoC in simpler task scenarios. Our findings demonstrate that sensorimotor noise and evaluative feedback independently contribute to task-specific SoC. Furthermore, affective feedback appears to be asymmetrically weighted in shaping the SoC, with negative feedback exerting a stronger influence than positive feedback. Crucially, the impact of low-level and high-level cues is modulated by depressive symptoms and individual differences in the external LoC. Future work should therefore account for individual differences when investigating the mechanisms underlying situated control experience.

Declaration of generative AI and AI-assisted technologies in the writing process

During the preparation of this work the author(s) used ChatGPT (OpenAI) in order to improve readability of individual sentences. After using this tool/service, the author(s) reviewed and edited the content as needed and take(s) full responsibility for the content of the published article.

CRediT authorship contribution statement

Maren Giersiepen: Writing – original draft, Visualization, Software, Project administration, Methodology, Formal analysis, Data curation, Conceptualization. **Nils Wendel Heinrich:** Writing – review & editing, Visualization, Software, Project administration, Methodology, Formal analysis, Conceptualization. **Annika Österdiekhoff:** Writing – review & editing, Software, Project administration, Methodology, Conceptualization. **Stefan Kopp:** Writing – review & editing, Supervision, Funding acquisition, Conceptualization. **Nele Russwinkel:** Writing – review & editing, Supervision, Funding acquisition, Conceptualization. **Simone Schütz-Bosbach:** Writing – review & editing, Supervision, Funding acquisition, Conceptualization. **Jakob Kaiser:** Writing – review & editing, Supervision, Methodology, Funding acquisition, Conceptualization.

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Declaration of Competing Interest

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

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Data availability

Data and study materials are available via Open Science Framework: https://osf.io/6ujth/?view_only=c1a4bf962e5d44f9b20443470987e6da

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3 General Discussion

The experience of being in control of our actions and their effects is central for goal-pursuit and adaptive behavior in everyday life (Gentsch et al., 2015; Karsh & Eitam, 2015). This sense of agency constitutes a core component of our sense of self and shapes how we perceive and interpret our environment (Haggard & Eitam, 2015). During goal-directed behavior, action effects often carry practical significance, meaning that positive outcomes reinforce preceding actions, while negative ones discourage their repetition. While theories and empirical findings point to a reciprocal, dynamic interplay between the sense of agency and affective processing (Gentsch & Synofzik, 2014; Gentsch et al., 2015; Kaiser, Buciuman, et al., 2021; Synofzik et al., 2013), the precise nature of this interaction remains unclear. To address this gap, this thesis investigated the relationship of the sense of agency and the affective value of action outcomes during goal-directed action. Across three empirical studies, the aim was to examine how the sense of agency shapes the processing of affective information (**Chapter 2.1** and **Chapter 2.2**) and, conversely, how affective outcomes influence the experience of agency (**Chapter 2.3**).

The first study (**Chapter 2.1**) examined how freedom of choice influences the neural processing of performance feedback in a motivationally salient reinforcement learning task. Behavioral results confirmed that participants experienced higher agency in the free-choice condition compared to the forced-choice condition. Notably, perceived autonomy (choice agency) increased more strongly than perceived outcome controllability (outcome agency), suggesting that participants experienced varying degrees of agency over different task components. Using electroencephalography (EEG), choice-induced changes in midfrontal oscillatory activity were measured in response to monetary gain and loss feedback. Results revealed that midfrontal theta (MFΘ) power was generally stronger for negative than positive feedback. Moreover, free choices elicited a similar increase in MFΘ power compared to forced choices, regardless of whether the feedback signaled a gain or a loss. Given that feedback-related MFΘ activity has been linked to the goal-directed processing of task-relevant feedback (Cavanagh et al., 2010; Van de Vijver et al., 2011), these findings suggest that choice-induced agency experience enhances the neural impact of affective action outcomes during learning, independent of their valence.

The second study (**Chapter 2.2**) examined the neurocognitive processes underlying the choice-induced increase in affective outcome monitoring during learning. Specifically, it investigated whether this enhancement is driven by the relevance of outcomes for guiding future actions or by their association with recent self-determined choice. EEG data were analyzed to capture both early (N100) and later (Reward Positivity [RewP], MFΘ oscillations) neural responses to feedback in free-choice, action-relevant forced-choice, and action-irrelevant forced-choice conditions. In free-choice blocks, participants retained full control over item selections and could maximize their gains by tracking item-outcome associations. In contrast, all item selections in action-irrelevant forced-choice blocks were predetermined, thereby making outcomes functionally irrelevant for subsequent actions. To disentangle choice autonomy and outcome relevance, action-relevant forced-choice blocks combined initial forced item selections with free choices at the end of each block, allowing feedback from forced-choice trials to inform later decisions. Thus, while outcomes from action-irrelevant forced choices lacked instrumental relevance, those from free choices and action-relevant forced ones carried practical significance for future behavior.

Behavioral results confirmed that participants experienced a higher sense of agency over their choices (choice agency) than over their outcomes (outcome agency). Furthermore, as expected, agency ratings were highest for free choices, followed by action-relevant, then action-irrelevant forced choices. Neurophysiologically, free choices elicited larger feedback-locked ERPs and stronger MFΘ power compared to both forced-choice conditions, reflecting enhanced outcome processing of self-determined action outcomes. Crucially, action-relevant forced choices did not elicit stronger MFΘ power than action-irrelevant forced choices. This shows that the ability to choose an action (choice agency) rather than the instrumental value of the outcome enhances neural feedback processing. While early outcome processing, as indexed by the N100, was unaffected by outcome value, choice opportunity induced a valence-specific bias during later stages of outcome evaluation, evidenced by a stronger increase in MFΘ power for negative feedback and the selective presence of a RewP following free choices. These findings suggest that choice autonomy, rather than the instrumental value of outcomes, drives enhanced outcome monitoring and valence-specific processing biases, underscoring the importance of agency in tracking the consequences of one's actions during learning.

The third study (**Chapter 2.3**) investigated how the affective value of action outcomes shapes moment-to-moment changes in the sense of agency during continuous, goal-directed action. Participants performed a motor control task in which the sense of agency was manipulated by varying sensorimotor noise (motor agency) across blocks, creating conditions of low and high difficulty. After each trial, participants received negative (monetary loss), neutral, or positive (monetary gain) feedback, and then rated their sense of control (SoC), indexing their agency experience over the motor task. Behavioral analyses examined how the affective value of feedback interacts with both sensorimotor control and individual differences in two important agency-related traits (depressive tendencies and the Locus of control [LoC]) in shaping the sense of agency.

