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From Interoception to Control Over the Internal Body: The Ideomotor Hypothesis of Voluntary Interoaction

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When it comes to body movements in external space, people are experts in learning fine-grained voluntary control, for example, when manipulating tiny objects. Voluntarily controlling actions in the internal body (e.g., decreasing heart rate), however, is far more difficult and requires dedicated training, for example, in meditation or yoga. Not much is currently known about the learning mechanism underlying the acquisition of voluntary control over internal visceromotor actions (i.e., interoaction) or why it is so difficult compared to controlling our external somatomotor actions (i.e., exteroaction). We propose the *ideomotor hypothesis of voluntary interoaction* in this article, which asserts that voluntary exteroactions and interoactions are governed by the same general principle, namely, the anticipation of sensory feedback. We apply this hypothesis to two techniques that can be used to acquire voluntary control over interoactions, that is, autogenic training and biofeedback training. As the afferent signal we receive from interoaction (i.e., interoceptive signals from the internal body) is of lower sensory quality than the afferent signal that we receive from exteroaction (i.e., exteroceptive signals from the external environment), this hypothesis explains why learning to control interoactions is more difficult. We propose ways in which to test predictions from this hypothesis and show its theoretical value by comparing it to other frameworks in the literature. We hope that this work motivates future empirical studies directly examining voluntary interoaction and its clinical applications, such as autogenic and biofeedback training, and mind–body practices more generally.

Keywords: ideomotor theory, voluntary action control, interoception, biofeedback training, autogenic training

Early on in life, infants learn to voluntarily move various parts of their body through somatomotor control, for example, when grasping a pacifier. Ideomotor theory asserts that we gain control over these somatomotor movements by anticipating their sensory consequences (Greenwald, 1970; Hommel et al., 2001; Prinz, 1997). In comparison to the relative ease with which we acquire voluntary somatomotor control (i.e., exteroaction), it is very hard to acquire voluntary control over visceromotor (or autonomic) responses (i.e., interoaction), such as decreasing our heart rate or increasing our skin temperature. Such control does not develop naturally and requires dedicated, often indirect training, for example, through breathwork practices in yoga. Why voluntary control over interoactions is so much harder to acquire than over exteroactions is poorly understood. We argue in this article that ideomotor theory provides a unifying mechanistic account for the learning process underlying the acquisition of voluntary control in both cases. Specifically, applied to interoactions, ideomotor theory states that we anticipate interoceptive feedback (i.e., sensory signals from the internal body) to voluntarily control the response, similar to how we anticipate exteroceptive feedback (i.e., sensory signals from the external environment) for exteroactions. This hypothesis implies that differences in terms of the quality of—and sensory capacity for—the afferent signal can largely explain the ostensible differences between both types of control learning. To note, while we do not deny that other factors can contribute as well (e.g., it might also be the case that top–down control mechanisms are less developed, as we examine at the end of this article), this hypothesis focuses primarily on the nature of the afferent signal. To introduce this hypothesis, we begin by reviewing how ideomotor theory explains voluntary exteroaction, after which we present techniques for gaining voluntary control over interoaction (i.e., autogenic training and biofeedback training). Next, we examine how ideomotor

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theory can be applied to these techniques and examine an earlier proposal along these lines (Brener, 1974a, 1974b, 1981). Following this, we distill several novel predictions from this hypothesis that can be used to explain control learning over voluntary interoaction, based on paradigms that have been successful in explaining exteroaction from an ideomotor perspective. We then emphasize the theoretical value of this hypothesis by comparing its explanatory power to other frameworks and explanations in the literature while also acknowledging its current speculative nature. It is our hope that this somewhat provocative proposal can motivate novel empirical research into the natural occurring limits of voluntary control over interoactions and can boost the use of mind–body practices such as autogenic and biofeedback training, which have beneficial effects on mental and physical health.

