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Attenuation and Agency: Understanding Perception through the Examination of Sensory Phenomena

Dissertation

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Acronyms

a.u.	-	arbitrary units
BOLD	-	Blood oxygen level dependent
EEG	-	Electroencephalography
ERP	-	Event-related potentials
fMRI	-	Functional magnetic resonance imaging
ISI	-	Inter-stimulus interval
JND	-	Just noticeable difference
MEG	-	Magnetoencephalography
PSE	-	Point of subjective equality
SA	-	Sensory attenuation
SoA	-	Sense of agency
VR	-	Virtual Reality

Summary

Sensory attenuation (SA) describes the process by which self-initiated sensory input is perceived with reduced intensity compared to externally generated sensory input. Motor-based forward models constitute the dominant approaches to explain this phenomenon. According to this framework, action-planning involves the generation of efference copies in addition to motor commands. These efference copies allow predictions about sensory consequences, which are then compared to the actual sensory input. Subsequently, the amount of sensory discrepancy deriving from this comparison assists in forming judgements about our sense of agency (SoA) - the experience of control over self-initiated actions and their sensory consequences.

However, recent studies have observed the influence of external mechanisms on SA, thereby challenging this explanatory approach. The theory of predictive processing proposes that all anticipated sensory stimuli, irrespective of their origin, can be subject to SA, potentially explaining the diverse range of observed results.

In this dissertation, I describe both explanatory approaches and provide an overview on the impact of temporal predictability, identity prediction and SoA. I continue with summarizing the four dissertation studies, which all examined the influence of motor and non-motor cues on perceptual processing. At last, I will discuss the implications, both methodologically and explanatory, of the observed effects.

In Study 1, we examined visual SA by comparing the intensities of virtually occluded stimuli to non-occluded stimuli in a Virtual Reality (VR) set-up. Participants were instructed to move their hands, which were not rendered (i.e., not visible) in VR, into their visual field. The hand movement triggered the appearance of the stimuli, which were either placed behind the participant's hand or elsewhere. The results indicated that the location of the hand had a stronger impact on perceptual sensitivity than the hand movement itself. In Study 2, using a two-phase comparison to examine auditory SA online, we observed enhancement instead of attenuation for self-initiated auditory stimuli. Overall, these findings suggested the influence of certain external factors, namely accompanying sensory input, identity prediction and signal strength. Study 3 investigated the influence of supraliminal and subliminal prime stimuli on SoA while avoiding post-hoc subject selection. The findings indicated that primes influenced SoA solely when consciously processed. In Study 4, we aimed to gain more control over stimulus presentation by implementing a novel VR set-up to examine somatosensory SA. The results suggested that SA is adaptive and influenced by external factors like signal strength and temporal predictability.

Deutsche Zusammenfassung

Die sensorische Attenuation (SA) beschreibt den Prozess, bei dem selbstinitiierte Reize im Vergleich zu extern generierten Reizen mit reduzierter Intensität wahrgenommen werden. Motorbasierte Vorwärtsmodelle sind der prominenteste Ansatz um dieses Phänomen zu erklären. Diese Erklärung folgt dem Reafferenzprinzip: Während der Aktionsplanung werden zusätzlich zu den motorischen Befehlen neuronale Repräsentationen der geplanten Aktion (d.h. Efferenzkopien) generiert. Diese Efferenzkopien ermöglichen Voraussagen über sensorische Konsequenzen, die dann mit dem tatsächlichen sensorischen Input verglichen werden. Anschließend trägt die Menge der sensorischen Diskrepanz aus diesem Vergleich dazu bei, Urteile über unsere Handlungsfähigkeit (SoA) zu bilden. Aktuelle Studien haben jedoch einen Einfluss externer Mechanismen auf die SA beobachtet, welchen Vorwärtsmodelle nur bedingt erklären können. Die „Predictive Processing“ Theorie schlägt ein generelles Verarbeitungsmodel vor. Nach diesem Ansatz können alle erwarteten sensorischen Reize, unabhängig ob selbst-initiiert oder extern generiert, der SA unterliegen.

In dieser Dissertation stelle Ich die verschiedenen theoretischen Ansätze vor und gebe einen Einblick in die Verbindung zwischen SA und SoA und die Auswirkungen von externen Faktoren, die die Voraussage über Zeitpunkt und Identität der Stimuli vereinfachen. Danach folgt die Zusammenfassung der vier Dissertationsstudien, die alle den Einfluss externer Faktoren auf die Wahrnehmungsverarbeitung untersuchten. Zum Schluss diskutiere ich die beobachteten Effekte, sowohl methodologisch als auch theoretisch.

In Studie 1 untersuchten wir die visuelle SA, indem wir die Intensitäten verdeckter Reize mit nicht verdeckten Reizen in einem Virtual-Reality-Setup (VR) verglichen. Die Teilnehmenden wurden angewiesen, ihre Hände, die in VR nicht dargestellt wurden und so für die Teilnehmenden nicht sichtbar waren, in ihr Sichtfeld zu bewegen. Die Handbewegung löste

das Erscheinen von visuellen Reizen aus, die entweder hinter der Hand der Teilnehmenden oder an anderer Stelle im visuellen Sichtfeld platziert wurden. Die Ergebnisse zeigten, dass die Position der Hand einen stärkeren Einfluss auf die Wahrnehmungssensitivität hatte als die Handbewegung selbst. In Studie 2 untersuchten wir die SA in der auditiven Modalität mit zwei Online Versuchen. Die Resultate zeigten eine sensorische Verstärkung anstelle einer SA für selbstinitiierte auditive Reize. Darüber hinaus beobachteten wir einen Einfluss externer Faktoren auf SA, genauer von (1) zeitgleich auftretenden Reizen; (2) gelernten Kombinationen, die die Identitätsvorhersage der Reize vereinfachten; und (3) die Signalstärke der Reize. Studie 3 untersuchte den Einfluss von supraliminalem und subliminalem Priming auf die SoA. Die Ergebnisse zeigten, dass Prime-Reize die SoA nur beeinflussten, wenn sie bewusst verarbeitet wurden. In Studie 4 implementierten wir ein neuartiges VR-Setup, um SA in der somatosensorischen Modalität zu untersuchen. Wir beobachteten Adaptivität in der SA, beeinflusst von externen Faktoren wie der Signalstärke und zeitlicher Vorhersagbarkeit der Reize.

1. Introduction

“From the fact that a child can hardly tickle itself, or in a much less degree than when tickled by another person, it seems that the precise point to be touched must not be known.”

(Darwin, 1872, pp. 201-202)

While we are constantly presented with a wide array of sensory information, our perceptual system enables us to engage meaningfully with our environment. In order to accomplish this, sensory inputs undergo differential processing. The phenomenon of sensory attenuation (SA), which describes the process by which self-initiated sensory input is perceived with reduced intensity compared to externally generated sensations, facilitates the differentiation between our own actions and those originating externally (Blakemore et al., 2000; 2002; Hughes et al., 2013a; Pyasik et al., 2021). Examples illustrating this phenomenon include the common experience of being unable to tickle oneself and the contrast between barely noticing our own chewing while finding another person's chewing noisy and intrusive (Klaffehn et al., 2019). Initially observed in the somatosensory domain (Blakemore et al., 2000; 2002), SA has since been examined in various modalities, including the visual (Schwarz et al., 2018) and auditory domain (for a review, see Kiepe et al., 2021). SA has been proposed to be a crucial component of perception, involving practical implications across multiple disciplines, from clinical psychology to human-computer interactions (Schwarz et al., 2018). For instance, disruptions in SA mechanisms have been implicated in neuropsychiatric disorders (e.g., schizophrenia), where symptoms may result from individuals struggling to distinguish between self-generated and external stimuli (Brown et al., 2019; Ford & Mathalon, 2012). Understanding the underlying mechanisms that take effect in SA may offer valuable insights into fundamental questions about our self-awareness and the Sense of Agency (SoA; Han et al., 2021).

1.1 Measuring Sensory Attenuation: Behavioral and Neurophysiological Approaches

Investigations into SA stem from the somatosensory realm specifically addressing the inquiry of why self-tickling is ineffective (Weiskrantz et al., 1971). The initial examination involved comparing self-administered strokes to those administered by an experimenter and participants were asked to compare both stimuli in terms of ticklishness. The findings indicated a diminished processing of self-induced stimuli across various pressure levels and frequencies. Several studies supported this notion (e.g., Blakemore et al., 1999; Bays et al., 2005; Hesse et al., 2010; Shergill et al., 2013; Kilteni & Ehrsson, 2022). Nowadays, studies examining SA encompass various modalities (auditory: Kiepe et al., 2021, visual: Schwarz et al., 2018, somatosensory: Kilteni, 2023) and methodologies.

Behavioral studies usually make use of a two-phase comparison task (Bays et al., 2005). Participants are exposed to two sequential stimuli: a test stimulus, which can be either self-initiated (i.e., “active” condition) or externally initiated (i.e., “passive” condition), followed by a standard stimulus, which is always externally initiated. Following this, participants are instructed to compare the intensity between test and standard stimuli (e.g., auditory: “which sound was louder?”, somatosensory: “which force was stronger?”). SA is evident when the intensity of the test stimulus is rated lower in the active condition compared to the passive condition.

Studies in the somatosensory domain also make use of the force-matching task (Shergill et al., 2005; Kilteni, 2023). Here, participants experience an externally generated force and are instructed to replicate this force. This task typically involves two conditions: participants either generate the matched forces by direct self-initiation (e.g., applying force on a sensor; “direct” condition) or by using a slider, adjusting force output linearly based on its position (i.e., “slider” condition). An overestimation of the applied force during the “direct” condition is considered indicative of SA (Shergill et al., 2005; Kilteni, 2023; McNaughton et al., 2023). Proposed to mitigate the bias towards overestimation, the "slider" condition is typically utilized as the control condition (Wolpe et al., 2016). However, recent studies observed significant variations in the “slider” condition (Kilteni et al., 2018; McNaughton et al., 2023), suggesting that it may not be eligible for a control condition. Indeed, note that the “slider” condition does involve self-initiation (i.e., using the slider) and a sensory consequence (i.e., changes in force intensity) based on the participant’s action. Therefore, SA effects may also be present in this condition.

A key challenge for behavioral SA is the translation of naturalistic, self-initiated behavior into the laboratory setting. For example, since in the laboratory, movement is often represented through a keypress, certain action-stimulus combinations must be learned beforehand (e.g., Schwarz et al., 2018). Neurophysiological approaches allow for the exploration of SA in natural behavior (e.g., speaking or blowing air; Ford et al., 2007; Mifsud and Whitford, 2017; for a review, see Kiepe et al., 2021). Additionally, they are proposed to provide real-time measurements of perception without relying on delayed behavioral responses. SA has been therefore studied in neuronal recordings of early stimulus-evoked brain activity employing neuroimaging methodologies such as Electroencephalography (EEG; e.g., Bäß et al., 2008) and magnetoencephalography (MEG; e.g., Hua et al., 2023). Here, the reduction in amplitude of event-related potentials (ERP; N1 and P2) after stimulus presentation indicates SA effects. Further, SA has been measured by blood oxygen level dependent (BOLD) suppression in functional magnetic resonance imaging (fMRI; e.g., Straube et al., 2017). Note, however, that while correlations between neurophysiological and behavioral measures of SA have been confirmed (e.g., Roussel et al., 2014), other studies observed no relationship between neurophysiological and perceptual SA (e.g., Palmer et al., 2016). This suggests a multifactorial interplay between both dimensions, which must be taken into account when interpreting the results.

1.2 Explanatory Approaches of Sensory Attenuation: Motor-Based Forward Models and Predictive Processing

Traditionally, SA has been explained by motor-based (i.e., auxiliary) forward models. This framework describes SA as a result of constant interactions between the designated structures in the sensorimotor system (Blakemore et al., 1999; Synofzik et al., 2008). When planning an action, efference copies are generated in addition to motor commands. These efference copies enable the brain to anticipate the sensory consequences of self-initiated actions and adjust for the difference between expected and actual sensory feedback (Figure 1; Bays & Wolpert, 2008; Miall and Wolpert, 1996). Subsequently, this information assists in forming judgements about the SoA (Synofzik et al., 2008). Note, that this model only explains the altered perceptual processing of self-initiated actions and omits the influence of prediction of externally generated sensory input (Christensen & Grünbaum, 2018).

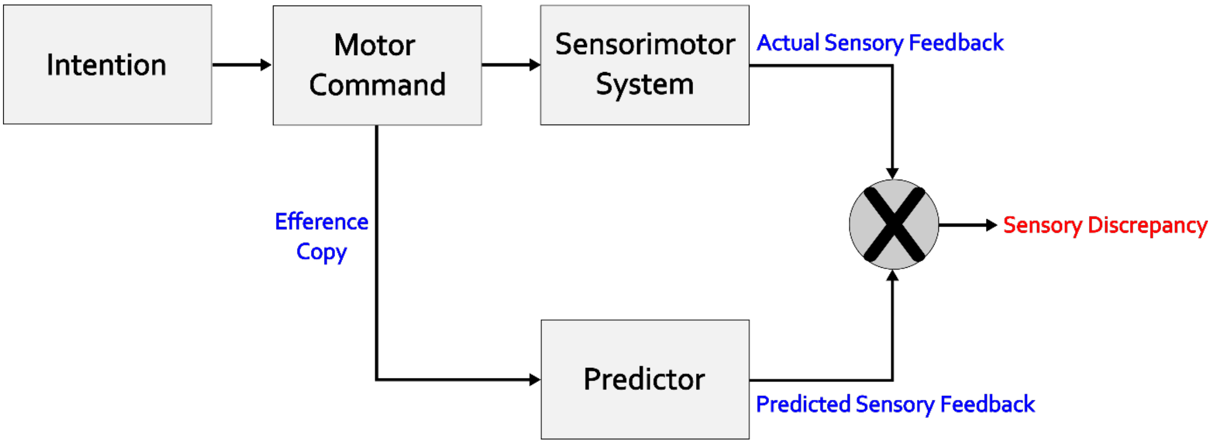

Figure 1. Motor-based Forward Models. When planning an action, efference copies are created alongside motor commands. These efference copies enable predictions about upcoming sensory input, which is then compared to the actual sensory input. Mismatches between predicted and actual sensory feedback lead to sensory discrepancy (e.g., ticklishness). Adapted from Blakemore et al. 2000.

In contrast, predictive processing suggests that all expected sensory stimuli, regardless of their origin, can be subject to SA. In this framework, the brain is assumed to constitute a generative model that constantly produces predictions over upcoming sensory signals, including interoceptive ones, on the basis of prior knowledge (Figure 2; Friston et al., 2016). This generative model constantly strives towards the reduction of surprise. Prediction errors (i.e., mismatches between expected and actual sensory input) are used to update and optimize the model for future predictions (Seth et al., 2012). SA is explained as a result of this process, in which processing capacity is oriented away from expected stimuli and towards unexpected sensory input, as these provide useful information for model updating (Brown et al., 2013).