Contrary to the hypothesis that evaluative feedback would more strongly affect agency experience under conditions of high sensorimotor noise, results revealed that sensorimotor noise and evaluative feedback independently contributed to SoC ratings. This suggests that affective feedback does not necessarily modulate the reliance on low-level sensorimotor cues during continuous goal-directed action. Notably, agency ratings reflected a valence bias, characterized by a stronger reduction in perceived control for negative feedback than the increase observed for positive feedback. Moreover, the effects of sensorimotor noise and high-level feedback were modulated by participants' LoC and depressive tendencies, indicating that the processing of both non-affective and affective determinants of task-specific agency experience are influenced by stable, trait-like control beliefs.

Taken together, the findings from this thesis provide novel insights into the affective dimension of the sense of agency. By examining how freedom of choice, a key determinant of the sense of agency, influences outcome processing, this work sheds light on neurocognitive mechanisms through which agency experience may support adaptive, goal-directed behavior. Moreover, by investigating how the affective value of action outcomes shapes self-reported control during continuous, goal-directed action, the results offer insight into the interplay of affective information with low-level sensorimotor cues of control and higher-level individual differences in the LoC and depressive tendencies. The following sections will summarize the central insights from this research project regarding self-reports of the sense of agency, the neural processing of goal-directed task feedback, and the role of inter-individual differences in determining agency experience.

3.1 Effects of Freedom of Choice and Motor Control on the Sense of Agency

Participants' self-reports substantiate and extend previous work on the influence of choice autonomy on agency experience. Across Studies 1 and 2, participants reported a greater sense of agency for free choices compared to forced choices, consistent with prior findings that self-determination enhances agency experience (Barlas & Obhi, 2013; Sidarus et al., 2017a).

Importantly, the results show that this effect is not confined to choice agency, the perceived feeling of being free to choose between actions, but also extends to outcome agency, the perceived control over action outcomes (see also Schwarz, Weller, Klaffehn, et al., 2019). This was reflected in reduced outcome agency ratings alongside lower choice agency ratings, despite identical reward schedules in both free-choice and forced-choice conditions.

Moreover, the findings support the view that the sense of agency is dynamically shaped by distinct cues of control (Synofzik et al., 2013). In the presented work, choice was manipulated deterministically (presence versus absence), whereas outcome controllability was probabilistic for both free choices and forced choices (75% reward probability following high-value item selections). Stronger effects of freedom of choice on choice than outcome agency ratings reflected this differentiation, indicating sensitivity to varying degrees of control over distinct task components.

In contrast to Studies 1 and 2, Study 3 manipulated motor agency by introducing sensorimotor noise to vary participants' motor control over goal-relevant actions. Sense of agency was assessed through SoC ratings after each trial, directly targeting aspects of agency linked to sensorimotor control. Results confirmed that increasing sensorimotor noise reduced perceived control. Crucially, the influence of sensorimotor noise on agency ratings was independent from the influence of outcome valence, providing initial evidence for an additive contribution of affective and non-affective processes to task-specific agency experience.

Together, these behavioral findings corroborate previous work on the influence of choice autonomy and motor control on the sense of agency (Barlas et al., 2017; Kaiser, Buciuman, et al., 2021; Moore et al., 2009; Synofzik et al., 2013). Importantly, they extend our understanding of the sense of agency as a multifaceted construct by demonstrating differential effects of choice opportunity on choice agency (i.e., perceived freedom of choice over actions) and outcome agency (i.e., perceived control over outcomes). This has important implications for studies that assess the sense of agency via self-report. While most studies rely on a single item to assess the sense of agency (see Dewey & Knoblich, 2014; Moore, 2016), this approach risks overlooking its multifaceted nature. Our results underscore the value of measuring distinct components, such as freedom of choice, motor control, and outcome controllability, to capture more accurately how different aspects of an action and the associated task contribute to the overall experience of agency.

3.2 Affective Influences on the Sense of Agency

While the affective dimension of the sense of agency has received comparatively little attention in agency research (Gentsch & Synofzik, 2014), Study 3 clearly shows that trial-wise agency experience is influenced by outcome valence. First, the results revealed that high-level affective feedback influences self-reported agency experience independently of low-level sensorimotor control. This finding diverges from evidence suggesting that reduced reliability of sensorimotor information increases the reliance on external cues of control (Desantis et al., 2011; Gentsch et al., 2012; Moore et al., 2009). This inconsistency may be related to the nature of the implemented task. Unlike many studies reporting interactions between sensorimotor information and other control cues, our experiment employed a dynamic task environment that afforded several seconds of continuous motor control. This was realized to create a lab environment that more closely resembles actions encountered in everyday life, where the sensorimotor system provides an ongoing stream of immediate, low-level feedback. In this context, sensorimotor input was present for most of the trial, whereas evaluative feedback occurred only after task completion. The dominance of sensorimotor input, together with the temporally delayed high-level feedback, may have led to a psychological decoupling of both cues, resulting in a parallel but independent contribution to the sense of agency. Moreover, participants were asked specifically about their SoC (i.e., motor agency) over the task, not over their perceived control over the outcome (outcome agency). As Studies 1 and 2 suggest, individuals are sensitive to their control over different task components. Thus, they may have distinguished their motor control (rated after each trial) from their outcome control (not assessed), potentially explaining the absence of the interaction between these two factors on agency experience in the current task.

Study 3 also sheds light on how affective valence shapes the sense of agency. The results revealed a negativity bias, characterized by a stronger impact of negative feedback than positive feedback on agency ratings. This pattern suggests that an enhanced sense of agency for positive compared to negative events is not primarily driven by a self-serving bias, which would be reflected in a stronger increase in the sense of agency for positive outcomes (Chambon et al., 2020). Instead, it suggests a predominant role of externalizing agency for negative outcomes. At first glance, the stronger influence of negative feedback could be explained by prospect theory, which posits that individuals weigh losses twice as much as equivalent gains (Kahneman & Tversky, 1979). However, in the present study, gains were set to be twice the size of losses, suggesting that prospect theory alone may not fully account for this bias. Alternatively, this finding may reflect emotional distancing from undesired effects (Yoshie & Haggard, 2017), which outweighs self-serving attributions of positive outcomes to the self (Gentsch & Synofzik, 2014).