To start on a conceptual note, we use the term interoaction in this article and differentiate it from exteroaction, which is the type of action that usually is investigated in the context of voluntary movement control (see Petzschner et al., 2017; Stephan et al., 2016, for a related use of these terms). *Exteroaction* refers to somatomotor action directed to the external environment, that is, body movements in space controlled by striated skeletal muscles. *Interoaction*, on the other hand, is visceromotor action directed to the internal body, that is, autonomic processes regulated by smooth muscles in and around the organs. This distinction mirrors the one between exteroception and interoception, which are the perception of signals stemming from the external environment and the internal body, respectively (see further). This mirroring is of theoretical relevance as ideomotor theory explicitly conceptualizes perception and action as two sides of the same coin (e.g., Greenwald, 1970; Hommel et al., 2001). An important difference between extero- and interoactions lies in the fact that interoactions in the autonomic nervous system are mostly self-regulated and, as a consequence, do not require people to voluntarily "act" on them. In the context of the current ideomotor hypothesis, however, it is useful to draw parallels between extero- and interoactions by viewing them both as "actions" that can be voluntary (i.e., with a component of conscious intent, intentional, top–down) and reflexive (i.e., without a component of conscious intent, autonomous, self-regulated, bottom–up). For example, when someone reaches their hand toward a hot cup of coffee on the desk in front of them, they perform a voluntary exteroaction, but when they pull their hand back if the cup is too hot, they perform a reflexive exteroaction. In the case of interoaction, an example of a voluntary interoaction is breathing slowly to activate the parasympathetic nervous system and place the internal body in a "rest-and-digest" mode while the actual digestion of the food is a reflexive interoaction in response to food being ingested. To note, voluntary interoaction directed immediately at the internal body should not be confused with voluntary exteroaction that mediates the resolution of internal needs (e.g., moving to a shaded area on a warm and sunny day; see Sennesh et al., 2022). That being said, exteroaction and interoaction are not fully independent. For example, voluntary interoaction (e.g., increasing heart rate) can be achieved by voluntary exteroaction (e.g., running). We discuss the theoretical implications of such somatomotor mediation on the voluntary nature of "direct" interoaction later on in this article.

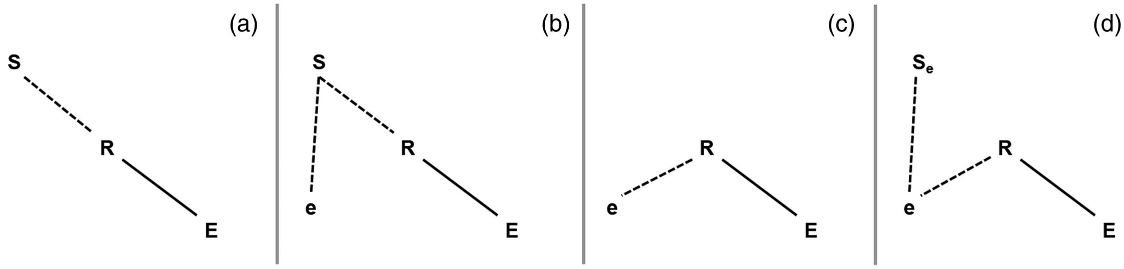
By focusing on voluntary control over interoaction, the current work carves out a new theoretical space at the intersection of voluntary control learning and functional interpretations of interoceptive processing. That is, previous theoretical work on voluntary actions has made impressive progress in understanding and explaining control over exteroaction but mostly neglected its application to interoaction. On the other hand, theoretical work on interoaction has focused mostly on the role of interoception in reflexive or self-regulated action but has not focused much on voluntary control. This hypothesis addresses this gap by providing a *learning account* of voluntary control over interoaction. This is an important topic of inquiry as (voluntary) learning is an important feature of life in general (i.e., adaptive for survival and well-being), and there are specific mental and health benefits associated with voluntary interoaction as we discuss later on. We start by examining ideomotor theory for exteroaction in more detail and selectively review relevant conceptual and empirical work in this area.

Ideomotor Theory

When it comes to exteroaction, the ideomotor principle has been very successful in explaining how people can acquire voluntary control (see Figure 1; Greenwald, 1970; Hommel et al., 2001; James, 1890; Pfister, 2019; von Holst & Mittelstaedt, 1950). Exteroactions are initiated by efferent somatomotor signals within the somatic nervous system, that is, the striate musculature, which is used to move our body and gives rise to exteroceptive and proprioceptive feedback (e.g., seeing and feeling the movement of an arm through visual and proprioceptive pathways). Ideomotor theory was formulated to explain how, when we do not have direct access to these motor signals, we can still gain voluntary control over them (James, 1890). The theory states that we instead learn to use afferent sensory consequences, or the action effects, to which we do have access (e.g., the visual and proprioceptive information resulting from an arm movement) to control the response. This learning process starts ontogenically with the random activation of motor responses, which leads to action-induced sensory consequences in the environment, that is, action effects. By exteroceptively and proprioceptively registering these action effects, we form (bidirectional) associations with the motor signal. Over time, we learn to control motor commands by anticipating these action effects in the form of a response image. As the response image contains both the relevant sensory and motor representations, its anticipation automatically initiates the motor response. Put differently, ideomotor theory states that we control our behavior by attempting to bring about the sensory consequences associated with the desired motor action. Moreover, the perception of a stimulus that resembles certain features of the action effect used to control the movement will activate the response image and its associated motor act, even when not necessarily resulting in an overt bodily movement. This view emphasizes a tight connection between perception and action (see also Hommel et al., 2001).