Further, the concept of active inference within predictive processing highlights the role of SA during active movement (Parr et al., 2021). In active inference, planning of an action is equivalent to predicting its sensory consequences, resulting in elevated rates of prediction errors. These prediction errors can subsequently be reduced through action execution. Crucially, this will include a temporal component before the alignment of predicted and actual sensory input. In this phase, signals from self-generated actions are attenuated (i.e., akin to orienting attention away), indicating these stimuli originate from one's own actions (Aru, 2019; Brown et al., 2013; Parr et al., 2021). Note, however, that the allocation of mental resources based on the predictability of the stimuli is a fundamental mechanism in predictive processing. Rather than a way to distinguish self from externally generated actions, it primarily serves to minimize surprise and facilitate efficient information processing (Seth et al., 2012; Parr et al., 2021).

In conclusion, motor-based forward models focus on reafference cancellation to explain SA, while predictive processing proposes that SA results from shifting processing capacity based on formed predictions. These predictions derive information from motor and non-motor cues. Although motor-based information is an especially reliable predictor, external mechanisms informing about upcoming changes in sensory input should therefore have an impact on SA, as well. To resolve the outlined discrepancies between the models depicted, it may be suitable to investigate the impact of both motor and non-motor predictive mechanisms on SA.

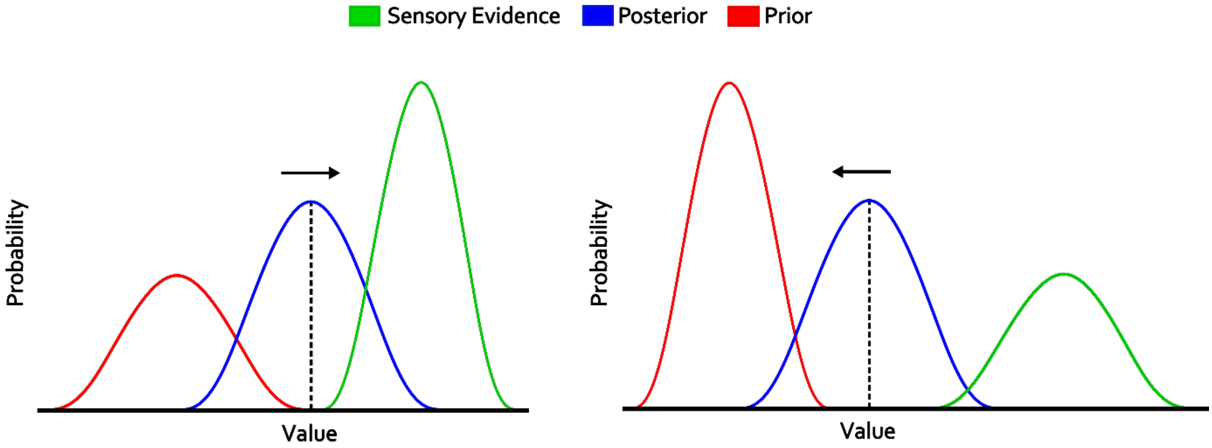

Figure 2. Predictive Processing. A simplified illustration on precision-weighted inferences (i.e., posterior beliefs) in predictive processing. Inferences are generated based on prior expectations and sensory evidence, and form predictions about upcoming sensory input. On the left, the precision of the sensory evidence has a greater impact on the posterior. On the right, prior expectations have a greater impact. Adapted from Williams, 2020.

1.3 Predictive Mechanisms

In what follows, I will outline the influence of certain predictive mechanisms on SA examined in my dissertation studies, specifically temporal prediction, identity prediction and SoA. For the sake of clarity, we compiled the results from various modalities (i.e., visual, auditory, somatosensory). It's worth noting that in previous studies the most pronounced attenuation effects were detected in the somatosensory domain (e.g., Wolpe et al., 2016; Hesse et al., 2010; Shergill et al., 2013; Kilteni & Ehrsson, 2022; Bays et al., 2005). Nonetheless, similar impacts of external predictive mechanisms have been identified across all modalities.

1.3.1 Temporal Prediction

Temporal predictability describes the ability to anticipate the temporal onset of the stimulus successfully (Hughes et al., 2013a; Kiepe et al., 2021). While classical motor-based forward models did not account for temporality, revisions of the model integrated the observed effects of onset delays as environmental noise, thereby complicating the comparison between predicted and actual sensory feedback (Blakemore et al., 2000; Pickering & Clark, 2014). Nevertheless, these models state that self-initiated motor behavior is necessary for SA. In predictive processing, the temporal component plays a crucial role in predicting future changes in sensory inputs and the corresponding reduction of processing intensity (Kahl & Kopp, 2018).

The possible impact of temporal predictability on perceptual processing becomes apparent in a study conducted by Kaiser and Schütz-Bosbach (2018): measuring ERPs in several conditions (i.e., self-initiated versus other-initiated, immediate onset versus delayed onset), the authors observed attenuation effects not only for self-initiated but also for externally generated stimuli when they were temporally predictable. The effect of temporality on SA is typically examined by delaying the onset of the test stimulus. Additionally, Bays et al. (2005) observed that not only delaying, but also advancing the onset of the stimuli has a similar effect on SA. For an onset delay to be truly unpredictable, it must also occur within varying intervals. In a study conducted by Kilteni et al. (2019), participants learned (in 400 trials) before the main experiment that the stimulus appeared either with a systematic delay (100ms) or immediately (0ms) after self-initiation. The results revealed attenuation effects only if the test stimuli were temporally predictable. For instance, if a delay of 100ms was introduced between movement and stimulus during the main experiment, SA was found for trials including the 100ms delay only. If no delay was introduced, SA was found only for trials wherein the stimulus appeared immediately after the movement. The minimum interval required to effectively manipulate temporal predictability remains debatable. While Kilteni et al. (2019; 2023) and Blakemore et al. (1999) observed significant influences of even brief onset delays (i.e., < 200ms) on sensory attenuation, other studies suggest that only more substantial delays, typically within the range of 700-800ms, have a notable impact (van Elk et al., 2014; Bays et al., 2005).

Note, however, that several studies did not find an effect of temporal predictability on SA. For example, in a study by Klaffehn et al. (2019), a visual cue in the form of a progress bar was implemented following self-initiated actions, leading up to the onset of the test stimulus. Although the stimuli were delayed, they remained temporally predictable. The findings revealed SA only for stimuli that were played immediately after self-initiation, suggesting a limited role of mere predictability. Further, Lange (2011) examined effects of temporal predictability by comparing N1 components in predictable contexts (i.e., fixed stimulus onset delays that were preceded by a visual cue) and unpredictable contexts (i.e., variable onset delays). The results revealed attenuated N1 components in predictable contexts despite stimulus onset delays of up to 950ms, suggesting that SA may not rely solely on temporal predictability.

In summary, the influence of temporality on SA remains ambiguous. While some studies observed attenuation effects in contexts where stimulus onset was temporally predictable, even without any movement involved, others emphasize the significance of self-initiation. Further research is needed to examine the impact of temporality on SA.

1.3.2 Identity Prediction

Predictions specific to identity (i.e., particular features of the upcoming stimulus) could lead to attenuation effects as well. Information about the stimulus' specific identity might originate from either self-initiated behavior (motor-based identity prediction) or external cues (non-motor-based identity prediction; Hughes et al., 2013a; Waszak & Herwig, 2007). Motor-based forward models propose that SA results from identity-specific motor predictions, based on information provided by efference copies (Pickering and Clark, 2014, Dogge et al., 2019a). This notion is supported by various studies. For example, Hughes et al. (2013b) observed stronger N1 attenuation for action-stimulus combinations that were congruent and pre-learned, as opposed to incongruent pairings. Similarly, Bäß et al. (2008) compared self-initiated auditory stimuli with a constant, hence predictable pitch (1.000 Hz) to self-initiated sounds with a randomized, hence unpredictable pitch (400-1.990 Hz). The results revealed stronger SA for trials where the stimulus identity could be predicted. Fuehrer et al. (2022) paired textured surfaces with vibrotactile feedback that was either congruent or incongruent to the participant’s stroking movement. The results suggested stronger SA for congruent (i.e., predictable identity) stimuli, compared to incongruent stimuli. Similarly, Myers et al. (2020) observed in a loudness comparison task, that attenuation effects varied based on the congruence of pre-learned action-sound combinations.

Non-motor identity predictions refer to attenuation effects based on external cues exclusively, thereby isolating SA from self-initiated behavior (Waszak & Herwig, 2007). According to motor-based forward models, self-initiation is crucial for SA. Thus, stimuli should not be attenuated if they are isolated from motor commands (Hughes et al., 2013a). In predictive processing theories, both self-initiation and external information contribute to successful prediction of succeeding sensory input (Friston et al., 2016; Talsma, 2015). Although exerting direct control over stimulus presentation through motor actions may indeed heighten predictability, it is no necessity for SA. Indeed, several studies observed attenuation of non-motor-based stimuli that were predictable due to external cues. For example, Lange (2009) observed in a passive listening paradigm, that auditory stimuli were attenuated if their pitch could be predicted from preceding tone patterns (i.e., ascending/descending versus variable). In another study, Hsu et al. (2014) compared N1/P2 component activity in subsequently presented tone pairs. The results revealed SA for the succeeding tone when it was identical to the first tone.

However, other studies have not found evidence supporting non-motor identity prediction effects. For example, Hsu et al. (2013) observed no differences in N1 component activity between cued tones whose pitch was predictable and tones with a random pitch. Similarly, the results of Dogge et al. (2019b) suggest that both motor and non-motor identity prediction only exert a weak impact on SA.

In conclusion, investigations into the impact of identity prediction on SA remain, akin to studies on temporal prediction, intermediate. Although motor-identity prediction appears to have an impact on SA, the influence of non-motor identity prediction is debatable. Note, that the variety of results may be also be a consequence of the various methodologies chosen. For instance, Hsu et al. (2013) used a passive listening paradigm. Here, the cues that preceded the target stimuli informed about the stimulus identity. In the studies by Lange et al. (2009) and Hsu et al. (2014), predictions about the identity (i.e., pitch) of the stimulus were formed through preceding tone patterns. Further, Dogge et al. (2019b) implemented a two-phase comparison task, where either preceding cues or the freely chosen keypress of the participants informed about stimulus identity.

1.3.3 Sense of Agency

SoA describes the individual's experience of control over self-initiated actions and their consequences on external events (Jeannerod, 2003; Haggard, 2017). Motor-based forward models propose that SoA results from comparing predictions of sensory consequences based on one's motor commands and the actual sensory input (Welniarz et al., 2021; Haggard, 2017). If these predictions are accurate, and actions are intentionally executed, individuals are considered to experience a heightened SoA. However, if predictions about sensory events based on one's own actions are incorrect, individuals should experience low SoA (Frith, 2000; Haggard, 2017). According to this model, the attribution of agency is (1) postdictive, and (2) efference driven, thus rooted in motor commands and signals (Haggard, 2017; Tsakiris & Haggard, 2005; Christensen & Grünbaum, 2018). Consequently, SA has been traditionally viewed as an implicit measure of SoA (Weiss et al., 2011). Note, however, that recent developments suggest that SoA may rather be a result of the interplay between various distinct concepts (Kaiser et al., 2021; Moore, 2016; Grünbaum & Christensen, 2020). For instance, Synofzik et al. (2008) proposed that the SoA encompasses both an implicit, non-conceptual feeling of agency and an explicit judgment of agency, each influenced by different factors. Further, Grünbaum and Christensen (2020) divided SoA into four sub-constructs, distinguishing between phenomenal character and ability, as well as bodily and external aspects. This implies that SoA does not derive information from a singular source but results from integrating various cues (Gentsch, 2011).

In contrast to forward models, predictive processing underscores the importance of predictive cues when attributing agency (Kahl & Kopp, 2018; Synofzik et al., 2013). The importance of prior information is exemplified in a study by Desantis et al. (2012). In this study, the authors displayed either the participant's or the experimenter's name at the start of each trial, intending to manipulate the participants' beliefs about who initiated the stimulus. Although stimuli were consistently triggered by the participants themselves, SA was observed only when the participants' name preceded the trial. Further, in a study by Borhani et al. (2017), participants were given the freedom to choose the pitch range (i.e., low or high) of the triggered sound before each trial. For active conditions, this free choice significantly altered attenuation effects, compared to trials where the pitch range was instructed (i.e., not freely chosen). Although both SA and SoA are informed by the predictiveness of sensory events, predictive processing does not posit a direct relationship between both concepts. Instead, it suggests that SA is a result of attention orienting (Schröger et al., 2015; Dogge et al. 2019a). This framework therefore does not consider SA to be a consequence of SoA, or vice versa (Burin et al., 2017). Several studies have indeed observed that attenuation effects did not correlate with agency judgements (Timm et al., 2016; Dewey & Knoblich, 2014; Reddy, 2022). However, in a study by Weiss et al. (2011), conditions involving a heightened SoA resulted in stronger attenuation effects. The study involved four conditions: (1) individual-self: stimuli were self-initiated and self-generated (i.e., no interaction between participant and experimenter), (2) individual-other: stimuli were other-initiated and other-generated, (3) interactive-self: stimuli were other-initiated (i.e., through interaction between experimenter and participant), but self-generated, and (4) interactive-other: stimuli were self-initiated, but other-generated. SA was found in all conditions where participants had a heightened SoA (i.e, (1), (3) and (4)). Strikingly, SA was strongest in interactive conditions, regardless if the stimuli were self- or other-generated. This suggests that, while SoA can be a modulating factor for SA, there may be no causal relationship. The results are best explained by considering the interactions between participant and experimenter as an additional source of information about upcoming sensory consequences.

In conclusion, evidence on the relationship between SA and the introduced non-motor predictive mechanisms (i.e., temporal predictability, identity prediction, SoA) is conflicted. While some studies can explain SA based solely on external cues, others underscore the integral role of self-initiated motor behavior. The four dissertation studies delved into the exploration of both motor and non-motor predictive mechanisms, and sought to incorporate innovative technologies and methodological approaches to contribute to this ongoing debate.

2. Summary of the Aims and Research Questions

The aim of this dissertation was to examine the explanatory approaches outlined in the Introduction (i.e., motor-based forward models versus predictive processing), by measuring SA and SoA behaviorally. Specifically, I intended to assess the role of motor (i.e., self-initiation) and non-motor (i.e., temporal predictability, identity prediction) predictive mechanisms by modulating stimulus predictability. In what follows, I will provide an overview of the research questions and individual hypotheses of the four dissertation studies. This is followed by a detailed summary of each dissertation study in the next chapter.

Does self-initiation lead to a reduction in perceived stimulus intensity?