Notably, the relative influence of positive and negative feedback may depend on the perceived capacity to learn from feedback (see Gentsch et al., 2015). Self-serving biases are thought to enhance self-esteem and contribute to well-being (Takahata et al., 2012). These biases may dominate when outcomes are perceived as unrelated to performance. In contrast, when a task emphasizes outcomes as performance indicators, self-serving tendencies may be outweighed by processes that promote feedback-driven behavioral adaptation. Negative feedback has been linked to the initiation of cognitive control mechanisms that guide feedback-guided learning, potentially indicating a more effective modulation of behavior than positive feedback (Cavanagh & Frank, 2014; Gershman, 2015; but see Chambon et al., 2020). In the present study, participants were told that feedback reflected their performance in the motor control task and that their goal was to maximize accuracy to increase their payout. Thus, instructions emphasized the relevance of feedback for adapting subsequent actions, potentially resulting in a stronger influence of negative compared to positive feedback on agency experience.

Another possibility is that negative feedback was less expected and therefore elicited greater surprise. In particular, consistent with the illusion of control (Langer, 1975), several studies show that people tend to overestimate their control in chance settings, especially when tasks are framed as performance-based (see Stefan & David, 2013). From this perspective, positive feedback would result in a modest increase in the sense of agency, whereas negative feedback would produce a stronger loss of control. It should be noted, though, that the study did not directly assess participants' beliefs about whether feedback truly depended on their performance. Therefore, alternative explanations cannot be ruled out. For instance, the negativity bias may have resulted from a gradual decline in the impact of positive feedback over time, reflecting humans' greater tendency to habituate to positive than to negative feedback (Rozin & Royzman, 2001; Yartsev et al., 2024).

Overall, explicit agency ratings indicate that perceived control is shaped by both low-level sensorimotor cues and high-level information, including choice autonomy and outcome valence. The present results offer initial evidence for independent contributions of affective and non-affective processes, with both sensorimotor control and evaluative feedback influencing perceived control during dynamic, goal-directed action. Moreover, in such contexts, valence-related biases appear not to reflect self-serving mechanisms, but rather the heightened salience or perceived instrumental value of negative feedback for guiding future behavior.

3.3 Freedom of Choice Enhances the Neural Processing of Affective Action Outcomes

Studies 1 and 2 provide insights into agency-related changes in the neural processing of goal-relevant affective feedback and its associated cognitive processes. Choice autonomy reliably enhanced the processing of affective action outcomes, evident in both early sensory (N100) and later evaluative EEG markers (RewP, MFΘ oscillations). By directly comparing the effects of choice on N100, RewP, and midfrontal oscillatory activity within the same paradigm, these studies extend prior work that largely examined the effects of the sense of agency on these processing stages in isolation.

Contrasting reports of attenuated processing of self-generated action effects (Gentsch & Schütz-Bosbach, 2015), N100 amplitudes were larger following free-choice than forced-choice feedback. The divergence in neural effects between these studies likely reflects differences in agency manipulation and outcome type. While most studies reporting N100 attenuation varied the degree of motor involvement in producing simple sensory effects (motor agency), the current study manipulated freedom of choice (choice agency), followed by instrumental affective feedback. Our findings are consistent with evidence that self-attenuation is absent when self- and externally determined events are equally predictable (Kaiser & Schütz-Bosbach, 2018) and further suggest self-enhancement of motivationally salient, goal-relevant action outcomes. Because this enhancement was not confined to the N100 but persisted into later stages of outcome processing, heightened monitoring likely involves increased attentional engagement for self-determined choices (Kaiser & Schütz-Bosbach, 2018; Krigolson et al., 2015).

While choice agency influenced the N100, outcome valence did not, suggesting that early, sensory processing of high-level performance feedback is not modulated by the affective value of action outcomes. In contrast, both Studies 1 and 2 showed greater MFϴ power for negative relative to positive feedback, indicating a processing bias for negative feedback (see also Cavanagh et al., 2010; Kaiser & Schütz-Bosbach, 2021; Luft et al., 2013). Importantly, the two studies partially diverged in how choice autonomy shaped this effect. In Study 1, free choices enhanced MFϴ power equally for positive and negative feedback, indicating a valence-independent boost in evaluative outcome processing. In Study 2, MFϴ power during free choices was again higher for both negative and positive feedback, but a valence-specific bias emerged, indexed by a stronger enhancement for negative than for positive feedback.

These partly conflicting findings raise the question of which factors determine whether choice effects on outcome processing are accompanied by valence biases. Forced choices in Study 1 and action-irrelevant forced choices in Study 2 were comparable, making differences in task design an unlikely explanation. More plausibly, because Study 2 included more participants (3 x 2 factorial design; *N* = 37) than Study 1 (2 x 2 factorial design; *N* = 30), the statistical power to detect two-by-two interactions of outcome valence and freedom of choice was higher in the latter compared to the former. Indeed, the descriptive pattern in Study 1 mirrored that of Study 2, with larger increases in midfrontal low-frequency power for negative compared to positive feedback during free choices. This may suggest that feedback-induced MFϴ oscillations are characterized by a processing bias for negative feedback during high agency, although the interaction in Study 1 did not reach significance, likely due to limited power. Complementing the choice-induced bias for negative feedback, Study 2 also revealed a RewP, indicating stronger processing of positive than negative feedback during free choices, whereas neither action-relevant nor action-irrelevant forced-choice trials revealed ERP evidence for a differential coding of outcome value.

Previous research indicates that opportunities for choice enhance learning and promote effective goal-directed behavior (Luo et al., 2022; Murayama et al., 2015). Building on this, Kaiser, Buciuman, et al. (2021) proposed that agency-induced benefits in behavior regulation may be partly mediated by changes in affective outcome processing. Notably, the RewP and MFϴ oscillations are promising neurophysiological mechanisms underlying this process. The RewP has been shown to vary with outcome value and reward prediction error (Becker et al., 2014; Zheng et al., 2020), while feedback-induced MFϴ oscillations index conflict monitoring and the instantiation of cognitive control (Cavanagh & Frank, 2014). Both markers have been implicated in learning from feedback within the anterior cingulate cortex (ACC; Cavanagh et al., 2010; Mühlberger et al., 2017; Williams et al., 2020). By examining how freedom of choice shapes the neural processing of affective feedback during reinforcement learning, this thesis provides initial insights into the hypothesis that these markers contribute to agency-induced benefits in behavior.