Within ideomotor theorizing, some important distinctions have been made in the past concerning the nature of action effects (see Pfister, 2019, for a recent overview), which are of relevance for contextualizing the ideomotor hypothesis of voluntary interoaction. To begin with, James (1890) distinguished "resident" from "remote" action effects, with the former referring to proprioceptive and kinesthetic changes produced by moving the body and the latter consisting of any other effect one may register. The distinction

Figure 1
The Ideomotor Principle



Note. (a) A stimulus (S) triggers a response (R), which leads to an action effect (E), that is, sensory feedback. (b) Over time, the stimulus (S) will activate the anticipation of the effect (e), which precedes the response (R). (c) The anticipated effect (e) becomes associated with the response (R) and allows us to control the response. (d) Observing a stimulus that resembles the effect of the response (S_e) can activate the response (R) by priming the anticipated effect (e). Adapted from "Sensory Feedback Mechanisms in Performance Control: With Special Reference to the Ideo-motor Mechanism.," by A. G. Greenwald, 1970, *Psychological Review*, *77*(2), p. 78 (https://doi.org/10.1037/h0028689). Copyright 1970 by the American Psychological Association.

between them lies in the sensory channel with which the action effect is registered, which is proprioceptive in the former and exteroceptive in the latter. In addition to this distinction between resident and remote, a distinction has been made between "intrinsic" and "extrinsic" action effects (Greenwald, 1970), which refers to the consistency with which the effect accompanies the action: Intrinsic action effects necessarily accompany an action, but extrinsic ones do not. For example, assuming one's arm is within the visual field, the visual perception of an arm moving is intrinsic but remote at the same time. As these intrinsic action effects always refer to the body in some way, some researchers have started referring to this distinction as "body-related" versus "environment-related" action effects (e.g., Pfister & Kunde, 2013), which is the terminology we will use in this article as well. A main theoretical assumption of ideomotor theory is that there is no functional difference in terms of these different action effects concerning their capacity to represent and control actions. We will exploit this assumption when formulating the ideomotor hypothesis of voluntary interoaction.

Even though both body- and environment-related action effect can, theoretically speaking, be used to control an action, empirical research on ideomotor theory in the past decades has mostly focused on environment-related effects (see also Pfister, 2019). In fact, whereas classical formulations of ideomotor theory focused primarily on body-related effects, more contemporary formulations and empirical tests of ideomotor theory refer almost exclusively to environment-related action effects (e.g., Greenwald, 1970; Kunde, 2001). This is likely because environment-related action effects are easier to place under stringent experimental control. There are two primary ways in which these environment-related action effects have been empirically investigated, that is, with action–effect acquisition (e.g., Elsner & Hommel, 2001, 2004) and action–effect compatibility (e.g., Kunde, 2001) paradigms. In action–effect acquisition paradigms, researchers investigate the process of ideomotor learning, with two distinct phases: an acquisition phase in which an (arbitrary) effect is repeatedly coupled to a certain action (e.g., left key press followed by a high tone and right key press followed by low tone) and a test phase in which this acquisition is probed. This is usually done with a reversal and nonreversal condition, where the action effect from the acquisition phase is used either as a cue to execute the action it was previously coupled with (e.g., high tone requires a left key press; "nonreversal") or the opposite one (high tone requires a right key press; "reversal"). Participants are faster in the nonreversal compared to the reversal condition, which is taken as evidence of bidirectional action–effect acquisition, a specific prediction for ideomotor theory (e.g., Elsner et al., 2002; Elsner & Hommel, 2001, 2004). In action–effect compatibility paradigms, a different approach is followed, which provides a stronger and more direct test of the ideomotor principle (e.g., Kunde, 2001): These paradigms test whether an action effect that appears only after the action has been executed affects the execution of the action. This is done by manipulating the features of the action effect to be compatible versus incompatible with features of the action (e.g., a right key press followed by a stimulus appearing predictably on the right vs. left side of the screen). Ideomotor theory predicts that participants are slower for actions that are followed by incompatible versus compatible action effects as the incompatible action effect interferes with the response image that is anticipated to control the action. Crucially, even though this effect only appears after the action has been executed, this prediction has been confirmed in empirical studies, providing strong and direct evidence for ideomotor theory (e.g., Chen & Proctor, 2013; Kunde, 2001).