As described above, self-initiation (i.e., motor behavior) is a crucial component in the explanatory approach of motor-based forward models (Blakemore et al., 1999; Synofzik et al., 2008). Predictive processing, on the other hand, proposes that all stimuli can be subject to SA if they are predictable. Note, however, that this framework recognizes planned motor behavior as a reliable predictor for upcoming sensory input (Friston, 2013). Thus, both explanatory approaches suggest that self-initiated sensory input should be perceived attenuated. Therefore, Study 1, Study 2 and Study 4 compared the perceived intensities of self-initiated stimuli with the perceived intensities of externally generated stimuli, and hypothesized attenuation effects for self-initiated stimuli.

Does temporal predictability lead to a reduction in perceived stimulus intensity?

Both explanatory approaches do differ in the suggested impact of external factors. Specifically, the temporal predictability of a stimulus, regardless if self-initiated or externally generated, is a proposed necessity for SA in predictive processing (Kahl & Kopp, 2018). In Study 1, we implemented a variable delay (700, 750, 800ms) between self-initiated movement and stimulus onset. We hypothesized that this induced difficulty in temporal predictability will lead to weakened SA effects. In Study 4, we introduced a visual cue preceding sensory input to enhance temporal predictability of externally generated test stimuli. Further, we included a variable onset delay (700, 750, 800ms) for both self-initiated and externally generated sensory input. We hypothesized that perceived stimulus intensity should be attenuated for stimuli that are temporally predictable (i.e., appear immediately after self-initiation or the visual cue), compared to delayed stimuli.

Does identity prediction lead to a reduction in perceived stimulus intensity?

Another external factor proposed to impact SA is identity prediction. While motor-based forward models suggest that information about the stimulus' identity is derived by efference copies only (Pickering and Clark, 2014, Dogge et al., 2019a), predictive processing entails that external information contributes to successful stimulus prediction, as well (Friston et al., 2016; Talsma, 2015). In Study 2, we therefore included a training phase before the main experimental phase, where participants learned certain cue-stimulus combinations, and examined differences in attenuation effects for stimuli (self-initiated and externally generated) which were either congruent or incongruent to the learned combinations. We hypothesized that both motor and non-motor identity prediction will lead to a reduction in perceived stimulus intensity.

Do subliminal and supraliminal prime stimuli influence the Sense of Agency?

As outlined above, motor-based forward models suggest that SoA is a result of the postdictive comparison between efference driven predictions about upcoming sensory events and the actual input (Haggard, 2017; Tsakiris & Haggard, 2005; Christensen & Grünbaum, 2018; Welniarz et al., 2021). In contrast, predictive processing proposes that agency judgements derive information from multiple cues and highlights the importance of external prior information when attributing agency (Kahl & Kopp, 2018; Synofzik et al., 2013; Gentsch, 2011). Further, since precision-weighted inferences are influenced by top-down predictions, consciously perceived stimuli should serve as more influential cues (Chennu et al., 2013). In Study 3, we examined the impact of subliminal and supraliminal stimuli on SoA in a control-judgement task, and hypothesized that subliminal stimuli will not exert a substantial influence on the conscious experience of agency.

3. Summary of the Dissertation Studies

The following section summarizes the dissertation studies and outlines their main implications.

3.1 Study 1: Virtual occlusion effects on the perception of self-initiated visual stimuli

This section is based on the following original publication:

Kiepe, F., Kraus, N., & Hesselmann, G. (2023). Virtual occlusion effects on the perception of self-initiated visual stimuli. *Consciousness and cognition*, *107*, 103460. https://doi.org/10.1016/j.concog.2022.103460

Research of SA in the visual domain is affected by the challenging translation of naturalistic behavior into the laboratory setting. Consequently, results have been inconclusive and subject to methodological compromises (Cardoso-Leite et al., 2010; Dewey & Carr, 2013, Straube et al., 2017; Uhlmann et al., 2020; Schmitter et al., 2021; Yon & Press, 2017; Schwarz et al., 2018). Recently, Laak et al. (2017) and Vasser et al. (2019) introduced a new approach, examining visual SA in VR. In the study by Vasser et al. (2019), participants were instructed to move their hand into a predefined target area. The hand movement triggered the presentation of two Gabor contrasts: one appeared in the same location as the moved hand (i.e., virtually occluded), the other was displayed at a horizontally distinct location. Importantly, the hands of the participants were not rendered in VR (i.e., invisible in the virtual environment). In a comparison task, participants then assessed the intensity of the two Gabor contrasts. The results revealed that self-initiated stimuli, which appeared behind the virtually invisible hand, were perceived with a weaker intensity, compared to stimuli that were not virtually occluded. Vasser et al. (2019) interpreted their findings in light of the active inference theory. According to this framework, SA poses a necessity during movement, as reducing the precision of sensory input resolves the mismatch between the prediction of the sensory consequence (i.e., the desired state after successful movement; e.g., “hand is grasping a glass”) and actual sensory input during movement initiation (e.g, “hand is moving towards the glass”). Specifically, this reduction is achieved by drawing away attentional resources (Aru, 2018; Vasser et al. 2019; Brown et al., 2013).

In our preregistered study, we aimed to examine the role of motor prediction and temporality on SA in this experimental paradigm. Therefore, we included the two conditions presented in Vasser et al. (2019): the Immediate condition (i.e., Gabor contrasts were presented immediately after hand movement including virtual occlusion) and the Control condition (i.e., Gabor contrasts were presented immediately after successful hand movement, no virtual occlusion). Additionally, we introduced two new conditions: the Delayed condition and the Static condition. Examining the impact of temporal predictability on SA, the Delayed condition differed from the Immediate condition only by incorporating a variable onset delay (700, 750, 800ms) between successful hand movement and stimulus presentation (van Elk et al., 2014; Klaffehn et al., 2019). Examining the role of motor behavior on SA (Lange, 2009), the Static condition involved no active movement. Note, that in preparation of this condition, the participant’s hand was placed into the target area, resulting in stimuli being virtually occluded but not triggered by self-initiation. Similar to Vasser et al. (2019), participants (N = 29) compared the intensity of the test (0.2, 0.24, 0.3, 0.36, 0.45; corresponding to the Michelson contrast values) and standard (0.3) Gabor contrasts, which were triggered by successful hand movement (i.e., into the target area). In the Immediate, Delay and Static condition, either standard or test stimulus was virtually occluded.

We examined the results by conducting parameter estimation for two aspects of psychometric curves, namely the point of subjective equality (PSE) and the slope, for each condition (i.e., Immediate, Delay, Static, Control). The PSE signifies the point at which the perceived intensity of the test stimulus matches the perceived intensity of the standard stimulus (Gescheider, 2015). The slope is inversely connected to the just noticeable difference (JND), which describes the minimum change in stimulus value that is necessary to perceive a difference (Gescheider, 2015). Therefore, it indicates changes in participant's performance rates based on stimulus intensity (Park, 2017; Reynolds & Heeger, 2009). Different to the results observed by Vasser et al. (2019), we found no differences in PSE values between the conditions. However, virtual occlusion resulted in a decrease of the slope. This indicated that relative perceptual sensitivity was attenuated for conditions (i.e., Immediate, Delayed, Static) where the Gabor contrasts were presented at the same location as the (virtually invisible) hand. Accordingly, this resulted in increased difficulty to discriminate contrast differences, compared to the Control condition, where the stimulus was presented at another location. Further, our study suggests that the location of the invisible hand turned out to be more influential than the hand movement. This observation extends the explanation proposed by Vasser et al. (2019), according to which attention is withdrawn from a sensory event, prompted by temporal prediction errors during movement initiation. This suggests that proprioceptive cues about the location of our hands, even in the absence of movement, might influence attention orienting as well.

3.2 Study 2: Self-initiation enhances perceptual processing of auditory stimuli in an online study

This section is based on the following original publication:

Kiepe, F., Kraus, N., & Hesselmann, G. (2024). Self-initiation enhances perceptual processing of auditory stimuli in an online study. *Attention, perception & psychophysics*, *86*(2), 587–601. https://doi.org/10.3758/s13414-023-02827-w

A key contrast between motor-based forward models and predictive processing in explaining SA lies in their emphasis on self-initiation. Motor-based forward models prioritize its importance (Hughes et al., 2013a; Waszak & Herwig, 2007), whereas predictive processing underscores the influence of external cues to successfully predict the stimulus' intensity. While self-initiation may indeed be a reliable cue for stimulus predictability, it is not deemed a necessity (Pickering and Clark, 2014, Dogge et al., 2019a). Further, predictive processing explains SA as a result of the interplay between predictions and attention (Chennu et al., 2016). Aiming to maximize efficiency, attention is shifted towards or away from a stimulus based on prior information (Chennu et al., 2016; Dogge et al., 2019a; Schröger et al., 2015; Wiese, 2017). Consequently, it was proposed that the results of behavioral SA studies in the auditory domain might be confounded by accompanying sensory input that arise during self-initiation (e.g., tactile and auditory input during a button press; Juralve et al., 2010; Fritz et al., 2022, Reznik et al., 2021).

In our preregistered study, we aimed to estimate the influence of identity prediction and accompanying sensory input of auditory SA. We implemented a two-phase comparison task in two online experiments. This study was supported by the Leibniz-Institute for Psychology

(ZPID) [Grant Number: 7757]. Participants (experiment 1: N = 224, experiment 2: N = 84) compared the loudness of two consecutive tones, a test tone and a standard tone (“Which tone was louder?”). Before the experimental phase, each participant learned specific cue-sound combinations (e.g., “#” = 300 Hz, “+” = 400 Hz). Moreover, the color of the cue indicated if the tones must be self-initiated or are externally generated (i.e., green = self-initiation, red = external generation). In the experimental phase, tones were always preceded by a visual cue. The test tone was either louder (T > S), lower (T < S) or equal (T = S), compared to the standard tone (condition: “amplitude difference”). In the active condition, the test tone was always self-initiated, and the standard tone externally generated. In the passive condition, both tones were externally generated (condition: “agency”). Trials differed based on the congruence of the pre-learned cue-sound combinations (condition: “congruency"; congruent = cue and sound matched with the pre-learned combinations, incongruent = cue and sound did not match with the pre-learned combinations). Further, to examine the influence of accompanying sensory input, a fixed onset delay (condition: “onset delay”) of 50ms was implemented before the test tone (i.e., in the active condition after the button press; in the passive condition after the visual cue) in half of the trials. As described above, previous research has shown that participants can adapt to delayed onsets of a sensory consequence if this delay is fixed (Kilteni et al., 2019; Hughes et al., 2013a). The two experiments only differed based on the sequence of the tones (i.e., whether actively or passively generated). In experiment 1, the first tone was always the test tone; in experiment 2, the second tone was always the test tone.

The results revealed enhanced perceptual processing, instead of attenuation, for self-initiated sensory input. Further, we observed a significant difference between immediate (0ms) and delayed (50ms, fixed) trials, suggesting that accompanying sensory input affects perceived loudness of self-initiated auditory events. Both experiments did not reveal a significant main effect for the congruence of pre-learned action-sound combinations (i.e., identity prediction).

However, explanatory analyses suggest an interplay among motor and non-motor predictive mechanisms, revealing a significant interaction between agency, amplitude difference, onset delay and congruence.

The observed impact of external factors on the perceived loudness of self-initiated auditory indicates the presence of a general predictive mechanism, and is best explained by recent approaches implying adaptiveness in perceived loudness of self-initiated auditory input (Reznik & Mukamel, 2019; Fritz et al., 2022; Myers et al., 2020; Reznik et al., 2021). These approaches highlight the interaction between motor and non-motor predictive mechanisms, proposing that self-initiated auditory stimuli are modulated (i.e., attenuated or enhanced) based on several factors, including context and signal strength.

3.3 Study 3: Prime-Induced Illusion of Control the Influence of Unconscious Priming on Self-Initiated Actions and the Role of Regression to the Mean

This section is based on the following original publication:

Kiepe, F., & Hesselmann, G. (2024). Prime-induced illusion of control: The influence of unconscious priming on self-initiated actions and the role of regression to the mean. *Consciousness and cognition*, *121*, 103684. Advance online publication. https://doi.org/10.1016/j.concog.2024.103684

SoA has been linked by comparator models to the congruence between predicted and actual sensory consequences of planned movement. Predictions are generated through information of the motor system (e.g., efference copies), which communicate the desired sensory consequences of the planned movement (Frith, 2000). These predictions are then compared to the actual sensory input, and if accurate, lead to heightened SoA. In contrast, the theory of apparent mental causation suggests that SoA is a result of perceiving correlations between intentions and actions and subsequently inferring causation. Accordingly, this theory minimizes the role of internal information, and proposes that SoA is influenced and manipulated by external cues (Wegner, 2002). This notion was supported by the results reported in Linser and Goschke (2007): in two experiments, participants were instructed to press a key (experiment 1: forced choice, based on a target stimulus; experiment 2: free choice) which triggered the appearance of an effect stimulus. At the beginning of each trial, masked primes were presented. When these primes were congruent with the effect stimuli, participants overestimated how much control they had over their identity. Critically, there was no relationship between keypress and the identity of the effect stimuli, hence they were objectively uncontrollable. However, the study by Linser and Goschke (2007) suffered from a methodological flaw when determining prime unawareness. Specifically, subgroups (i.e., “prime aware” and “prime unaware”) were determined based on post hoc data selection. Creating subgroups (e.g., aware versus unaware) post-hoc, using extreme cutoffs on one dimension (e.g., awareness measure), can result in regression-to-the-mean artifacts in the subgroup's scores on another variable (e.g., performance measure; Shanks, 2017; Rothkirch et al., 2022; Stein et al., 2024).

In our preregistered study, we aimed to explore the findings of Linser and Goschke (2007) while circumventing post-hoc data selection, so that each participant underwent both non-visible and visible conditions. In experiment 1, prime visibility of N = 39 participants was adjusted prior to the experiment based on JsQuest, a Bayesian adaptive psychometric method to estimate individual thresholds of stimulus intensities (Kuroki & Pronk, 2023; Watson & Pelli, 1983). On the basis of this method, the prime color-contrasts were adjusted for each participant individually to be non-visible. For the visible condition, we introduced an inter-stimulus interval (ISI; duration: 64ms) between prime and mask. The experiment consisted of three tasks: control judgement task, semantic priming task, prime identification task. In the control judgement task, following a masked, semantic prime (capitalized German words BLAU [English: “BLUE”], GELB [English: “YELLOW”], or the non-word AGLB; duration: 48ms), participants were instructed to freely select between two non-related keys (e.g., u, j). The keypress triggered the appearance of a colored circle (blue or yellow), which was either congruent, incongruent or neutral with the prime stimulus. Subsequently, participants rated their perceived control over the circle's color based on their key presses, using a scale from 0% (no control) to 100% (complete control). As in the study of Linser and Goschke (2007), the keypress did not influence the color of the circle. Colors appeared consistently with a 75/25% probability, independent of which key was selected. The semantic priming task and the prime identification task had a similar set-up and assessed the successful processing of primes and the identification rate across conditions (i.e., visible and non-visible). Contrary to the study of Linser and Goschke (2007), this experiment demonstrated that predictive information affected SoA solely when primes were consciously processed.