In Study 1, self-determined choices enhanced MFϴ oscillations, consistent with more efficient learning when experiencing a high sense of agency. This effect may reflect differences in the instrumental relevance of outcomes, which were informative for future choices in the free-choice condition but not in the forced-choice condition. However, processes unrelated to learning, such as the inherent valuation of self-determined choice (Ly et al., 2019), could also account for this effect. To isolate the mechanisms underlying choice-induced facilitations in outcome monitoring, Study 2 contrasted free choices with two forced-choice conditions whose outcomes were either irrelevant or relevant for subsequent behavior. Freedom of choice increased the N100, the RewP, and MFΘ power relative to both forced-choice conditions. Crucially, outcome processing did not differ between the two forced-choice conditions, indicating that the opportunity to choose, rather than the instrumental value of outcomes, amplifies affective outcome monitoring during learning. As reinforcement learning performance was similar in free and action-relevant forced choices, the observed processing differences may further indicate that choice-related effects on outcome processing do not translate into improved learning. These findings have implications for interpreting the functional relevance of choice-induced enhancements in RewP and MFΘ activity. If these neural markers index feedback-guided learning (Cavanagh & Frank, 2014; Williams et al., 2020), then comparable learning across choice contexts indicates that enhanced responses following free choices do not explain agency-related benefits in behavior. Instead, the findings support the view that choosing is inherently rewarding (Leotti et al., 2015; Ly et al., 2019) and may enhance the subjective value and motivational salience of self-determined action outcomes. Within this framework, the RewP reflects greater salience of self-determined positive outcomes, whereas enhanced MFΘ oscillations index heightened cognitive conflict associated with greater aversiveness of self-induced negative action effects.

The absence of learning differences appears to conflict with findings on choice-related benefits for goal-directed behavior (Luo et al., 2022; Murayama et al., 2015). This may plausibly be explained by the relative ease of succeeding in the reinforcement learning task. In both Studies 1 and 2, participants learned which of two options was more rewarding under a 75-25 reward-loss schedule and typically acquired this association after a quarter of trials in each block. Consequently, the tasks may have lacked sensitivity to reveal choice-related performance benefits. Alternatively, learning differences may have been present but were not statistically detected. Comparing condition-level averages of performance and neural responses, as in the present studies, may lack the sensitivity to capture trial-wise dynamics of learning, outcome valence, and neural feedback processing. Trial-by-trial analyses via computational modeling would allow for a more fine-grained evaluation of learning dynamics by relating behavioral adjustments to prediction errors and neurophysiological responses, and by estimating learning rates as a function of choice context. This approach could provide a more detailed understanding of how choice-induced differences in outcome processing relate to feedback-guided learning.

To summarize, the presented studies show that choice autonomy reliably amplifies the processing of affective action outcomes, both during early sensory and later evaluative stages. Self-determined choices biased evaluative outcome processing toward positive and negative feedback, as reflected in the selective presence of a RewP and enhanced MFΘ activity, respectively, while inducing a valence-independent increase during early sensory processing (N100). These effects appear to reflect the inherent valuation of choosing rather than the instrumental value of outcomes. More demanding learning environments and trial-wise modeling of brain-behavior associations are needed to evaluate the temporal dynamics and neurophysiological mechanisms through which agency experience may influence behavior.

3.4 Individual Differences Modulate Cue Integration During Goal-Directed Action

Inter-individual differences are thought to modulate how much control we perceive over our actions and their outcomes (Gentsch & Synofzik, 2014), yet their influence on task-specific agency experience has received comparatively little attention. Results from Study 3 suggest that task-specific variations in the sense of agency are shaped by individual differences in LoC and depressive symptoms. Both traits have been linked to alterations in attributional processes and perceived controllability over life events (Disner et al., 2011; Nießen et al., 2022; Rotter, 1966; Yu & Fan, 2016), and depression in particular, is linked to heightened sensitivity to negative information (Gotlib & Joormann, 2010; Roiser et al., 2012). We therefore hypothesized that LoC and depressive symptoms would modulate how low-level sensorimotor cues are integrated with higher-level affective feedback. The findings supported this idea, though in ways that refine our initial predictions.

Contrary to the expectation that a more external LoC would increase the reliance on evaluative feedback, it selectively influenced the effect of sensorimotor noise on the sense of agency under high task difficulty, where a higher external LoC was associated with elevated agency ratings. Following Carstensen (2024), one interpretation is that generalized beliefs about the ability to control events in life may be distinct from moment-to-moment tasks-specific agency experience. In the current task, the salience of sensorimotor noise in the difficult condition may have led participants with a more external LoC to attribute errors in the motor task to situational interference rather than to themselves, allowing them to discount these externally imposed disruptions when estimating their control experience. Because SoC ratings referred to the perceived control over the motor task (motor agency), rather than over its outcomes (outcome agency), this differentiation may have resulted in higher agency ratings under high sensorimotor noise.

Depressive symptoms modulated the influence of both sensorimotor noise and, to a lesser extent, affective feedback on perceived control. Although depression is typically associated with heightened processing of negative information (Gotlib & Joormann, 2010; Roiser et al., 2012), we observed that increasing depressive symptoms were associated with a reduced influence of negative feedback and a stronger effect of sensorimotor noise on trial-wise agency ratings. The reduced impact of negative feedback may reflect decreased affective reactivity in individuals with higher depressive symptoms, thereby reducing its influence on agency experience (Steele et al., 2007). Alternatively, depressive tendencies may lead to a generally increased readiness to assume responsibility for negative outcomes, resulting in a smaller decrease in perceived control from momentary feedback (Zahn et al., 2015).

Notably, the opposite effects of depressive symptoms on self-reported agency experience via sensorimotor noise and affective feedback may also be reconciled with findings on depressive realism, which describes a more accurate perception of contingencies in depressed compared to non-depressed individuals (Alloy & Abramson, 1979; Yoshie & Haggard, 2013). In particular, whereas positive and negative feedback were unrelated to task performance, increasing sensorimotor noise diminished performance accuracy. Participants with higher depression scores may have been more sensitive to the dissociation of low-level sensory information and experimentally manipulated affective feedback, resulting in a reduced impact of negative feedback and an increased influence of sensorimotor feedback on agency ratings.