To note, in the current context, we are not primarily interested in providing evidence for ideomotor theory in itself, but we aim to examine how it can be applied to interoactions. We will therefore focus on action–effect acquisition paradigms in the section where we provide our own empirical blueprint. Specifically, we will argue that the logic of such paradigms can be exploited with biofeedback training to investigate the role of action–effect learning for voluntary interoaction. In addition, it should be noted that apart from these action–effect acquisition and compatibility paradigms, researchers have also developed motor priming paradigms inspired by ideomotor theory, such as the automatic imitation paradigm (e.g., Brass et al., 2000, 2001). The logic behind these priming paradigms is to present participants with either the compatible or incompatible action effects of the exteroaction they are instructed to carry out and that the passive observation of this action effect will affect performance due to its conflict with the response image. For example, participants can perform a task where they lift their index finger or middle finger based on a certain cue. When cued to lift the index finger, participants can see either a compatible (index finger) or incompatible (middle finger) exteroaction on screen (e.g., Brass et al., 2000, 2001). Compared to a neutral trial (no movement), facilitation is observed for compatible trials and interference for incompatible trials. These facilitation and interference effects indicate that the response image is used to plan and execute the exteroaction. We will also discuss this priming logic and its relevance in the section where we provide the empirical blueprint.

As stated above, these empirical approaches have mostly focused on environment-related effects. Some researchers, however, have attempted to investigate body-related action effects using proprioceptive and tactile manipulations (e.g., Janczyk et al., 2009; Pfister & Kunde, 2013; Pfister et al., 2014; Wirth et al., 2016). For example, Pfister et al. (2014) used an action–effect compatibility paradigm with vibrotactile stimulation following a key press to probe the role of body-related action effects. Participants pressed a left or right key, and each key press resulted in a vibration either for the (compatible) key that was pressed or the other (incompatible) one. Results showed that participants were faster in the compatible compared to the incompatible condition, indicating that body-related action effects can actually be used to represent actions and that the response image is anticipated in a similar manner as environment-related ones. Further support for body-related action effects was provided in an action–effect compatibility study by Wirth et al. (2016). In a series of experiments with a device that provided compatible versus incompatible tactile stimulations to the arm of participants, these authors found a reliable effect on the planning and initiation of actions, particularly when these tactile action effects were task relevant. In sum, there exists evidence from several studies that both environment- and body-related action effects are anticipated during action control and are used to control and execute voluntary exteroactions (see also Ansorge, 2002; Chen & Proctor, 2013; Dignath et al., 2014; Földes et al., 2017; Wolfensteller & Ruge, 2011).

Given that ideomotor theory is, in principle, compatible with any motor response for which we have sensory feedback, however, most ideomotor theorists would presumably agree that this theory is applicable to interoaction as well. Interoactions are motor or endocrine responses within the autonomic nervous system (e.g., increasing or decreasing heart rate), which receives feedback from the visceral effectors via the mechanical, chemical, and thermal interoceptive system. This feedback is accessed through interoception, which consists of the sensing of signals from inside the body (e.g., Brener & Ring, 2016; Desmedt et al., 2023; Khalsa et al., 2018; Leder, 2018). Similar to sensory signals in the somatic nervous system, these interoceptive signals are used for communication within the autonomic nervous system. However, while both the somatic and autonomic systems are branches of the peripheral nervous system, which connects the central nervous system (i.e., brain and spinal cord) to the rest of the body, an important difference between them is that the autonomic one is mostly self-regulating. That is, the autonomic nervous system reflexively uses interoceptive information to maintain homeostasis, by regulating the function of smooth muscles (or cardiac striated muscle) inside the body (e.g., heart rate or digestion). As a result, the properties of interoceptive signals might differ significantly from those of exteroceptive experience (e.g., Leder, 2018), potentially making them ill-suited to be used as action effects that can represent and control actions.