Experiment 2 used figurative, instead of semantic, prime stimuli. Further, individual threshold estimation did not appear necessary. Visible and non-visible conditions differed in the inclusion of an ISI (duration: 96ms) during the visible condition. N =35 participants rated their perceived control over the effect-stimulus' identity during a forced-choice paradigm (i.e., keypress corresponded to the given target stimulus; contingency between target and effect stimulus: 75%/25%). The observed results suggested that control judgements did not significantly vary based on prime visibility (i.e., visible or non-visible) or congruence (i.e, congruent, incongruent or neutral).

Overall, the results of our study are fundamentally different from those reported by Linser and Goschke (2007). While Linser and Goschke (2007) observed that participants overestimated their agency over objectively uncontrollable stimuli when congruent masked primes (subliminal and supraliminal) were presented just before the action, our results suggest that subliminal primes do not influence the conscious experience of agency (i.e., SoA) significantly. Following the findings of Shanks et al. (2017), Rothkirch et al. (2022) and Stein et al. (2024), the results reported by Linser and Goschke (2007) might be interpreted as a regression-to-the-mean artifact, underestimating prime awareness of the "non-visible" sample due to post-hoc subject selection. Overall, our results do not support the notion of Wegner (2002)'s theory of mental causation, and emphasize the role of consciously perceived stimuli to adjust intentions and develop SoA.

3.4 Study 4: Sensory attenuation of self-initiated tactile feedback is modulated by stimulus strength and temporal delay in a virtual reality environment

This section is based on the following submitted manuscript:

Kiepe, F., & Hesselmann, G. (2024). Sensory attenuation of self-initiated tactile feedback is modulated by stimulus strength and temporal delay in a virtual reality environment [Manuscript submitted for publication].

Research on SA originated with investigations into the somatosensory domain, particularly focusing on the question of why we cannot tickle ourselves. Within this domain, the most pronounced SA effects for immediate sensory consequences have been observed (Wolpe et al., 2016). However, note that, similar to the auditory and visual domain, these findings are not always consistent (Thomas et al., 2022). Behavioral studies typically involve hardware (i.e., an electronic motor) which measures the forces applied by the participants' active extremity (e.g., right index finger) and translates these forces onto the participants' passive extremity (e.g., passive index finger). This analogue set-up has been shown to include variable intrinsic delays between action and sensory consequence (Kilteni et al., 2019; 2023). While these delays are minimal (i.e., ~50ms) and have been shown to not have a significant impact on attenuation effects if fixed (i.e., learned; Kilteni et al., 2019; Hughes et al., 2013a), their variability might introduce uncertainty in temporal predictability and thus affect SA. In order to have precise control over the sensory feedback in response to movement, we developed a two-phase comparison task in a VR environment.

In this preregistered study, participants (N = 33) underwent an active and a passive condition where they were instructed to compare the intensity of two consecutive vibrations. In the active condition, participants moved their hands to elicit a touch as soon as the fixation point's color turned green. Importantly, visual perception was altered within the VR environment, causing participants to touch their virtual - but not physical - hands. The virtual touch triggered the onset of a test vibration on the VR controllers (0.2, 0.35, 0.5, 0.65, 0.8; in arbitrary units (a.u.)). Thereafter, the fixation point's color turned red, triggering the onset of the standard vibration (0.5 a.u.). In the passive condition, both vibrations were preceded by the fixation point's color turning red, indicating external generation of the vibration (i.e., no movement needed). At the end of each trial, participants compared the intensity of the test and standard vibration ("Which vibration was stronger?"). Additionally, test vibrations were presented either immediately or with a variable onset delay (700 - 800ms).

Results revealed that attenuation effects were modulated by both stimulus strength and temporal predictability. We observed SA of self-initiated stimuli for test vibrations with high intensities (i.e., 0.65, 0.8 a.u.) only. For delayed test vibrations with low intensities (i.e., 0.2. a.u.) we observed enhancement instead of attenuation. We further conducted parameter estimation for two aspects of psychometric curves, namely, the PSE and the slope, for each condition (i.e., agency: active versus passive, onset: immediate versus delay). The PSE describes the point at which the test stimulus is perceived as equivalent in intensity to the standard stimulus (Gescheider, 2015). The slope describes the rate at which the participant's performance changes (Park, 2017; Reynolds & Heeger, 2009). The results revealed no discernible shifts in the PSE values between the conditions. This can be explained by the modulation effects observed: If the perception of self-initiated stimuli is not consistently attenuated (but enhanced when signal strength is low and attenuated when signal strength is high), differences in PSE values between the conditions may not be observed. Concerning the slope of the psychometric function, we observed a significant decrease for self-initiated, delayed stimuli, compared to externally generated, delayed stimuli. This suggests that uncertainty about the temporal onset of the stimulus (through a variable delay) affects the participant's performance more if these stimuli are self-initiated, thus highlighting the role of prior information in the perceptual processing of self-generated stimuli.

Overall, the results highlight the influence of external factors (i.e., stimulus strength and temporal predictability) on SA, as the perceived intensity of self-initiated sensory input appears to be adaptable and modulated (i.e., attenuated or enhanced) by external factors. These findings challenge traditional explanations offered by classic motor-based forward models, which typically attribute SA solely to self-initiation. Rather, it appears that the predictability of a stimulus influences whether attentional resources are oriented away (leading to attenuation of the stimulus' intensity) or towards (leading to enhancement of the stimulus' intensity) the stimulus. This is in line with recent approaches to SA, which propose adaptability in the perception of self-initiated stimuli based on their predictability, modulated by external factors (Reznik & Mukamel, 2019; Dogge et al., 2019a).

4. Original Publications

4.1 Study 1: Virtual occlusion effects on the perception of self-initiated visual stimuli

Kiepe, F., Kraus, N., & Hesselmann, G. (2023). Virtual occlusion effects on the perception of self-initiated visual stimuli. *Consciousness and cognition*, *107*, 103460. https://doi.org/10.1016/j.concog.2022.103460

4.2 Study 2: Self-initiation enhances perceptual processing of auditory stimuli in an online study

Kiepe, F., Kraus, N., & Hesselmann, G. (2024). Self-initiation enhances perceptual processing of auditory stimuli in an online study. *Attention, perception & psychophysics*, *86*(2), 587–601. https://doi.org/10.3758/s13414-023-02827-w

4.3 Study 3: Prime-Induced Illusion of Control the Influence of Unconscious Priming on Self-Initiated Actions and the Role of Regression to the Mean

Kiepe, F., & Hesselmann, G. (2024). Prime-induced illusion of control: The influence of unconscious priming on self-initiated actions and the role of regression to the mean. *Consciousness and cognition*, *121*, 103684. Advance online publication. https://doi.org/10.1016/j.concog.2024.103684

4.4 Study 4: Sensory attenuation of self-initiated tactile feedback is modulated by stimulus strength and temporal delay in a virtual reality environment

Kiepe, F., & Hesselmann, G. (2024). Sensory attenuation of self-initiated tactile feedback is modulated by stimulus strength and temporal delay in a virtual reality environment [Manuscript submitted for publication].

Sensory attenuation of self-initiated tactile feedback is modulated by stimulus strength and temporal delay in a virtual reality environment

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Abstract

Despite extensive research across various modalities, the precise mechanisms of sensory attenuation (SA) remain debated. Specifically, it remains unclear to what extent SA is influenced by stimulus predictability alone, as opposed to the distinct impact of self-generated actions. Forward models suggest that efference copies of motor commands enables the brain to predict and distinguish anticipated changes in self-initiated sensory input. Predictive processing proposes that predictions about upcoming changes in sensory input are not solely based on efference copies, but rather generated in the form of a generative model integrating external, contextual factors, as well. This study investigated underlying mechanisms of SA in the tactile domain, specifically examining self-initiation and temporal predictions within a virtual reality (VR) framework. This set-up allowed for precise control over sensory feedback in response to movement. Participants (N = 33) engaged in an active condition, moving their hands to elicit a virtual touch. Importantly, visual perception was modified in VR, so that participants touched their rendered – but not physical – hands. The virtual touch triggered a test vibration on a touch controller (intensities: 0.2, 0.35, 0.5, 0.65, 0.8; in arbitrary units.), the intensity of which was then compared to that of a standard stimulus (intensity: 0.5). In the passive condition, vibrations were presented without movement and were preceded by a visual cue. Further, test vibrations appeared either immediately or after a variable onset delay (700 - 800ms). Our results revealed a significant effect of the factor "onset delay" on perceived vibration intensity. Additionally, we observed interactions between the factors "agency" and "test vibration intensity" and between the factors "agency" and "onset delay", with attenuation effects for immediate vibrations at high intensities and enhancement effects for delayed vibrations at low intensities. These findings emphasize the impact of external, contextual factors and support the notion of a broader, attention oriented predictive mechanism for the perception of self-initiated stimuli.

Introduction

The human perceptual system allows individuals to interact meaningfully with their environment by processing a wide range of sensory information simultaneously. To achieve this, not all sensory information is treated equally. One phenomenon that captures differential processing is sensory attenuation (SA) — the process by which self-initiated sensory input is perceived with a lesser intensity or salience compared to the same sensations generated externally (Hughes et al., 2013; Pyasik et al., 2021). It is suggested that this phenomenon helps us to distinguish stimuli produced by our own actions from those originating externally (Blakemore et al., 2002). SA encompasses various modalities (e.g., auditory: see Kiepe et al., 2021; visual: see Schwarz et al., 2018), though research examining this process originates from the somatosensory domain and the question why we cannot tickle ourself (Blakemore et al., 1998). The first studies in the somatosensory domain compared self-applied strokes with strokes applied by the experimenter, using subjective rating scales for evaluation. The results suggested attenuated processing of self-initiated stimuli, for differing pressure levels and frequencies (Blakemore et al., 1998; Blakemore et al., 2000).

Nowadays, behavioral studies examining SA usually make use of a two-phase comparison task (Bays et al., 2005). This method involves participants receiving two consecutive tactile stimuli: a test stimulus, which is either self-initiated or externally generated, and a standard stimulus. Subsequently, participants are tasked with comparing the intensity of the stimuli. The general set-up for studying SA in the somatosensory domain involves a hardware consisting of components such as an electric motor with its controller, a lever equipped with a probe connected to the motor and a force sensor attached to the lever for measuring forces applied to the passive hand or finger by the motor (Kilteni, 2023). Common findings support the notion that the force intensity delivered to one's passive hand by their active hand (i.e., self-initiated touch), is perceived as weaker when contrasted with externally generated forces (e.g., Hesse et al., 2010; Shergill et al., 2013; Kilteni & Ehrsson, 2022; Bays et al., 2005). However, these observations are not always consistent. A recent study by Thomas et al. (2022), for example, observed enhancement, instead of attenuation, in the perception of expected self-initiated sensory input. This enhancement effect was found in different domains, as well (visual: Dogge et al., 2019a, Yon et al., 2018; auditory: Kiepe et al., 2023, Paraskevoudi & SanMiguel, 2021, Reznik et al., 2015). These mixed findings have been debated in light of different explanatory theories over the function and etiology of SA.

Traditionally, SA has been explained by forward models: self-initiated actions involve constant communication among designated structures in the motor system. This communication not only generates motor commands but also produces efference copies of these commands. Efference copies, which are assumed to be forwarded to sensory cortices, allow the brain to predict how the intended behavior will change sensory inputs, enabling it to subtract predicted from actual changes. This process cancels out the sensory consequences of self-initiated behavior, helping the brain anticipate and distinguish between self-initiated and externally caused changes in sensory inputs (Blakemore et al., 2002). The primary function of sensorimotor control in these models is to predict and cancel the sensory effects of movement, facilitating the differentiation of self-initiated actions from externally induced ones (Hughes et al., 2013).

However, recent study results have challenged traditional notions of sensory processing, suggesting that SA may also depend on other predictive mechanisms to anticipate sensory input resulting from movement (Bays et al., 2006). For example, in a study by Kilteni et al. (2019), participants learned (for >400 trials) prior to the main experiment, that the self-initiated stimulus (i.e., force) appeared either with a systematic delay (100ms) or immediately (0ms). The results showed attenuation effects only if the test stimuli were temporally predictable (i.e., if a delay of 100ms was introduced between movement and stimulus, during the main experiment, SA was found for trials including the 100ms delay only; if no delay was introduced, SA was found only for trials wherein the stimulus appeared immediately after the movement). Bays et al. (2005) examined the temporality of attenuation effects by either delaying or advancing the stimuli (i.e., 400ms and 200ms) triggered by the participant's action (i.e., tapping a force sensor mounted above their finger). The results revealed that, with increasing temporal asynchrony, the attenuation effect diminished. However, the duration required for the onset delay to effectively influence attenuation effects is still up to debate. Although research by Kilteni et al. (2019, 2023) and Blakemore et al. (1999) demonstrated that even relatively brief delays of 100-200ms can influence sensory attenuation (SA), van Elk et al. (2014) and Klaffehn et al. (2019) suggest that only more substantial delays in the range of 700-800ms exert an impact on SA.

SA could be found in conditions involving no active movement of the participants, as well. Scott (2022) compared conditions where participants observed active touch (e.g., a video depicting a finger reaching to touch a ball) and passive touch (e.g., a video showing a ball rolling to touch the passive finger). The findings revealed that during the observation of active touch, the touch sensation was perceived as less intense compared to the observation of passive touch. Pyasik et al. (2021) observed SA when a fake hand, positioned egocentrically with respect to the participant's body (i.e., the fake hand's position was based on the participant's body), initiated the stimulus. Interestingly, SA effects were not evident when the fake hand was placed allocentrically in relation to the participant's body (i.e., the fake hand's position was based on external reference points opposite to the participant's body). Further, in a study by Fuehrer et al. (2022) participants stroked their finger over textured objects, inducing predictable vibrotactile feedback on the moving finger. External vibrotactile stimuli were applied shortly before touching the texture, with frequencies either congruent or incongruent with the stroking movement. Stronger attenuation was observed for stimuli congruent with the predicted sensory feedback. Taken together, these findings complicate distinguishing between the role of self-initiation and motor commands and the general predictability of an anticipated sensation as contributing to SA.

Notably, these results entail that predictions about upcoming changes in sensory input cannot be solely based on efference copies of voluntary motor behavior, but rather might be generated in the form of a generative model. Predictive processing regards the predictability of a stimulus central for its potential to be attenuated, irrespective of whether it is self-initiated or externally generated (Friston et al., 2016). Predictions about upcoming changes in sensory input involve prior information in general. Discrepancies between these predictions and the actual sensory evidence, also known as prediction errors, are incorporated into the continuously updating model for subsequent predictions. Throughout this Bayesian updating, the brain consistently strives to maximize model evidence, thus minimizing prediction error and surprise (Seth, 2012). Active inference emphasizes the role of motor behavior in altering surroundings to match predicted sensory inputs, and consequently minimize prediction errors. Before the predicted outcome and actual sensory input match, signals from self-initiated behavior are attenuated, signaling self-initiated behavior (Parr et al., 2021, Brown et al., 2013). However, although direct control over stimulus appearance via motor behavior can enhance predictability, it is not a mandatory condition for attenuation (Friston, 2013).