Notably, although both the external LoC and depressive symptoms interacted with low- and high-level control cues, we found no evidence that they moderated the relative influence of sensorimotor noise and affective feedback (as e.g., reported in Chang & Wen, 2025). This may suggest that inter-individual differences in cue integration are not captured by these traits, implying that external LoC and depressive symptoms modulate the weighting of low- and high-level processes while leaving their relative contribution to the experience of agency unchanged. Alternatively, the null effect of trait-like differences on the relative weighting of sensorimotor information and evaluative feedback may reflect methodological limitations. Because a more external LoC and depressive symptoms are characterized by reduced perceived control over life events (Disner et al., 2011; Nießen et al., 2022; Rotter, 1966; Yu & Fan, 2016), their moderating effects may more likely manifest when obtaining outcome agency ratings rather than the SoC (indexing motor agency). Moreover, because the primary aim of Study 3 was to assess the relative influence of affective feedback and sensorimotor information on the sense of agency, the sample size was powered for within-subject effects. Detecting between-subject effects, especially for three-way interactions (here: traits, low-level control cues, high-level control cues) typically requires larger samples (Cohen, 1988). Consistent with this notion, the effects of external LoC were characterized by wide confidence intervals and large standard errors, pointing towards an inadequate sensitivity to detect significant between-subject effects and their interactions with within-subject experimental factors. Likewise, depressive tendencies were assessed in a non-clinical sample with generally low depression scores, which may underestimate their influence on task-specific agency ratings. Testing between-subject effects and their interaction with experimental factors would require larger samples, ideally comparing healthy with clinically depressed individuals.

In summary, Study 3 shows that individual differences shape task-specific agency experience during continuous, goal-directed action. Although the robustness of these effects requires validation in larger samples, the findings provide initial evidence that trait-like control beliefs do not modulate the integration of immediate sensorimotor versus post-trial affective feedback but instead independently influence the reliance on individual agency cues. Alterations in the relevance of individual cues may be driven by changes in the assumed contingency between sensorimotor noise, evaluative feedback, and actual task control (see Chang & Wen, 2025). For example, individuals with a higher external LoC may externalize responsibility for impaired task performance under high sensorimotor noise, thereby protecting their sense of agency despite reduced accuracy in the motor task. In contrast, depressive symptoms may be associated with a stronger decline in agency experience in the presence of noise and may further alter the weighting of affective cues.

These findings might have implications for our understanding of the development of learned helplessness. If the negativity bias reflects a higher perceived utility of negative relative to positive feedback for guiding subsequent actions, then its attenuation with elevated depressive symptoms may signal reduced learning from negative events. This may impair adaptive behavior regulation and, ultimately, contribute to the emergence of learned helplessness. Alternatively, because feedback in the current study was not performance-contingent, the diminished response to negative feedback may reflect processes unrelated to learning, such as more accurate control estimates among individuals with higher depressive symptoms. Resolving these alternatives might be possible via future experiments that employ learnable task environments with performance-contingent feedback to track how depressive tendencies shape outcome evaluation during learning.

3.5 Theoretical Implications, Future Directions, and Methodological Considerations

The findings from the three studies presented in this thesis support a multifaceted account of the sense of agency that encompasses not only low-level sensorimotor and high-level cognitive processes but is also reliably influenced by affective information. These facets shape agency experience across different levels, influencing both early and late stages of outcome processing, as well as subjective judgments. In particular, the present thesis shows that affective information systematically modulates both measures, underscoring the importance of studying agency experience in the context of goal-directed behavior, where outcomes carry inherent affective value.

The comparator model describes low-level sensorimotor contributions to the sense of agency (Blakemore et al., 2002; Frith et al., 2000). According to this model, agency experience arises from a match between predicted and actual sensory feedback. Findings typically reveal a reduced explicit sense of agency and larger N100 amplitudes for unpredicted or erroneously predicted consequences, whereas correct action-effect anticipations are associated with enhanced agency experience and attenuated N100 responses. Hence, N100 attenuation has been interpreted as a neural marker of the sense of agency (see Moore, 2016). In contrast, our results revealed enhanced N100 amplitudes in high agency contexts. Importantly, whether N100 amplitude is enhanced or attenuated likely depends on the nature of action outcomes. Contrasting much previous work, feedback in the studies presented in this thesis was not only a sensory consequence of action but also informative about participants' performance. In such contexts, the positive or negative value of action effects may outweigh evaluations of action-effect associations within the sensorimotor system, leading to enhanced rather than attenuated processing. This highlights that a comprehensive understanding of how agency experience shapes outcome perception requires examining it not only in tasks with simple sensory effects but also during goal-directed actions.

Furthermore, while the comparator model and empirical evidence supporting this account largely revolve around sensorimotor aspects of the sense of agency (motor agency), manipulating choice autonomy primarily targets higher-level beliefs. Consequently, choice-related aspects of the sense of agency may shape early sensory processing through mechanisms not accounted for by the comparator model (Synofzik et al., 2008). Thus, while the comparator model may provide a useful account of the sense of agency in simple tasks where outcome predictability depends on sensorimotor processes, it does not capture the influence of higher-level cognitive and affective factors examined in this thesis (see also Synofzik et al., 2013).

Our results can partly be reconciled with the cue integration account, which posits that agency experience arises from a dynamic integration of low-level and high-level cues of control (Moore et al., 2009; Synofzik et al., 2008; Synofzik et al., 2013). In our data, high-level cognitive and affective cues included choice autonomy (Studies 1 and 2), trait-like differences (Study 3), and post-trial feedback (Studies 1-3), while sensorimotor noise (Study 3) provided low-level information via sensory feedback. The cue integration account predicts that these levels jointly influence agency experience and highlights the importance of affective processes in modulating their integration (Moore & Fletcher, 2012; Synofzik et al., 2013). It proposes that immediate feedback from the sensorimotor system typically dominates agency experience, whereas external information, such as higher-level feedback or prior beliefs, receive increasing weight when sensorimotor information becomes less reliable.

In contrast to this prediction, Study 3 revealed an independent contribution of low-level and high-level feedback to the sense of agency, reflected in a comparable influence of affective feedback under both low and high sensorimotor noise. As outlined in the discussion of Study 3, this discrepancy might be related to the temporal imbalance between ongoing sensorimotor feedback during trials and post-trial evaluative feedback, which contrasts with simpler tasks where sensorimotor information and evaluative feedback occupy a comparable share of each trial. Thus, rather than contradicting the cue integration account, these findings may extend it by highlighting an independent yet parallel contribution of affective and non-affective cues to agency experience in dynamic, goal-directed tasks. In doing so, the present work contributes to a broader understanding of the sense of agency, providing insights into cue integration during continuous goal-directed behavior, which may differ from the patterns observed in simpler, non-goal-directed tasks.

Alternatively, the cue integration account may explain the absence of an interaction between sensorimotor noise and evaluative feedback through mechanisms related to the perceived reliability of individual agency cues. While instructions can alter cue integration by shaping control beliefs (Desantis et al., 2012), such beliefs were not explicitly assessed in the presented study. It can therefore not be excluded that participants suspected that feedback was not performance dependent. According to the cue integration account, this could have reduced the perceived reliability of high-level feedback, resulting in a constant weighing of affective feedback even when sensorimotor noise increased.