In the following sections of this article, we systematically address this question. We directly build on the literature that we have reviewed in this section, which provides evidence that both environment- and body-related action effects are used for the control of exteroaction. This evidence has been taken as support for the theoretical assumption in ideomotor theory that both environment- and body-related action effects are functionally equivalent for action control (see Pfister, 2019). The current work moves the theoretical debate forward by investigating whether the same holds for all types of actions, including interoactions with body-related interoceptive action effects (see Figure 2). While this question is, in principle, compatible with original formulations of ideomotor theory, it goes beyond existing work, which has restricted its investigation to action effects in the service of exteroaction. Moreover, even though they might be functionally equivalent from an ideomotor perspective, tactile and proprioceptive feedback are, physiologically speaking, different from interoceptive feedback as we review further on. Indeed, proprioception has been placed more closely to exteroception and distinguished it from interoception, for example, by grouping exteroception and proprioception under term of "somatic sense" (Ceunen et al., 2016). While both proprioception and interoception are crucial for bodily awareness, they are associated with different aspects of human experience and function through different pathways that operate independently, suggesting specialized roles in body awareness and regulation (Borthwick & Brindle, 2023). For our purposes, interoception focuses on the internal (or viscerosensory) state of the body,while proprioception focuses on the body's position and movement in space—thereby also requiring exteroceptive inputs and being in the service of exteroaction. As such, it remains open until now whether existing research on body-related action effects would generalize to interoception, even if we neglect the difference between extero- and interoactions.

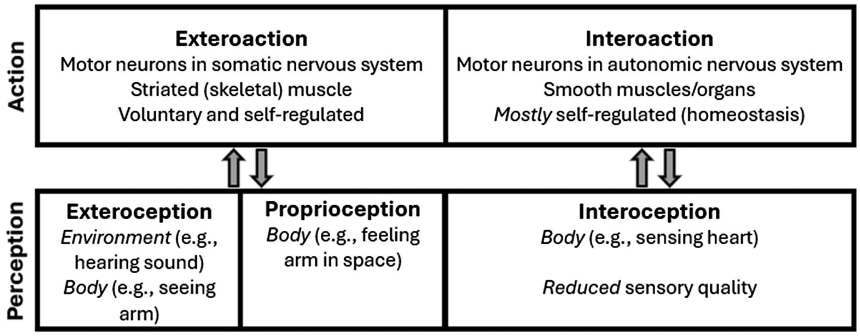
To sum up, a theoretical picture is emerging suggesting that ideomotor theory can, in principle, be applied to the learning of voluntarily control over interoactions. Moreover, while body-related action effects have been investigated in past ideomotor research, interoaction and interoceptive action effects are an area of inquiry that has not directly been addressed. Voluntary interoaction nonetheless provides an excellent opportunity for studying ideomotor learning, as for most people they are "virgin territory" when it comes to voluntary control (Brener, 1981) and, thus, can reveal how control is acquired without prior familiarity. In the following section, we will first examine existing techniques for controlling interoaction before applying ideomotor theory to them.

Existing Techniques to Control Interoaction

Despite the difficulty in voluntarily controlling interoactions, there have been many people throughout history that have achieved some measure of control over them through extensive training procedures, for example, in yoga and meditation (see also Benson et al., 1982, 1990; Bornemann et al., 2019; Green & Green, 1977; Kox et al., 2014; Kozhevnikov et al., 2013). A famous

Figure 2

Exteroactions, Interoaction, and Their Action Effects



Note. Whereas exteroactions are initiated by motor neurons in the somatic nervous system, which controls striated (skeletal) muscle, interoactions are initiated by motor neurons in the autonomic nervous system, which controls smooth muscles and organs. Exteroactions occur both voluntarily and self-regulated, but interoactions are mostly governed in a self-regulated way. Moreover, whereas exteroactions result most directly in exteroceptive and proprioceptive feedback, interoaction leads to interoceptive feedback, which has a comparatively reduced sensory quality. As we examine in this article, this difference can explain the difficulty for learning voluntary interoaction and might be mitigated by calibrating the interoceptive feedback from interoactions with an exteroceptive biofeedback stimulus. We do not discuss here the potential use of interoceptive feedback for exteroaction (but see e.g., Eder, 2023).

example is Swami Rama, an advanced yoga practitioner that participated in a series of experiments several decades ago to determine the degree to which he could voluntarily control specific interoactions (Green & Green, 1977). Among other feats, it was found that he could lower his heart rate at will (about 20 heartbeats lower within 1 min) and that he could control the temperature in his hand in a very precise localized manner (up to an 11°F, or 6°C, difference for two adjoining places on his hand). These experiments should of course be replicated, but current research on expert practitioners of voluntary control over interoaction suggests that precise control is indeed possible. For example, several experiments with Wim Hof, often referred to as the "ice man" for his extraordinary ability to thermoregulate his body, show that high levels of voluntary control can be achieved through extensive training (e.g., Muzik et al., 2018).