Our study aimed to further investigate the underlying mechanisms of SA in the tactile domain, utilizing a vibration discrimination task within a virtual reality (VR) environment. The VR setup enabled the examination of more natural movements (in contrast to, e.g., pressing on a lever) and precise control of sensory feedback in response to the movement (see also Kiepe et al. 2023). By employing controlled manipulation of sensory feedback in VR, we aimed to examine the predictive mechanisms of SA and elucidate the differences between motor-based forward models and predictive processing.

We have formulated two hypotheses. Hypothesis 1 posited that if self-initiated sensory input leads to a reduction in the sensory signal during processing, the perceived stimulus intensity of self-initiated vibrations should be lower than that of externally triggered vibrations. Hypothesis 2 posited that if the temporal predictability of a stimulus leads to a signal reduction during sensory processing, the perceived stimulus intensity should be attenuated for vibrations that appear immediately after successful hand movement (active condition) or cue-onset (passive condition), compared to delayed vibrations.

Methods

Participants

Prior to data collection, study procedures and primary analyses were preregistered and can be accessed at https://aspredicted.org/zg48e.pdf. We provide details on the determination of the sample size, any data exclusions, the criteria for inclusion/exclusion, whether these criteria were established before data analysis, all manipulations, and all measures employed in the study. The study received approval from the local ethics committee at the Psychologische Hochschule Berlin (PHB; approval number PHB22102020).

Instead of relying on a frequentist a priori power analysis based on previous results, the sample size in this study was determined through sequential Bayesian testing, as outlined by Schönbrodt et al. (2017). To obtain Bayes Factors, we compared the proportions of "test > standard" reports for trials with a test stimulus intensity of 50% (i.e. the same intensity as the standard stimulus) between active and passive trials (H1) and delayed versus immediate (H2) trials, using two-sided Bayesian paired t-tests. We pre-registered two stopping rules: a) Bayes Factors (BFs) would be computed sequentially until a critical BF > 10 was reached, either in favor of the null or the main hypothesis; b) sampling would cease when a maximum sample of N = 30 valid datasets was attained.

Anticipating the exclusion of several datasets, 38 participants (26 female, 12 male; mean age = 25.26, SD = 5.29) were recruited from the student pool at the Psychologische Hochschule Berlin (PHB). Four participants were excluded due to poor psychometric fits (see Figure S1), and one additional participant was excluded due to poor performance in the hand movement task (refer to exclusion criteria below). Consequently, the final sample comprised 33 participants (22 female, 11 male; mean age = 25.33, SD = 5.62).

All participants had normal or corrected-to-normal vision and no history of neurological or psychiatric disorders. They were unaware of the experiment's purpose, provided written informed consent, and received either monetary compensation (€10/h) or course credit for their participation.

Stimuli and procedure

In this experimental setup, we used a Meta Quest 2 head-mounted VR display with a refresh rate of 72Hz. The experiment ran on a Windows 10 PC equipped with an AMD Ryzen 5–1600 CPU and an NVIDIA GeForce Titan XP GPU, provided through the NVIDIA academic hardware grant program. Participants' hand movements were tracked using the Meta Quest 2's integrated hand tracking system, capturing data on position, velocity, and orientation. Haptic feedback was delivered through the Meta Quest 2 touch controllers. The virtual environment consisted of a uniform grey area (RGB:128, 128, 128). To control for accompanying auditory feedback of the haptic feedback, participants wore Over-Ear headphones (Sennheiser HD 25) during the experiment.

Each trial involved a vibrotactile comparison task, wherein participants received two consecutive haptic impulses occurring on both hands: a standard vibration and a test vibration (Figure 1). The test vibrations exhibited varying intensities (duration: 100ms) ranging from 0.2 to 0.8 arbitrary units (a.u., with a minimum of 0.0 and a maximum of 1.0), presented in randomized order. Simultaneously, the standard vibration was consistently maintained at an intensity level of 0.5 (duration: 100ms). Afterwards, participants were asked to compare the intensity of the two impulses ("Which vibration was stronger?"). Participants responded by pressing the trigger buttons of the touch controllers (left-trigger and right-trigger; counterbalanced). The response triggered the next trial.

The experiment followed a within-subject design with three experimental factors: agency (active versus passive), test vibration intensity (0.2, 0.35, 0.5, 0.65, 0.8) and onset delay of the test vibration (immediately (0ms) versus a variable delay of 700-800ms). Each vibration during the experimental phase was preceded by a visual cue (i.e., the fixation point changing its color), indicating the agency condition (green = active, red = passive). Test vibrations of every intensity level (0.2, 0.35, 0.5, 0.65, and 0.8) were presented 35 times in each of the four experimental conditions (agency x onset delay), resulting in a total of 700 trials.

In the active condition, participants were instructed to move their hands towards each other to elicit a touch as soon as when the fixation point's color turned to green (presentation duration: 97ms). Importantly, visual perception was modified in VR, so that participants touched their rendered – but not physical – hands. This virtual touch triggered the test vibration (duration: 100ms). Participants were instructed to keep their hands still following the successful hand movement. After a variable offset (1000, 1100, 1200, 1300, 1400 or 1500ms), the fixation point's color turned red (duration 97ms) and thereafter the standard vibration (duration: 100ms; 0.5 a.u.) was presented on both hands. Thus, the inter-stimulus interval (ISI), i.e., the time between the onset of the first vibration and onset of the second vibration, varied between 1100, 1200, 1300, 1400, 1500 and 1600ms. The "passive" condition differed from the active condition only in that both cues indicated external generation of the presented vibration (i.e., cue color: red), so that participants did not have to initiate any motor response. During the passive condition, participants were instructed to keep their virtual hands together during the whole trial.

Agency conditions were presented in blocks of trials, with the order of these blocks randomized across participants. To circumvent potential temporal adaptation to the onset delay (700 – 800ms), we opted to randomize the onset delays (immediately (0ms) versus 700 – 800ms) across trials and integrate them into both agency blocks, rather than subdividing them into distinct blocks. Thus, a variable onset delay (700-800ms) was included in half of the active trials, after successful hand movement (175 trials) and in half of the passive trials after the first visual cue (175 trials). The order of the onset delay was randomized across all trials. It is worth noting that the integration of various onset delays in random order may introduce increased cognitive load and participant uncertainty, potentially influencing their responses. However, a comparative analysis of results, as demonstrated by Myers et al. (2020), successfully reproduced previously reported findings of auditory comparison tasks within the context of a mixed trial design.

Training phases lasting a minimum of 20 trials (participants were given the possibility to extend the training phase on request) preceded each block. Here, participants acquired the desired hand movement/position, depending on the specific conditions. The experiment had a duration of approximately 90 minutes.

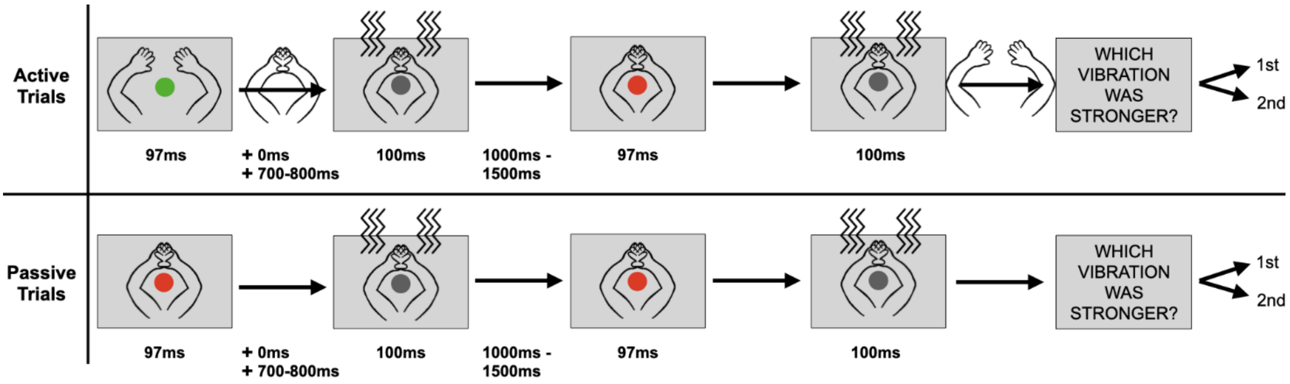

Fig. 1. Experimental paradigm: Vibrotactile Comparison Task. In each trial, participants had to compare two consecutive vibrations The intensity of the test vibrations varied (0.2, 0.35, 0.5, 0.65, and 0.8 a.u; in randomized order), the standard vibration remained constant at 0.5. Trials varied in agency (active, passive) and onset delay (0ms, 700-800ms). In "active" trials, participants self-initiated the test vibrations by moving their virtual hands towards each other, eliciting a virtual touch. In "passive" trials, both, standard and test tone, were generated externally. Test vibrations were presented either immediately (0ms) or after a variable onset delay of 700 - 800ms.

Data preprocessing and analysis

Data preprocessing and analysis were performed in R (version 4.0.1; R Core Team 2018) using the following R packages: afex (Singmann et al., 2022), dplyr (Wickham et al., 2021), and ggplot2 (Wickham, 2016). Sequential BFs were computed using JASP 0.16.3.0 (JASP Team, 2022). We used the default Cauchy prior with the scale parameter r = 0.707 (see Figure S2). Raw data and R scripts are available at OSF (https://osf.io/y4z8h).

As preregistered, participants with data indicating a poor psychometric fit were excluded. For this, we calculated McFadden's pseudo-R^2 as a goodness-of-fit measure of a logistic regression model for each participant, in which the proportion of correct trials (collapsed across all conditions) was calculated by intensity level of the test stimulus. Participants with pseudo-R^2 < 0.2 were excluded (Louviere et al., 2000). The exclusion criterion applied to six participants (see Figure S1 for individual psychometric curves). Six participants were excluded due to this exclusion criteria (see Figure S1 for individual psychometric fits). Additionally, we excluded trials where the hand movement was not within the allowed constraints. The average percentage of trials discarded was 4%. One participant (#7) was excluded due to poor performance in the hand movement task (27% of trials discarded in the active condition).

We computed a repeated-measures ANOVA with factors “agency” (2 levels: active, passive), “onset delay” (2 levels: immediate (0ms), delay (700 - 800ms)) and “test vibration” (5 levels: 0.2, 0.35, 0.5, 0.65, 0.8; a.u.). Further, we employed Bayes Factors (BFs) through Bayesian repeated measures 2x2x5 ANOVAs and one-sided Bayesian paired t-tests. Bayes Factors (BFs) represent the ratio of marginal likelihoods for different models, indicating changes in model odds from prior beliefs to posterior beliefs based on the observed data. Subscripts on BFs denote the compared models, with the first subscript corresponding to the numerator model and the second to the denominator model. For instance, a BF_{10} of 5 implies that the data is five times more likely under the alternative hypothesis (H1) than the null hypothesis (H0). Two-sided Bayesian paired t-tests were conducted in JASP 0.16.3 (JASP Team, 2022) using the default Cauchy prior with a scale parameter of $r = .707$. Bayesian repeated measures ANOVAs were performed using default coefficient priors (i.e., prior scale for fixed effects: $r = 0.5$; prior scale for random effects: $r = 1$; prior scale for covariates: $r = 0.354$) and a uniform model prior. Classification schemes, as proposed by Lee and Wagenmakers (2013), categorize BFs into different levels of evidence. BFs between 1 and 3 suggest anecdotal evidence, BFs between 3 and 10 indicate moderate evidence, BFs between 10 and 30 imply strong evidence, BFs between 30 and 100 point to very strong evidence, and BFs greater than 100 suggest extreme evidence.

Using the psignifit4 toolbox in MATLAB (Schütt, Harmeling, Macke, & Wichmann, 2016), we conducted parameter estimation for two aspects of psychometric curves, namely, the Point of Subjective Equality (PSE) and the slope. A logistic model was applied to the proportion data, representing the percentage of "test stimulus intensity > standard stimulus intensity" responses from each participant, with the test contrast strength as the independent variable. Here, the PSE describes the point at which the participant perceived test stimulus intensity as being equal to the standard stimulus intensity. The logistic model allowed for the determination of the PSE for each participant individually. This modeling procedure was performed separately for each condition (agency, onset delay). Additionally, the model was also used to compute slopes at psychometric curve thresholds, with the slope inversely linked to the just noticeable difference (JND), representing the smallest stimulus change required for a perceptible increase in sensation (Gescheider, 2015). A steeper psychometric function (i.e., smaller JND) signifies that an observer can discriminate small stimulus differences, while a shallower function (i.e., larger JND) suggests that the observer can only discriminate relatively coarse differences.

Results

First, we examined differences in intensity judgements between all conditions (agency, onset delay, test vibration intensity). Figure 2 shows the average response curves observed in our experiment, separately for each condition. As expected, the curves show an increasing slope, as participants tended to report the test over the standard stimulus more often with increasing intensity of the test vibration. Accordingly, the preregistered repeated-measures ANOVA with factors “agency”, “onset delay” and “test vibration intensity” showed a significant main effect of factor “test vibration” ($F(1,32) = 292.34$, $p <.001$, $\eta p2 = 0.901$, $BF_{10} > 100$).

We then examined if self-initiated stimuli are perceived with a lesser intensity, compared to externally generated stimuli (Hypothesis 1). Visual inspection reveals that we can observe attenuation of self-initiated stimuli only for test vibrations with higher intensity (i.e., 0.8; active: 0.72 [0.67., 0.77] versus passive: 0.83 [0.79, 0.87]; mean percentage and 95% CI). With lower test vibration intensities, the attenuation effect diminishes (e.g.: intensity of 0.5: active 0.45 [0.4., 0.5] versus passive: 0.45 [0.41., 0.49]). Notably, for test stimuli with a vibration intensity of 0.2, we can observe an enhancement, as opposed to attenuation, in the perception of self-initiated stimuli (active: 0.21 [0.16, 0.26] versus passive: 0.17 [0.14, 0.21]). Accordingly, the ANOVA revealed no significant main effect for "agency" ($F(1,32) = .99$, $p = .328$, $\eta_p^2 = .03$, $BF_{10} = .359$), but a significant interaction between "agency" and "test vibration" ($F(1,32) = 13.56$, $p < .001$, $\eta_p^2 = .298$, $BF_{10} > 100$).