Finally, Study 3 also examined whether individual differences shape cue integration. The cue integration account predicts that such differences modulate the influence of sensorimotor and task-specific beliefs, and may themselves be shaped by affective processes (see Synofzik et al., 2013). Consistent with this view, we found that external LoC and depressive symptoms influenced the impact of low- and high-level feedback on agency experience. However, unlike recent computational evidence suggesting that individuals differ in how they weigh low- and high-level task cues (Chang & Wen, 2025), we found no evidence that the examined characteristics modulated the relative weighting of sensorimotor noise versus higher-level feedback in shaping the sense of agency. Whether this reflects limited measurement sensitivity or sample size constraints, or instead indicates that the assessed traits do not affect task-specific cue weighting remains to be clarified. Nonetheless, the present work supports the cue integration account by highlighting the relevance of trait-like differences for explaining variability in agency experience.

In summary, the findings of this thesis are broadly consistent with the cue integration account of the sense of agency. While the conditions that determine the dynamics of cue integration (e.g., task learnability, task complexity) and the possibility of diverging effects across measures (e.g., implicit vs. explicit, motor vs. outcome agency) remain to be clarified, the results demonstrate the relevance of affective processes for shaping the sense of agency during goal-directed action. These findings provide a valuable basis for examining the cognitive, neurophysiological, and computational mechanisms through which affective processes influence the sense of agency, and, in turn, contribute to adaptive action control.

One important insight from this thesis is that future research investigating agency experience during goal-directed behavior should focus on using paradigms with demanding yet learnable experimental tasks. Compared to studies with non-learnable reward schedules (as in Study 3) or simple reward contingencies (as in Studies 1 and 2), such tasks would provide adequate sensitivity and a methodological prerequisite for examining whether agency-induced enhancements in outcome processing translate into measurable performance improvements. Moreover, because the relative impact of positive and negative feedback likely depends on the perceived opportunity to learn from feedback (Gentsch et al., 2015), such tasks would allow testing whether valence-specific biases in self-reported agency experience and neural outcome processing are functionally related to learning from feedback or whether these biases reflect more general mechanisms of outcome evaluation, unrelated to behavior.

To disentangle the influence of affective value on distinct facets of the sense of agency, future studies should also independently manipulate choice, motor, and outcome agency, and examine their effects on explicit measures of each component. When assessed on a trial-by-trial basis, this would allow investigating whether affective value differentially modulates self-reports of choice, motor, and outcome agency, and whether cue integration dynamics vary across these components. Since manipulations of motor control and choice autonomy target low-level and high-level aspects of the sense of agency, respectively, cross-paradigm comparisons could further clarify whether affective value exerts comparable effects on neural measures of outcome processing when the sense of agency is manipulated via choice opportunity versus sensorimotor control. To obtain a fine-grained understanding of the impact of affective value on neural responses, performance, and self-reported agency experience, these studies should combine trial-by-trial analyses with computational modeling, thereby quantifying learning rates as a function of agency experience and relating them to neurophysiological markers of outcome processing, such as the RewP and MFΘ oscillations.

Future work should also compare healthy samples with clinically depressed individuals in adequately powered designs to investigate whether differences in trait agency are associated with systematic changes in outcome evaluation. These comparisons would also help clarify whether such personality-dependent changes in outcome evaluation are functionally linked to alterations in adaptive behavior regulation. If the finding that higher depression scores are associated with a reduced negativity bias is replicated, and if MFΘ oscillations are central to feedback-guided learning (Cavanagh & Frank, 2014), this may suggest a relative decrease in weighting signals linked to MFΘ activity, potentially pointing to a mechanism underlying impaired behavior regulation in depression. Given that the influence of affective value may differ between implicit measures and explicit judgments (Gentsch et al., 2012; Moscarello & Hartley, 2017; Synofzik et al., 2013), a joint examination of neural measures of feedback processing and agency ratings could shed light on the neurophysiological and behavioral dynamics of cue integration and their relation to learning-related changes in depression.

In summary, this thesis highlights the importance of distinguishing between different facets when manipulating agency experience, while also underscoring the need to systematically compare their effects on the sense of agency over distinct task components and on neural outcome processing. Moreover, the findings demonstrate that affective processes shape agency experience, emphasizing the value of using demanding, learnable tasks for advancing our understanding of how these processes contribute to agency-related changes in behavior. Building on these insights, two follow-up studies are currently underway.

Notably, as outcome evaluation is influenced not only by the sense of agency but also by other factors relevant to self-other distinction (Krigolson et al., 2013; Turk et al., 2011; Xu, 2021), one of these studies additionally investigates how the sense of agency interacts with the self-relevance of action outcomes (outcome ownership) in shaping this process.

The first follow-up study examines whether manipulating motor agency elicits effects on affective outcome processing that are similar to, or distinct from, those previously observed for choice agency during reinforcement learning. On each trial, participants make a binary item choice, each associated with a high or low reward probability and then move a cursor from the screen center to the selected target using a computer touchpad. In easy blocks, cursor movements align with standard computer settings, whereas in difficult blocks cursor responses are systematically manipulated, requiring adaptation to novel sensorimotor contingencies. Upon reaching the target, participants receive monetary gains and losses as affective action effects, and EEG is recorded to examine outcome processing as a function of motor control and outcome valence. To directly compare valence biases in self-reported sense of agency with neural markers of outcome processing, trial-wise ratings of motor and outcome agency are collected.

The second follow-up study, conducted in collaboration with the Theoretical and Applied Neuroscience Laboratory (University of Victoria, Canada), employs a 2 x 2 x 2 factorial design to manipulate choice agency (free vs. forced-choice), outcome ownership (self- vs. other-owned), and feedback valence (positive vs. negative feedback; performance-dependent). The EEG study investigates how choice agency interacts with outcome ownership in shaping affective feedback processing and examines how these factors influence reinforcement learning performance. To increase sensitivity to capture learning differences across conditions and to avoid ceiling effects in performance, the task involves trial-wise selections among four options with different reward probabilities (10 %, 20 %, 40 %, or 70 %), making item-outcome associations more demanding than in the two-option tasks used in the studies presented in this thesis. Computational modeling is applied to estimate learning rates as a function of self-relevance and to relate them to differences neural markers of feedback processing, providing a more nuanced understanding of learning-related changes in outcome processing.