While these are clearly exceptional and unique individuals—we discuss below the possibility that they were born with traits that deviate from the general population—there exist systematic methods for learning voluntary control over interoaction that are in essence available to any healthy individual. One such technique is autogenic training, which is devoid of the spiritual connotations sometimes present in yoga and meditation contexts. Autogenic training is an auto-suggestive meditation technique in which a mental image of the (interoceptive) consequences related to relaxation are used to induce such relaxation (Kanji, 1997; Schultz & Luthe, 1959). The interoceptive consequences of relaxation are captured in six standard exercises. For example, a reduced heart rate is aimed at by the repetition of the sentence "My heartbeat feels calm and regular," and increases in skin temperature are aimed at by the repetition of the sentence "My [right arm] is warm."

Ever since its conception, researchers have attempted to characterize both the clinical (e.g., self-reported stress or anxiety) and physiological (e.g., blood pressure and skin temperature) outcomes of autogenic training (e.g., Linden, 1994). At the clinical level, autogenic training has mostly been used to treat stress- and anxiety-related illness, for which medium-sized positive effects have been found (Stetter & Kupper, 2002). In the current context, however, we are mostly interested in the physiological outcomes. Generally, it has been suggested that autogenic training works by promoting a low-arousal parasympathetic nervous system response, for which increases in heart rate variability have been used as a correlate. However, physiological measurements have not provided a coherent picture of autogenic training outcomes (Kanji et al., 2006b). Whereas activation of the parasympathetic nervous system has been observed after autogenic training, as indexed by changes in heart rate variability (e.g., Mishima et al., 1999; Mitani et al., 2006), this is not always the case (e.g., Lim & Kim, 2014). More specific physiological effects have also been reported, though not consistently (see Stetter & Kupper, 2002). For example, Tebēcis et al. (1976) found that skin temperature increases following autogenic training. On the other hand, Shapiro and Lehrer (1980) found that even though participants self-reported feelings of heaviness and warmth, there was no evidence for differences in heart rate or skin conductance. It is nonetheless assumed that this technique does not just instill a subjective feeling of relaxation but that it activates the relevant interoaction (Kanji, 1997). In sum, more empirical research is necessary to systematically map the parameters of change. Moreover, functional interpretations of how autogenic training can be used to control voluntary interoaction are currently lacking.

A different technique for gaining voluntary control over interoactions is biofeedback training, which has a rich tradition of dedicated empirical research (Glueck & Stroebel, 1975; Kimmel & Hill, 1960; Lehrer et al., 2000; P. M. Lehrer & Gevirtz, 2014; Wheat & Larkin, 2010). This technique facilitates the learning of voluntary interoactions by providing objective exteroceptive feedback contingent on the interoaction (e.g., a visual stimulus can be used that changes when heart rate decreases, providing easily detectable changes in the feedback). For example, a recent study has shown that participants can gain voluntary control over their arousal state using a (3-day) pupil-based biofeedback training—through the mechanistic link between locus coeruleus/noradrenergic activity, arousal, and pupil size—which also resulted in changes in heart rate (Meissner et al., 2024). Understanding the neural implementation underlying such biofeedback control is still an active domain of research, often framed within an operant conditioning framework (e.g., Yoshimoto et al., 2024; see also P. M. Lehrer & Gevirtz, 2014).