We further examined if temporal predictability affects perceived intensities of self-initiated sensory input (Hypothesis 2). Indeed, we can observe enhanced perception of self-initiated stimuli with a delayed onset, compared to self-initiated with an immediate onset, if the intensities of the vibration are low (0.2; immediate: 0.21 [0.17, 0.25] versus delay: 0.24 [0.2, 0.28]). However, for high intensities, the effect reverses, and we observe enhanced perception of self-initiated stimuli with an immediate onset, compared to self-initiated, delayed stimuli (0.8; immediate: 0.72 [0.68, 0.76] versus delay: 0.67 [0.62, 0.72]). The ANOVA revealed a significant main effect for "onset delay" ($F(1,32) = 17.16$, $p < .001$, $\eta_p^2 = .349$, $BF_{10} = 31.74$), as well as a significant interaction between "agency" and "onset delay" ($F(1,32) = 4.98$, $p = .033$, $\eta_p^2 = .135$, $BF_{10} = 14.982$). The full ANOVA tables are available in the supplement (Table S1 and S2).

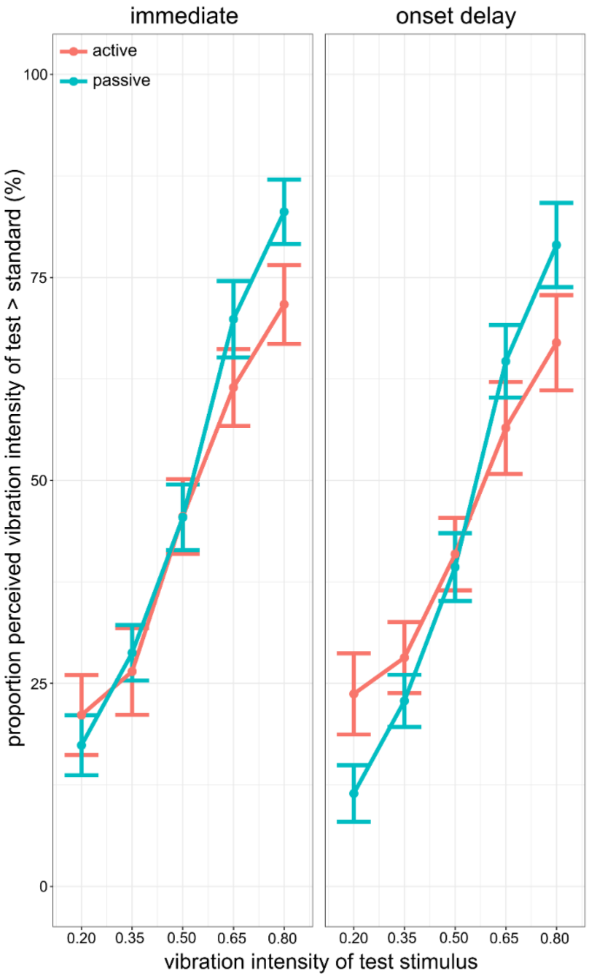

Fig. 2. Results. Shown are the mean percentages of responses in which participants (N=33) judged the subjective intensity of the test vibration as higher than the intensity of the standard vibration. The intensity of the test vibrations varied (0.2, 0.35, 0.5, 0.65, and 0.8 a.u), the standard vibration remained constant at 0.5. The test vibration was either self-initiated ("active" trials, red curves) or externally generated ("passive" trials, blue curves), and were presented either immediately (0ms) or with a variable onset delay (700 - 800ms). Error bars indicate 95% confidence intervals calculated for within-subject data using the summarySEwithin function from the *Rmisc* package (version 1.5.1).

Concerning the parameters derived from the fits of psychometric functions, our preregistered analysis focused on the PSE and the slope. For the PSE analyses, the threshold parameter for each participant and psychometric function (i.e., Active-Immediate, Active-Delay, Passive-Immediate, Passive-Delay) was computed and subjected to a repeated measures ANOVA with factors "agency" and "onset delay." Figure 3A displays the psychometric functions for a single exemplary participant. Figure 3B illustrates the results, revealing no discernible shift in the PSE based on whether stimuli were self-initiated or externally generated (active: 0.55 [0.52, 0.58] versus passive: 0.5 [0.47, 0.53]). Additionally, when test vibrations exhibit a variable onset delay, the PSEs of actively and passively generated vibrations increase visibly and align (active: 0.57 [0.53, 0.61] versus passive: 0.56 [0.53, 0.59]). The repeated measures ANOVA (Table S3) shows no main effect for “agency” ($F(1,32) = 1.62$, $p = .212$, $\eta_p^2 = .048$, $BF_{10} = .658$), a significant main effect for “onset delay” ($F(1,32) = 13.44$, $p < .001$, $\eta_p^2 = .296$, $BF_{10} = 15.365$) and no interaction between "agency" and "onset delay" ($F(1,32) = 2.09$, $p = .158$, $\eta_p^2 = .061$, $BF_{10} = 6.994$).

To estimate the slope of the psychometric functions, we applied the same logistic model we used to determine the PSEs. We computed the slope for each participant and psychometric function in the four experimental conditions (i.e., Active-Immediate, Active-Delay, Passive-Immediate, Passive-Delay) and subjected the values to a repeated measures ANOVA with factors "agency" and "onset delay". Figure 3C shows the mean slope estimates. Here, we can observe differences in the slopes between self-initiated versus externally generated stimuli during the onset delay condition. Accordingly, the repeated measures ANOVA (Table S5) shows a significant main effect for “agency” ($F(1,32) = 5.49$, $p = .026$, $\eta_p^2 = .146$, $BF_{10} = 2.84$), however, no main effect for “onset delay” ($F(1,32) = .93$, $p = .342$, $\eta_p^2 = .028$, $BF_{10} = .288$), and no interaction between “agency” and “onset delay” ($F(1,32) = 3.94$, $p = .056$, $\eta_p^2 = .110$, $BF_{10} = 1.454$).

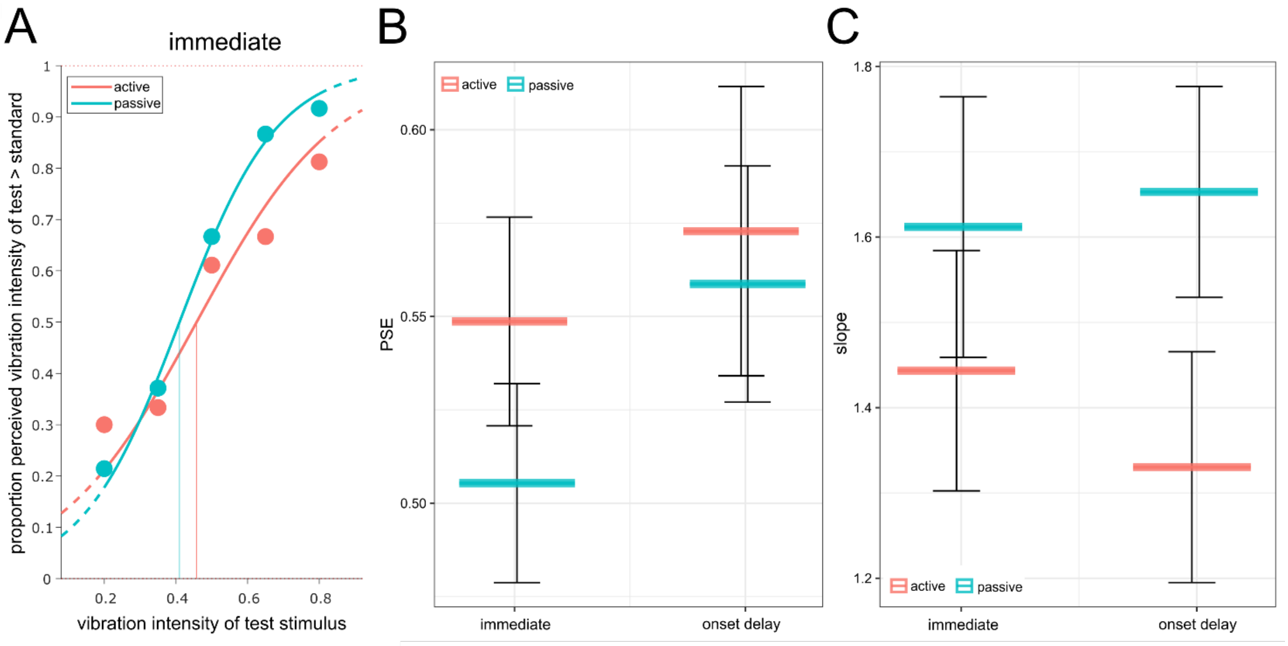

Fig. 3. Results. **3A)** Psychometric functions of an example participant (#19). Proportions of "test > standard" reports are shown against physical vibration intensity of the test stimuli (i.e., 0.2, 0.35, 0.5, 0.65, 0.8 a.u.). **3B)** Mean PSE estimates of N = 33 participants. **3C)** Mean slope estimates of N = 33 participants. Psychometric fits are based on a logistic model with two free parameters (threshold, width). The test vibration was either self-initiated (“active” trials, red curves) or externally generated (“passive” trials, blue curves), and were presented either immediately (0ms) or with a variable onset delay (700 - 800ms). Error bars indicate 95% confidence intervals calculated for within-subject data using the summarySEwithin function from the Rmisc package (version 1.5.1).

Discussion

This study investigated the underlying mechanisms of SA in the tactile domain, specifically examining self-initiation and temporal predictions within a virtual reality framework. The VR set-up allowed for more natural behavior and precise control over sensory feedback in response to movement. Participants engaged in an active condition, moving their hands to elicit a touch. Importantly, visual perception was modified in VR, so that participants touched their rendered – but not physical – hands. The virtual touch triggered a test vibration on the meta quest touch controllers, the intensity of test vibration was then compared to that of a standard stimulus. In the passive condition, vibrations were presented without movement and were preceded by a visual cue. Further, test and standard vibrations appeared either immediately or after a variable onset delay. Our results revealed a main effect of the factor "onset delay" and an interaction between "agency" and "test vibration intensity" on perceived comparative stimulus intensity, suggesting that both variable onset delays and test vibration intensities modulate the perception of self-initiated stimuli.

Our findings are difficult to explain on the basis of motor-based forward models. Generally, forward models emphasize the significance of efference copies generated by self-initiated actions, informing perceptual processing areas about anticipated alterations in sensory inputs. These efference copies are then believed to induce modifications in the processing of self-generated stimuli, establishing a foundation for distinguishing changes in the environment that are self-generated from those caused externally (Hughes et al., 2013). Our results provide a more nuanced insight into the multifactorial mechanisms of SA, as we can observe attenuated self-initiated sensory input only if the stimulus strength (i.e., vibration intensity) reaches a certain threshold (e.g., 0.8), and if the stimuli are presented immediately after successful movement. For weak, delayed stimuli, the effect appears to be even reversed, showing enhanced perceived intensities for self-initiated stimuli. It appears that the overall predictability of a self-initiated stimulus affects if attentional resources are being drawn away from (i.e., attenuation) or towards (i.e., enhancement) this stimulus.

Predictive processing emphasizes the interplay between predictions and attention, by conceiving attention as synaptic gain control that regulates the precision of prediction errors (Chennu et al., 2016). According to this framework, attentional resources are oriented based on predictive information, leading to energy-efficient processing of sensory input. In this context, SA results from reducing the precision of expected sensory events; a mechanism which can also be described as drawing away attentional resources from this specific sensory input (Schröger et al., 2015; Chennu et al., 2016; Wiese, 2017; Dogge et al., 2019a; Brown et al., 2013). Note, that this approach does emphasize self-initiation as an important factor for SA, as it generally increases stimulus predictability (Brown et al., 2013). The effect of attention orienting on perceptual processing has been repeatedly demonstrated in various domains. Anton-Erxleben & Carrasco (2013) showed that drawing attention away or towards a visual stimulus can affect the perception its spatial features (i.e., position and size). Fritz and Zimmernann (2022) detached tactile feedback usually occurring from motor behavior (i.e., pressing a button) by transferring an auditory comparison task in a virtual environment. Their results suggested SA for self-initiated auditory stimuli only when tactile feedback from the motor behavior occurred simultaneously, hence attention was directed away from the auditory modality. The presented results may have been caused by a similar mechanism in which visual and sensorimotor processing of movement completion are demanding of attentional resources, attenuating the processing of the immediate sensory consequences that are caused by the movement. However, increasing the delay between movement completion and its sensory consequences will allow for a restoration of attentional resources, leading to the observed enhancement effect.

Such a mechanism would be supported by recent approaches to SA, which suggest a broader, attention oriented predictive mechanism (Press et al., 2023, Dogge et al., 2019a; Kemenade et al., 2016). In the auditory domain, Reznik and Mukamel (2019) proposed a model emphasizing contextual factors in the perception of self-initiated stimuli. According to this model, predictable stimuli are enhanced or attenuated, depending on the specific context and task demands. For instance, self-initiated stimuli may be attenuated in salient contexts but need to be attended to (i.e., enhanced) in faint contexts. This model highlights the role of self-initiation and internally generated motor signals, as they provide a reliable source of expected sensory consequences. Thus, while it is generally efficient to anticipate stimulus strength through contextual factors, self-generated motor signals facilitate this process through direct modulatory connections between motor and somatosensory cortex. Moreover, stimuli may not only be enhanced or attenuated based on environmental context, but also based on the signal strength of the stimulus itself (Myers et al. 2020; Reznik et al., 2015).

The results of our study revealed a main effect for "onset delay" and an interaction between "agency" and "vibration intensity" on perceived stimulus intensity. In trials, where the vibration intensity of the test stimulus was high (i.e., 0.8) and the vibration appeared immediately after movement, we observed a classic attenuation effect of self-initiated stimuli. With weaker intensity of the test stimulus, the perceived intensity of self-initiated and externally generated vibrations aligned. However, for trials with weak vibration intensity (i.e., 0.2) and delayed occurrence, we observed an enhancement effect of self-initiated stimuli. In other words, if self-initiated stimuli are temporally (i.e., through immediate appearance of the stimulus after successful movement) and individually (i.e., high vibration intensity) predictable, these stimuli are attenuated. If, on the other hand, self-initiated stimuli are temporally (i.e., delayed appearance) and individually (i.e., low vibration intensity) unpredictable, the stimuli are enhanced. These results are in line with the proposed model by Reznik and Mukamel (2019), and suggest that the dynamic perception of self-initiated stimuli (i.e., either attenuating or enhancing stimulus intensity), modulated by contextual factors (i.e., signal strength and temporality) may be applied to the somatosensory domain. The adaptiveness observed in the perception of self-initiated stimuli could account for the absence of an agency effect in our PSE analysis. It's noteworthy that this finding aligns with previous observations in the SA literature (Dogge et al., 2019b; Paraskevoudi & SanMiguel, 2021). If the perception of self-initiated signals is consistently modulated by the signal strength itself, rather than being consistently attenuated or enhanced, it could pose challenges in detecting differences between conditions in the PSE values.