Finally, beyond the limitations of the individual studies discussed in the previous sections, some additional methodological and conceptual considerations should be noted, both for evaluating findings in agency research in general and for interpreting the results of this thesis. Although assessing the sense of agency through self-report is common practice (see Dewey & Knoblich, 2014; Tapal et al., 2017), such explicit measures have been criticized for their susceptibility to demand characteristics (Moore, 2016). Moreover, some researchers propose that the sense of agency is primarily a pre-reflective process, which cannot be fully assessed via explicit self-report, but might be more accurately assessed via implicit measures (Gallagher, 2000; Pacherie, 2008). Importantly, empirical work often reports a lack of correlation between implicit and explicit measures in agency research (Dewey & Knoblich, 2014; Schwarz, Weller, Klaffehn, et al., 2019; but see Kühn et al., 2011; Weller et al., 2017). Such dissociations may partly reflect limits of explicit judgments in capturing pre-reflective processes, but they may also arise from challenges associated with implicit measures. In particular, intentional binding and sensory attenuation, the two most common implicit measures, may be influenced by general mechanisms such as causal inference and stimulus predictability, rather than by sense of agency per se (Grünbaum & Christensen, 2020; Gutzeit et al., 2023; Kaiser, Buciuman, et al., 2021; Kirsch et al., 2019; Schwarz, Weller, Pfister, et al., 2019). Accordingly, the present work did not attempt to directly measure the pre-reflective sense of agency but instead examined how manipulations of agency modulate neural outcome processing. Conversely, self-reports obtained in the present studies are best understood as higher-level evaluative judgments of control that are related to but may sometimes diverge from moment-to-moment experiences of control. Future research could investigate if affective information has a similar or dissociable interrelation with implicit and explicit measures.

Complementary to the distinction between pre-reflective and reflective aspects of the sense of agency, and the difficulty of relating measures across these levels, is that different manipulations target different facets of the sense of agency, which may be associated with distinct cognitive and neurophysiological mechanisms (Kaiser, Buciuman, et al., 2021). As outlined earlier, sensorimotor noise primarily targets low-level processes, whereas choice autonomy influences higher-level beliefs about control. Although these levels interact (Synofzik et al., 2013), the entry point of the manipulations differ, potentially resulting in diverging effects on the perception of actions and outcomes. For instance, in Study 2, choice enhanced N100 amplitude, whereas prior work found attenuation when varying motor control. These findings may not be contradictory but indicate that different aspects of the sense of agency influence action and outcome perception in distinct ways.

Notably, this distinction is often not made explicit in agency research, leading to conceptual ambiguity and apparent inconsistencies in the reported associations between agency experience and stimulus processing (Grünbaum & Christensen, 2020). While the terminology used to describe and assess the sense of agency in the studies of the present thesis was selected to be concise regarding the facet under consideration, it partly originates from different frameworks, which risks contributing to conceptual ambiguity. In particular, Studies 1 and 2 distinguished between agency experience through self-determined choice

(choice agency) and agency for action effects (outcome agency). At a third level, this approach also describes the sense of agency over an action (motor agency). This distinction was originally introduced to describe different experimental manipulations of the sense agency (Kaiser, Buciuman, et al., 2021), which themselves influence distinct components of agency experience (see Table 1). In contrast, Study 3 drew on Pacherie's (2007) conceptualization, which differentiates phenomenological components of agency, including the *sense of control* (SoC; i.e., the felt control over an action), the *sense of intentional causation* (i.e., the feeling that one's intention or movement caused an effect), and the *sense of initiation* (i.e., the experience of having initiated an action). As apparent from these definitions, the SoC most closely overlaps with the concept of motor agency in experimental research. Classifying SoC ratings within the distinction of choice, motor, and outcome agency therefore allows integrating the results across studies. Yet, it is important to acknowledge that these terms are not identical and originate from different conceptual approaches.

Finally, although the results of this work support the view that the sense of agency and affective processing are fundamentally related, an open question is how experimental effects such as those reported in this thesis translate to everyday action. Using experimentally controlled reward contingencies allows for a systematic evaluation of how the sense of agency and affective processing relate to underlying learning mechanisms. Accordingly, lab-based based studies frequently employ positive and negative feedback, such as monetary gains and losses, to emphasize the instrumental value of an action. While actions in everyday life can likewise be understood as means to achieve positive and avoid negative events, this feedback may differ from the feedback presented in experimental settings. First, such feedback is typically less explicit, with positive and negative value being implicitly and indirectly related to action success or failure. Second, feedback is often not conveyed by a single modality, such as visual feedback on a screen, but may be characterized by multisensory integration, including, for example, auditory, proprioceptive, and interoceptive signals. Third, while once-acquired action-effect contingencies in experimental tasks often remain consistent throughout the experiment, action-effect associations in everyday life are more volatile, requiring continuous monitoring of environmental conditions and flexible behavior adaptation. Such adaptations have been shown to influence feedback processing (Kaiser, Belenya, et al., 2021) and may therefore affect outcome monitoring during learning beyond the effects reported in this thesis. Thus, while the present findings provide important insights into the interplay between the sense of agency and affective processing from a basic research perspective, further experimental work in more ecologically valid task settings is needed to test their generalizability.

In summary, the multifaceted nature of the sense of agency is mirrored in considerable conceptual diversity, which, together with methodological constraints, complicates direct comparisons across studies. These considerations highlight the need for greater conceptual clarity in the use of terminology, and for an explicit differentiation between distinct facets of agency experience. Recognizing these issues and testing the generalizability of the interplay of agency and affective processing in tasks with feedback resembling everyday life is essential for the advancement of our current understanding of the sense of agency and its role in goal-directed behavior.

4 Conclusion

During goal-directed behavior, the affective value of outcomes provides instrumental feedback for evaluating action success or failure, thereby guiding future actions in accordance with our goals. While previous research has primarily examined its sensory and cognitive determinants, much less is known about the affective dimension of the sense of agency. As a result, the interplay between the sense of agency and affective processing during goal-directed behavior remains poorly understood. To address this gap, this doctoral thesis investigated the bidirectional relationship between the sense of agency and affective processes across three empirical studies.

The first two studies provided converging evidence that choice autonomy enhances both the subjective experience of agency and the neural processing of goal-relevant affective outcomes, indicating heightened attentional engagement when individuals feel in control over their actions and effects. While choice effects on early processing (N100) were unaffected by valence, later stages revealed valence-specific biases for the processing of positive (RewP) and negative feedback (MFΘ). Importantly, enhanced outcome monitoring was not driven by the instrumental relevance of outcomes for future behavior, but by the psychological significance of making a self-determined choice. Together, the findings suggest that the selective presence of a RewP during free choices reflects the inherent rewarding value of choice autonomy, whereas heightened MFΘ power indicates increased cognitive conflict when negative outcomes follow one's own choices compared to externally imposed ones.