Our findings also reveal a decrease in the slope of the psychometric function for self-initiated, delayed stimuli, compared to externally generated, delayed stimuli. The slope can serve as an indicator of perceptual noise and variability in responses. Generally, a steep psychometric function indicates a high level of discrimination, indicating that participants were able to discriminate even small differences between test and standard stimuli. A shallow psychometric function suggests more difficulty in stimulus comparison (Park, 2017; Reynolds, 2009). Thus, the observed decrease in the slope for self-initiated, delayed stimuli would suggest, that temporal unpredictability (through a variable onset delay of 700-800ms) affects self-initiated stimulus more than externally generated stimuli. This effect emphasizes the role of prior information in stimulus perception. Note that the difference between the conditions not only lies in the delayed stimulus onset, but also in its variability. While stimulus onset was fixed (i.e., 0ms) during the immediate condition, it varied within a range of 100ms during the delayed condition (700 - 800ms). Moreover, we included immediate and delayed stimulus onset into each block, varying randomly. Recent studies could show that the perception of self-initiated touch is temporally adaptable, if delays between self-initiation and stimulus onset are pre-learned extensively (e.g., >400 trials before the main experiment; Kilteni et al., 2019; Fritz & Zimmermann, 2022). However, our study set-up increased temporal uncertainty for self-initiated, delayed trials. Typically, self-initiated motor behavior is associated with an immediate sensory input in response. Moreover, typically, self-initiation is regarded as an exceptionally reliable source of expected sensory input (Reznik & Mukamel, 2019). In our VR-setup, the usual sensory input was detached from the participant's motor behavior, and manipulated temporally. This might have led to more uncertainty during self-initiated, delayed trials, as their sensory consequences substantially deviated from the participants' expectations. To further investigate the impact of temporal unpredictability and adaptability, future studies could incorporate separate blocks featuring either immediate or delayed stimulus onset exclusively. Additionally, future studies could investigate the impact of temporal uncertainty by including a condition with a variable range of relatively short delays (i.e., 0 - 100ms) in stimulus onset. Bays et al. (2005) and Kilteni et al. (2019, 2023) observed that onset delays of <100ms may not have an impact on attenuation of self-initiated stimuli, if presented constantly. Adding temporal uncertainty within this timeframe could provide valuable insights into the temporality of SA.

Limitations and Further Research

Our experiment included a fixed stimulus order, i.e., the first vibration was always the test vibration. Because of this fixed stimulus order it was possible to control for possible variations in inter-stimulus intervals (ISIs) between test and standard stimulus caused by self-initiation. However, this constant stimulus order might introduce a response bias, i.e., the possibility of a bias to choose the first stimulus over the second, dependent on the stimulus order and independent on other factors (i.e., agency). When comparing the two stimuli, the first stimulus intensity always acts as a reference point for the second stimulus intensity (Myers et al., 2020; Bausenhart et al., 2015; Zeng & Turner, 1994). Indeed, in our study, we observed that perceived vibration intensity of the test vibration (i.e., first vibration) was relatively low in the passive condition, as well (e.g., for comparing standard vibration intensity of 0.5 with test vibration intensity of 0.5: 0.45 [0.41., 0.49]), indicating a bias in response behavior towards the second stimulus. However, preceding experiments which investigated stimulus order effects using a similar experimental setup indicate that it appears unlikely that this response bias accounts for differences between perception differences of self-initiated and externally generated stimuli (Reznik et al., 2015, Kiepe et al., 2023, Myers et al., 2020). Note also that, in our study, the fixed stimulus order was applied for both agency conditions (i.e., active and passive). Still, future studies should include stimulus order as a factor in their study design.

Our results also suggest that the comparison of test versus standard vibration intensities in our experiment was rather difficult. Across all conditions, when comparing the largest differences (i.e., test: 0.2/0.8, standard: 0.5; a.u.), participants perceived the objectively stronger intensity as stronger in 78.38% of the trials, only. Note, that the fitted psychometric functions (including PSE-values and slopes) are limited to the data they are based on. The uncertainty is reflected in variations of pattern of results when the psychometric function is parameterized differently. Future studies should integrate a wider range of test stimuli (e.g., 0-1: in a.u.) to reach true minimum/maximum endpoints in the data. Furthermore, to arrive at more reliable parameter estimates, future studies should aim at maximizing the amount of trials that are conducted (Wichmann & Hill, 2001). Another way to reduce uncertainty during behavioral SA studies might be the implementation of the force-matching task (Shergill et al., 2005). Here, participants experience an externally generated force (e.g., on their left finger) and then match it with a self-generated force (e.g., by pressing their right finger against their left finger). The matched forces of this condition are then compared with the control condition (e.g., a “slider” condition using external devices to match the force; Kilteni 2023; McNaughton et al., 2023).

In conclusion, the results of our study suggest adaptiveness in the perceived intensity of self-initiated sensory input, with perception of vibrotactile intensity being modulated by contextual factors such as signal strength and temporality. Further research is needed to explore the impact of these mechanisms on somatosensory perception.

Declarations

Ethical Approval

All procedures performed in studies involving human participants were in accordance with the ethical standards of the local ethics committee at the Psychologische Hochschule Berlin (PHB; approval number PHB22102020) and with the 1964 Helsinki declaration and its later amendments or comparable ethical standards.

Competing interests

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.

Authors' contributions

FK and GH wrote the manuscript. All authors contributed to the article and approved the submitted version.

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Availability of data and materials

Preregistrations can be accessed at Aspredicted (https://aspredicted.org/zg48e.pdf). The raw data and R script for this experiment can be accessed at the Open Science Framework (OSF; https://osf.io/y4z8h).

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5. General Discussion

SA, the phenomenon that self-initiated sensory input is perceived as less intense as externally generated input, has been often assumed to be a key principle for successful movement and the perception of self (Schwarz et al., 2018; Aru et al., 2018; Brown et al., 2013). Motor-based forward models emphasize the role of self-initiation, and explain SA through efference copies, which are informing perceptual processing areas over expected sensory consequences (Hughes et al., 2013a; Pickering & Clark, 2014). However, over the decades, several studies suggested a multifactorial framework, proposing that other, non-motor predictive mechanisms have an impact on attenuation effects as well (Dogge et al., 2019a; Brown et al., 2013; Schwarz et al., 2018; Kiepe et al., 2021). Contrary to forward models, predictive processing does not attribute SA to reafference cancellation but rather to predictions based on motor and non-motor cues. Here, SA is interpreted as a logical consequence of attention orienting by a generative model which constantly strives to minimize surprise.

This dissertation delved into the influence of motor and non-motor predictive mechanisms on SA and SoA. We further aimed to circumvent methodological limitations by introducing technological and methodological advances into this domain. In Study 1, using VR to examine occlusion effects on visual SA, the results indicated that the location of the hand affects perceptual sensitivity more than the hand movement itself. The results of Study 2, examining auditory SA in two online samples, revealed enhancement instead of attenuation for self-initiated auditory stimuli. Further, these findings implied the influence of accompanying sensory input, identity prediction and signal strength on the perceptual processing of self-initiated sensory input. Study 3 examined the impact of supraliminal and subliminal prime stimuli on SoA while circumventing post-hoc subject selection. The results suggested that primes affected SoA only when they were processed consciously. Study 4, investigating somatosensory SA in VR, suggested that SA is adaptive and modulated by external factors, such as signal strength and temporal predictability. In what follows, I will discuss the study results in light of the aims and research questions of this dissertation. I will further discuss their implication on explanatory and methodological approaches of SA and SoA.

Does self-initiation lead to a reduction in perceived stimulus intensity?

While the results of Study 2 and Study 4 indicated that self-initiation has a significant impact on perceptual processing, we did not observe SA based on self-initiation in Study 1. Here, it appeared that the location of the hand affected perceptual sensitivity more than the hand movement itself. Moreover, in both Study 2 and Study 4, we did not consistently observe SA for self-initiated stimuli. Instead, we found enhancement in perceived sensory input when the stimulus intensity was low, and attenuation effects only for heightened stimulus intensities. Hence, SA appeared to be modulated by external factors (e.g., signal strength).

Does temporal predictability lead to a reduction in perceived stimulus intensity?

While Study 1 did not suggest an impact of temporal predictability, we observed in Study 4 that variable onset delays (700, 750, 800ms) significantly influenced the perception of self-initiated stimulus intensities. Hence, the role of temporal predictability in SA remains ambiguous. Moreover, we only investigated onset delays within the range of 700-800ms. As outlined above, other studies observed significant influences of onset delays >200ms (Kilteni et al., 2019; 2023; Blakemore et al., 1999), as well as no influence of onset delays up to 950ms (Lange, 2011). Accordingly, the length of the onset delay might modulate its impact. Future research is needed to examine the effect of temporality on SA.

Does identity prediction lead to a reduction in perceived stimulus intensity?

To examine the role of identity prediction, Study 2 implemented a training phase before the main experiment, where certain cue-sound combinations were learned beforehand. The results revealed no main effect of identity prediction on SA. However, explanatory analyses demonstrated a significant interaction between, agency, signal strength, accompanying sensory input and identity prediction, suggesting a multifactorial interplay among motor and non-motor predictive mechanisms. Accordingly, identity prediction may not solely be responsible for SA effects. Nevertheless, it can be a modulating factor.

Do subliminal and supraliminal prime stimuli influence the Sense of Agency?

Study 3 comprised in two experiments investigating the effects of external cues (i.e., subliminal and supraliminal prime stimuli) on judgements of SoA. The results suggested that only supraliminal prime stimuli can affect control judgements, and contradict earlier observations of Linser and Goschke (2007), indicating that unconsciously processed primes have a significant impact on SoA.

Overall, our study results indicate that SA and SoA are not solely attributable to self-initiation but influenced by other, external factors, as well. These results challenge the explanatory approach of motor-based forward models, which suggest self-initiated motor behavior, and the according efference copies, as the crucial component for both SA and SoA (Haggard, 2017; Tsakiris & Haggard, 2005; Christensen & Grünbaum, 2018; Welniarz et al., 2021; Blakemore et al., 1999). Rather, our results are more in line with the explanatory approach of predictive processing, which highlights the influence of external cues (Kahl & Kopp, 2018; Synofzik et al., 2013; Gentsch, 2011; Friston, 2013). However, both concepts do not inherently accommodate for enhancement effects we observed in Study 2 and Study 4. Further, the impact of temporal predictability and identity prediction remains ambiguous. In what follows, I will discuss our results in light of alternative explanatory approaches.

5.1. Implications of the Observed Results on Explanatory Approaches

Enhancement effects have been observed by various studies across different domains (visual: Dogge et al., 2019b; Yon et al., 2018; somatosensory: Press et al. 2020; Yon et al. 2021; Thomas et al., 2022; auditory: Paraskevoudi & SanMiguel, 2021; Hsu et al., 2014; Reznik et al., 2015). These studies in particular challenge the notion that the perception of self-initiated sensory consequences is exclusively influenced by motor behavior. Instead, they illustrate that (ambiguous) sensory information is interpreted through predictions - and the anticipated sensory input derived from these predictions (Yon et al., 2018; 2021; Pelegrin et al., 2024; Bingham & Wickelgren, 2008; Fritz & Zimmermann, 2023). Rather, these results support the notion that SA may be a result of attention orienting (Press et al., 2023, Dogge et al., 2019a; van Kemenade et al., 2016; Chennu et al., 2016). Several studies indeed highlight the influence of attention orienting on SA effects. For example, in an auditory detection task, Cao and Gross (2015) instructed participants to attend to a specific target tone following self-initiated movement. Attention towards a specific stimulus resulted in a decrease of attenuation effects. Fritz et al. (2022) detached and manipulated sensory consequences arising from motor behavior within an auditory comparison task using VR. In the active condition, participants were instructed to press a virtual button to trigger the test tone. However, the tactile feedback usually associated with the button press was temporally manipulated, occurring either before, during, or after the button press. The results revealed SA only when tactile feedback coincided with the auditory stimuli, indicating that SA might stem from reduced attentional capacity. Reznik et al. (2015) examined the impact of stimulus intensity (near-threshold versus supra-threshold) in a two-phase comparison task. Perceived intensity was enhanced for near-threshold stimuli, and attenuated for supra-threshold stimuli. Note, that this effect was observed to a lesser extent in the passive condition as well.

Accordingly, Reznik and Mukamel (2019) proposed a framework emphasizing the adaptiveness of perceptual processing. This framework proposes that self-initiated stimuli are either attenuated or enhanced based on the interaction between motor and non-motor predictive mechanisms. For example, in a salient context, where the sensory consequence of a self-initiated action is noticeable and conventional, these stimuli can be attenuated. Conversely, in a faint context (i.e., where self-initiated stimuli are not prominent), the self-initiated stimulus requires attention, leading to enhancement in its perceived intensity. This context can also be based on environmental factors (i.e., accompanying sensory input) or the stimulus intensity itself (Myers et al., 2020; Reznik et al., 2015). This framework highlights the influence of self-initiation and internally generated motor signals as a reliable predictor and emphasizes the role of external factors, including temporality, identity and intensity of the stimulus, as well as contextual factors (e.g., accompanying sensory input, task difficulty). However, it is important to note that, consistent with findings from other studies (Dogge et al., 2019b; Hughes et al., 2013b), Study 2 revealed only a modest influence of identity prediction on SA. The extent to which internal and external factors affect SA remains a topic of ongoing debate.

A concept emphasizing the role of internal factors is active inference. This framework proposes that perception is interpreted as a result of prediction error minimization based on a Bayesian updating scheme, which uses prediction errors to constantly adapt the internal model to match predicted and actual sensory input (Dogge et al., 2019a). Importantly, this concept implies a general predictive mechanism where prediction errors can be minimized in two ways: either by altering one’s predictions, or by actively generating predicted sensory input (Dogge et al., 2019a; Brown et al., 2013). Similarly, the ideomotor theory suggests a bidirectional relationship between movement and sensory consequences. Therefore, action-planning generally involves the pre-activation of sensory events that arise from the planned action (Roussel et al., 2013; Dogge et al., 2019a; Harrison et al., 2021; Fritz & Zimmermann., 2023). For example, Vasser et al. (2019) showed that moving a virtually invisible hand into the visual field led to attenuated processing for stimuli presented in that visual field. The authors interpreted these findings as indicating that the movement entailed a prediction of its sensory consequence, hence obstructing the view of this visual area. Consequently, attention was oriented away from this region. However, in Study 1, we did not find a significant influence of self-initiation on perceptual processing. It appeared that instead the hand's placement was crucial.

In conclusion, the studies outlined in this dissertation propose that explanations of SA and SoA need to consider external predictive mechanisms. Further, SA might be an integral component of an adaptive perceptual process for self-initiated actions, shifting attention based on predictions about upcoming sensory events derived from both internal and external cues. Future research is needed to examine the role of attention orienting.

5.2 Implications of the Observed Results on Methodological Approaches

5.2.1 Measuring Sensory Attenuation

As outlined above, most behavioral SA studies incorporate a two-phase comparison task: participants compare the intensity of two consecutive stimuli with one stimulus being self-initiated while the other is externally generated. However, this leads to a methodological compromise. The time needed to generate a successful movement to initiate a stimulus varies within and between participants. Accordingly, trials where the second stimulus as self-initiated result in varying and longer ISIs between the first and second stimulus, compared to trials where the self-initiated stimulus is presented first. In this case, the ISIs between stimuli can be controlled for and kept constant. The varying ISIs can potentially diminish the impact of self-initiation on SA. Conversely, a constant stimulus order where the first stimulus is always self-initiated could lead to a primacy bias, resulting in an overestimation of the influence of self-initiation on SA (Myers et al., 2020). Moreover, according to Reznik & Mukamel (2019) and Myers et al. (2020), stimulus enhancement or attenuation is partially influenced by contextual factors such as task difficulty and the range of intensity levels. Reznik et al. (2015), for instance, observed in an auditory comparison task that self-initiated tones supra-threshold are attenuated, while those near threshold were enhanced.

In study 1, the experimental setup attempted to circumvent sequential presentation of stimuli by presenting both Gabor contrasts after successful hand movement, with one in the target area (i.e., virtually occluded) and one in an unobstructed view. However, there was a critical difference between the conditions in the arrangement of the Gabor contrasts. In the Immediate, Delay, and Static conditions, the Gabor contrasts were presented horizontally. In the Control condition, they were arranged vertically. Examining the slopes of the psychometric curves across conditions revealed decreased mean slope estimates for the Immediate, Delay, and Static condition, compared to the Control condition. A steep psychometric function typically signifies a high level of discrimination, indicating that participants could discriminate even minor differences between test and standard stimuli. Conversely, a shallow psychometric function implies greater difficulty in stimulus comparison (Park, 2017; Reynolds & Heeger, 2009). While this finding can certainly imply that virtual occlusion resulted in changes in perceptual sensitivity, we cannot determine whether the arrangement of the Gabor contrasts contributed to the differences in slope estimations.

Study 2 comprised two experiments: the initial one featured a constant stimulus order where the first stimulus was always self-initiated. To counteract possible confounds of a primacy bias, the stimulus order was reversed in the subsequent experiment. Both experiments indicated enhancement, instead of attenuation, for self-initiated stimuli. However, it is important to note that, since we did not counterbalance the stimulus order within these experiments, potential effects of stimulus order within subjects thus cannot be discounted. A possible solution for this methodological compromise could be a "yoked control" (or, "replay" in the context of binocular rivalry) procedure, where one condition mimics the (perceptual) dynamics of a second condition (Lumer et al., 1998; Frässle et al., 2014). In this case, one could measure the time participants need to initiate the successful movement beforehand, and integrate these RTs into the experimental design.

To the best of our knowledge, Study 2 was the first study to examine auditory SA in two online samples. Online experiments typically benefit from the possibility of reaching a large and diverse sample with minimal resources (as was the case in our study: experiment 1: N = 224, experiment 2: N = 84). Diverse contexts, however, pose a key challenge for online experimentation. The contextual diversity ranges from technical set-ups to the environment in which the study is completed (e.g., outside versus at home). This diversity influences the relative intensity of the stimulus, which in turn might have an impact on SA (Reznik & Mukamel, 2019). In our study, we approached this issue by including individual discrimination thresholds to ensure supra-threshold stimulus intensity (Zhao et al., 2022). Further, we included a headphone performance check (Woods et al., 2017) and attention checks. Online studies will, nevertheless, inevitably entail a degree of uncontrollability (Woods et al., 2017). This might be best addressed by adapting the experimental procedure and research question to accommodate the particular constraints inherent in online experimentation.

Study 4 approached the influence of external factors during somatosensory SA examination with a novel VR setup. As described above, typical study designs in the somatosensory realm involve an analogue setup susceptible for accompanying sensory input and uncontrolled temporal variations (~50ms) in stimulus onset (Kilteni et al., 2019; Kilteni et al., 2023). By employing a VR setup wherein participants moved their virtual, but not physical, hands to elicit a touch, we aimed to circumvent accompanying sensory input and enhance control over stimulus onset. However, the intended procedure of this two-phase comparison task (i.e., participants were instructed to move their hands to elicit a touch, triggering the first vibration, then keep their hands together during the second vibration) included a fixed stimulus order. To minimize the effect of a response bias, we applied the fixed stimulus order of the test and standard vibration to the control (i.e., passive) condition as well. Note that we observed in Study 2 that the effects of stimulus order did not account for differences in perception between self-initiated and externally generated stimuli.

The findings from Study 4 indicate a heightened level of task difficulty when comparing test and standard stimulus intensities. This difficulty may have led to increased uncertainty, potentially influencing attention orienting and thus SA effects. As previously mentioned, a force-matching task may reduce uncertainty in behavioral SA studies (Shergill et al., 2005). In this task, participants are exposed to an externally generated force, and are then instructed to replicate the intensity with a self-generated force. Note, however, that this task does not yet include an appropriate control condition. Studies employing this task usually compare the self-initiated matched forces with a condition where participants match forces with an external device (i.e., slider), in contrast to applying force (Kilteni, 2023; McNaughton et al., 2023). However, this slider condition still involves active movement during force-matching, potentially making it unsuitable as a control condition.

5.2.2 Measuring Sense of Agency

As outlined above, SoA encompasses multiple concepts (Gentsch, 2011; Kaiser et al., 2021; Moore, 2016; Grünbaum & Christensen, 2020). For Study 3, an examination of Linser and Goschke (2007)'s findings, we opted for the understanding that SoA describes the individual's experience of control over self-initiated actions and their consequences on external events (Jeannerod, 2003; Haggard, 2017). To assess SoA, we adopted the same measurement approach as Linser and Goschke (2007): a control judgment task. In experiment 1, participants were presented with a semantic prime followed by a free choice between two keys, each triggering the appearance of a colored circle. Subsequently, participants rated their perceived influence over the circle's color based on their keypress, using a rating scale ranging from 0% (no control) to 100% (complete control). In experiment 2, involving symbolic primes, participants were instructed to to press a key corresponding to a target stimulus (contingency between the target and effect stimulus was 75%/25%) and subsequently rate their SoA over the identity of the effect stimulus on a rating scale ranging from 0% to 100%. The aim of this task was to induce participants to perceive a level of control (i.e., SoA; via their key-presses) in determining the identity of the effect stimuli, even though they were objectively unrelated to the participant's keypresses. In our study, we observed that around 40% of the ratings indicated perceived control at 0% (i.e., no control) across all conditions. This relatively high prevalence of "no control" ratings raises concerns about the validity of the agency measure. Employing a 0–100% scale with labels only at each endpoint (i.e., 0%: no control, 100%: complete control) may lead to varied interpretations among participants, resulting in subjective and less comparable responses. In ambiguous contexts, participant's judgments of agency may be susceptible to heuristic responses, resorting to simplified strategies (i.e., congruence between prime and effect stimuli) to rate their perceived control (Dong et al., 2015, Reddy, 2022). Further, Dong et al. (2015) observed that for agency measurements, participants consistently favored a 6-point Likert scale with clear and meaningful labels. Future research could benefit from modifying the experimental setup to reduce uncertainty, both in the main task and in the agency measurements. This might be achieved by asking a clear, categorical questions (i.e., "who did it?") instead of the ambiguous ones (i.e., "how much control is felt?").

The studies outlined in this dissertation aimed to avoid methodological limitations by implementing technological and methodological advancements. In Study 1, we aimed to circumvent sequential sequential presentation of stimuli by presenting both test and standard stimulus simultaneously. Study 2 consisted of two experiments that were identical except for a modified stimulus order. In Study 3, we sought to circumvent post-hoc subject selection by adjusting prime visibility individually prior to the main experiment. Study 4 implemented VR to include controlled manipulation of sensory input. Further, this section demonstrated a number of observed caveats in the study of SA and SoA. Future research might benefit from the exhaustive description of possible confounds.

6. Conclusion and Outlook on Further Research

The aim of this dissertation involved an examination into the underlying mechanisms for our accurate interpretation of self-initiated sensory input. Classically, SA is explained through motor-based forward models: efference copies are created alongside planned movement, serving as cues to predict and attenuate the sensory consequences of this movement (Hughes et al., 2013a). However, it does not become apparent why this differentiated processing appears in the form of attenuation (Burin et al., 2017; Kiepe et al., 2021). Recent approaches proposed an explanation on the basis of a broader, attention-oriented predictive mechanism (Dogge et al., 2019a; Reznik & Mukamel, 2019).

The results of our studies are in line with the recent explanatory approaches, as they suggest adaptiveness in the perception of self-initiated stimulus intensities, modulated by external factors. Although we specifically examined the impact of temporality and identity prediction, our results suggest a multifactorial interplay of motor and non-motor predictive mechanisms on perceptual processing. In particular, we observed the possible influence of additional external factors, hence signal strength and accompanying sensory input. In conclusion, the results of our studies suggest a model that highlights the significance of self-initiated motor signals, but also emphasizes the modulating effects of external factors on both SA and SoA. Future research should further examine the influence of the described external factors. We propose that the influence of signal strength might best be explored by incorporating a diverse range of intensities into the paradigm. Further, the implementation of VR, as well as pre-learned, fixed onset delays (~50ms), may offer effective solutions for detaching accompanying sensory inputs.

Each study was preregistered and collected data from a substantial amount of participants. Raw data and R scripts of all studies are publicly available. Additionally, we intensively outlined possible confounds and limitations of the used measures. Overall, the work presented in this dissertation offers a valuable contribution, both theoretically and practically, towards unraveling the multifactorial interplay of predictive mechanisms in the perception of self-initiated sensory input.

Declarations

During the preparation of this dissertation, I used ChatGPT in order to improve readability. After using this tool, I reviewed and edited the content as needed and take full responsibility for the content of the dissertation.

7. References

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8. Appendix

8.1 Anteilserklärung

Kiepe, F., Kraus, N., & Hesselmann, G. (2023). Virtual occlusion effects on the perception of self-initiated visual stimuli. *Consciousness and cognition*, *107*, 103460.

- Entwicklung der Konzeption (mehrheitlich)
- Literaturrecherche (mehrheitlich)
- Versuchsdesign (mehrheitlich)
- Datenerhebung (in Teilen)
- Datenauswertung (mehrheitlich)
- Ergebnisdiskussion (mehrheitlich)
- Anfertigung der ersten Version des Manuskripts (mehrheitlich)
- Einreichung des Manuskripts und Korrespondenz (mehrheitlich)
- Überarbeitung des Manuskripts (mehrheitlich)

Kiepe, F., Kraus, N., & Hesselmann, G. (2024). Self-initiation enhances perceptual processing of auditory stimuli in an online study. *Attention, perception & psychophysics*, *86*(2), 587–601.

- Entwicklung der Konzeption (mehrheitlich)
- Literaturrecherche (mehrheitlich)
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Kiepe, F., & Hesselmann, G. (2024). Prime-induced illusion of control: The influence of unconscious priming on self-initiated actions and the role of regression to the mean. *Consciousness and cognition*, *121*, 103684.

- Entwicklung der Konzeption (mehrheitlich)
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Kiepe, F., & Hesselmann, G. (2024). Sensory attenuation of self-initiated tactile feedback is modulated by stimulus strength and temporal delay in a virtual reality environment [Manuscript submitted for publication].

- Entwicklung der Konzeption (mehrheitlich)
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- Überarbeitung des Manuskripts (mehrheitlich)

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Fabian Kiepe

Berlin, 20.05.2024

8.2 Eigenständigkeitserklärung

Eidesstattliche Erklärung nach § 7 Abs. 4 der Gemeinsamen Promotionsordnung zum Dr. rer. nat. des Fachbereichs Erziehungswissenschaft und Psychologie der Freien Universität Berlin vom 22. Mai 2023:

Hiermit erkläre ich,

- die vorliegende Dissertation selbstständig verfasst und ohne unerlaubte Hilfe angefertigt habe.
- dass ich die Stellen der Arbeit, die dem Wortlaut oder dem Sinn nach anderen Werken (dazu zählen auch Internetquellen und KI-basierte Tools) entnommen sind, unter Angabe der Quelle kenntlich gemacht habe.
- Alle Hilfsmittel, die verwendet wurden, habe ich angegeben. Die Dissertation ist in keinem früheren Promotionsverfahren angenommen oder abgelehnt worden.

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Fabian Kiepe

Berlin, 20.05.2024

8.3 Curriculum Vitae

Experience	**2020 – 2024**	Research Associate at Psychologische Hochschule Berlin Department for General and Biological Psychology, Prof. Guido Hesselmann
	Teaching	Seminar on Theories of Perception Seminar on Theories of Motivation and Emotion Seminar on Research Methodologies
	2016 - 2017	Student Assistant at the VU Vrije Universiteit Amsterdam
Education	**2015 – 2018**	M.Sc. in Clinical and Developmental Psychopathology, VU Vrije Universiteit Amsterdam
	2012 – 2015	B.Sc. in Psychology, Rijksuniversiteit Groningen
	2011	Abitur am Gymnasium Marianum Meppen
Lectures and Conferences		Tagung experimentell arbeitender Psychologen (TEAP; 2021 - 2024); Mind, Body & Brain (MBB; 2021 - 2024); European Conference on Visual perception (ECVP; 2022); Association of Scientific Studies of Consciousness (ASSC; 2022); Lange Nacht der Wissenschaft (LNDW; 2022)
Workshops		Berlin Oxford Summer School (2020); PTOS: A practical introduction to Bayesian Statistics (2023)

8.4. List of Publications

Kiepe, F., Kraus, N., & Hesselmann, G. (2021). Sensory Attenuation in the Auditory Modality as a Window Into Predictive Processing. *Frontiers in Human Neuroscience*, *15*. https://doi.org/10.3389/fnhum.2021.704668

Kiepe, F., Kraus, N., & Hesselmann, G. (2023). Virtual occlusion effects on the perception of self-initiated visual stimuli. *Consciousness and cognition*, *107*, 103460. https://doi.org/10.1016/j.concog.2022.103460

Kiepe, F., Kraus, N., & Hesselmann, G. (2024). Self-initiation enhances perceptual processing of auditory stimuli in an online study. *Attention, perception & psychophysics*, *86*(2), 587–601. https://doi.org/10.3758/s13414-023-02827-w

Kiepe, F., & Hesselmann, G. (2024). Prime-induced illusion of control: The influence of unconscious priming on self-initiated actions and the role of regression to the mean. *Consciousness and cognition*, *121*, 103684. Advance online publication. https://doi.org/10.1016/j.concog.2024.103684

Kiepe, F., & Hesselmann, G. (2024). Sensory attenuation of self-initiated tactile feedback is modulated by stimulus strength and temporal delay in a virtual reality environment [Manuscript submitted for publication].

8.5. Danksagung

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