The third study confirmed a reciprocal relation between agency and affective processing by showing that affective value influenced the self-reported sense of agency. In line with previous findings, positive outcomes were associated with higher control ratings than negative ones. Crucially, this effect was driven by a stronger reduction in ratings following negative feedback compared to the increase observed for positive feedback. Consistent with a negativity bias, this indicates that motivationally salient negative outcomes exert a greater impact on agency experience than equally relevant positive ones. Beyond predictions of the cue integration account, the findings also suggest that sensorimotor cues and affective feedback independently shape agency experience during goal-directed action, though the relative weighting of these cues may vary across task contexts and measurement approaches. Finally, evidence for the influence of individual differences on the weighting of affective and non-affective task cues highlights the importance of considering trait-level factors when explaining how agency experience emerges during goal-directed behavior.

Together, the insights into the affective dimension of the sense of agency obtained from the three studies presented in this thesis suggest that affective processes are not incidental to our actions but may actively shape how goals are pursued and evaluated. The sense of agency enhances the processing of affective outcomes, while outcome value, in turn, shapes the experience of agency during goal-directed action. These findings broadly support theoretical accounts that emphasize the role of affective information for the emergence of agency experience, such as the cue integration account. Importantly, the influence of affective cues may be shaped by contextual factors, such as the (perceived) instrumental value of outcomes, and by the specific aspect of agency under consideration. Although no single study can capture the multifaceted nature of the sense of agency in its entirety, the presented studies consider the interplay of individual sensory and cognitive cues with affective processes, thereby offering a more comprehensive account of the emergence of agency experience during goal-directed action. The insights gained from this work provide a valuable foundation for future research on the functional role of affective processes in regulating behavior, advancing our understanding of the mechanisms through which the sense of agency supports adaptive, goal-directed behavior.

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Declaration of Generative AI and AI-Assisted Technologies in the Writing Process

ChatGPT (OpenAI) was used during the preparation of this work to improve readability. After using this tool, the content was reviewed and edited as needed. I take full responsibility for the content of the presented work. The following prompts (in these or similar wordings) were used during this process: '*Please improve the provided text passage with regard to readability*.'; '*Please revise the syntactical structure of this sentence*.'; '*Is this section well readable?*'. No AI tools were used for de novo content or text generation in this thesis.

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instrumental value of outcomes enhances outcome monitoring during learning (Giersiepen et al., 2024, *Cerebral Cortex*) the Brain Products Young Scientist Award 2025. Receiving this prize at the PuG conference in Würzburg was both a surprise and a great honor. It reminded me of the skills I have acquired as a young researcher over the past years, made possible by the support of my supervisors and colleagues.

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List of Publications

Giersiepen, M., Heinrich, N. W., Österdiekhoff, A., Kopp, S., Russwinkel, N., Schütz-Bosbach, S., & Kaiser, J. (2025). Am I in control? The dynamics of sensory information, performance feedback, and personality in shaping the sense of control. *Consciousness and Cognition*, *135*, 103938. https://doi.org/10.1016/j.concog.2025.103938

Giersiepen, M., Schütz-Bosbach, S., & Kaiser, J. (2024). My choice, my actions: self-determination, not instrumental value of outcomes enhances outcome monitoring during learning. *Cerebral Cortex*, *34*(8), bhae325. https://10.1093/cercor/bhae325

Giersiepen, M., Schütz-Bosbach, S., & Kaiser, J. (2023). Freedom of choice boosts midfrontal theta power during affective feedback processing of goal-directed actions. *Biological Psychology*, *183*, 108659. https://10.1016/j.biopsycho.2023.108659

Declaration of Author Contributions

Chapter 2.1 (Publication 1): (Giersiepen et al., 2023) 'Freedom of choice boosts midfrontal theta power during affective feedback processing of goal-directed actions.'

Giersiepen, M, Schütz-Bosbach, S, & Kaiser, J.

M.G., S.SB., and J.K. conceptualized the study and designed the experiment. M.G. administered the study, programmed the experiment, and collected, analyzed, and visualized the data. J.K. contributed to data analysis. M.G., S.SB., and J.K. interpreted the data. M.G. drafted the original manuscript. S.SB. and J.K. commented on the manuscript and acquired funding for conducting the study.

My contribution to this publication in detail:

For this study, I developed the study design and programmed the experiment in MATLAB. I recruited participants and, with the help of student research assistants, collected all behavioral and neurophysiological data. I adapted and applied scripts previously developed by J.K. for analyzing and visualizing the neurophysiological data in MATLAB. I performed behavioral data analyses and visualizations in RStudio. I interpreted the data together with S.SB. and J.K. and drafted the manuscript for publication. I submitted the manuscript as the corresponding author.

Chapter 2.2 (Publication 2): (Giersiepen et al., 2024) ‘My choice, my actions: self-determination, not instrumental value of outcomes enhances outcome monitoring during learning.’

Giersiepen, M, Schütz-Bosbach, S, & Kaiser, J.

M.G., S.SB., and J.K. conceptualized the study and designed the experiment. M.G. administered the study, programmed the experiment, and collected, analyzed, and visualized the data. J.K. contributed to data analysis. M.G., S.SB., and J.K. interpreted the data. M.G drafted the original manuscript. S.SB. and J.K. commented on the manuscript and acquired funding for conducting the study.

My contribution to this publication in detail:

For this study, I developed the study design and programmed the experiment in MATLAB. I recruited participants and, with the help of student research assistants, collected behavioral and neurophysiological data. I analyzed and visualized the neurophysiological data in MATLAB and performed behavioral analyses and visualizations in RStudio. I interpreted the data together with S.SB. and J.K. and drafted the manuscript for publication. I submitted the manuscript as the corresponding author.

Chapter 2.3 (Publication 3): (Giersiepen et al., 2025): 'Am I in control? The dynamics of sensory information, performance feedback, and personality in shaping the sense of control.'

Giersiepen, M, Wendel Heinrich, N, Österdiekhoff, A, Kopp, S, Russwinkel, N, Schütz-Bosbach, S, Kaiser, J.

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My contribution to this publication in detail:

For this study, I initiated and led the planning of an in-person workshop in Berlin to conceptualize the study. I coordinated regular meetings and took the lead in developing the experimental design. Together with N.W.H. and A.Ö., I piloted the experiment and subsequently collected and pre-processed all experimental data in RStudio. Under the lead of N.W.H., I contributed to statistical data analysis in RStudio, and interpreted the data together with him. I drafted the manuscript for publication and submitted it as the corresponding author.