However, few exceptions aside, theoretical questions concerning the functional mechanism underlying voluntary control learning with biofeedback training have also been neglected, and it has so far not been clarified why the provision of exteroceptive biofeedback aids the learning of interoaction. Brener (1974b), who developed an ideomotor model of biofeedback learning that we examine in the next section, argued to move beyond the operant conditioning approaches that were in vogue to explain biofeedback training during its emergence. Specifically, he critiqued that operant conditioning assumes that an operant, which can be defined as "a response that is systematically influenced by its programmed consequence (reinforcing stimulus)" (Brener, 1974b, p. 337), drives the learning process. Brener (1974b) rightfully pointed out that it is problematic that learning is explained in terms of its effect (or "programmed consequence") and is assumed to occur to achieve goals. This explanation is teleological and does not provide the mechanism through which learning might be achieved. He argued that instead of assuming that the reinforcing stimulus is the final cause of behavior, a mechanism is necessary through which this event drives changes in behavior. In other words, a critical step needs to be included through which the effect that one wants to bring about (e.g., decreasing heart rate) can become an antecedent for voluntary behavior. A similar critique had been raised against associative learning theory in the context of exteroactions (e.g., the issue of backward causation, see Elsner & Hommel, 2004). As we will see in the next section, this mechanism is provided by ideomotor theory, which postulates that these previous action effects can acquire antecedent properties through ideomotor association, after which a response image can be used to control the action (e.g., Greenwald, 1970; von Holst & Mittelstaedt, 1950).

To sum up, both autogenic training and biofeedback training provide techniques for the acquisition of voluntary control over interoaction. However, theoretical questions concerning the cognitive mechanism underlying these techniques have mostly been neglected. In what follows, we present the ideomotor hypothesis of voluntary interoaction in more detail, examine the relevant properties of interoceptive signals, and propose ways to test this hypothesis for both biofeedback and autogenic training procedures.

The Ideomotor Hypothesis of Voluntary Interoaction

Simply put, the ideomotor hypothesis of voluntary interoaction states that, to learn to control an interoaction, people need to acquire bidirectional associations between the interoaction and its interoceptive feedback in the form of an (interoceptive) action effect. Once this association has been learned, an interoaction can be voluntarily controlled by anticipating its interoceptive action effect, in the form of a response image. That is, directing attention to the response image activates the relevant interoaction. For example, to increase one's skin temperature, one can focus attention on the mental image of a warm feeling in the limbs. This ideomotor hypothesis of voluntary control is a learning account, insofar that it can explain how voluntary control emerges in a situation where such control previously did not exist, which is often the case for interoactions.

To unpack the ideomotor hypothesis in more detail, we here examine and build on a previous theoretical model that has applied the ideomotor principle to biofeedback training (Brener, 1974a, 1974b, 1981). This model described biofeedback training as a process in five steps, mirroring the ideomotor model for exteroaction. First, to start the learning process, a response needs to be elicited in an involuntary reflexive fashion. Second, a response image of the act is created, consisting of the afferent feedback consequent on the act (i.e., the action effect, reflected in the change in the biofeedback signal). Third, an interoceptive action effect, to which we have limited access, is calibrated in terms of the exteroceptive action effect that is provided through the biofeedback stimulus. Fourth, when the exteroceptive biofeedback stimulus is shown, it activates the neural circuit that stores the response image. Last, the activation of the response image leads to an interoaction, which produces interoceptive feedback. This afferent interoceptive feedback is compared to the response image, and the interoaction is continued until the feedback and response image are in line. As such, this model applied ideomotor principles to explain how voluntary control can be acquired in biofeedback training.

Two aspects of Brener's (1974a, 1974b, 1981) model are worth highlighting here. The first is that the response needs to be elicited in an involuntary reflexive manner to start the learning process. Even though this is a central aspect for ideomotor theory, it is often obscured when studying exteroaction, where we usually have some measure of prior voluntary control (but see Piaget, 1954). Moreover, the involuntary, reflexive nature of the response means that it is unspecific at first. Voluntary control learning, then, is a process of response differentiation where we increase the specificity of control with the goal of reaching a maximally efficient motor act. This potential specificity, in turn, is a function of the discriminability of alterations in the feedback from the relevant effector. For example, when we move our arm, we can easily perceive the relevant alterations in exteroceptive and proprioceptive feedback. In contrast, when decreasing our heart rate, alterations in the feedback are hard to discriminate (e.g., a vague sensation in the chest). As such, in this model, there will always remain differences in the specificity between extero- and interoactions, perhaps conditional on individual differences in interoceptive accuracy, the ability to detect internal bodily signals (Desmedt et al., 2023).

A second aspect in the learning of voluntary control over interoaction, specific for biofeedback training, is the process of calibration. This is proposed as the process through which we can achieve response differentiation for interoactions (Brener, 1974a, 1974b, 1981). Brener (1981) emphasized that voluntary control learning is possible as long as we are able to label the afferent feedback produced by the response and classify it in terms of its environmental consequences (i.e., exteroceptive action effects). However, as interoceptive feedback does not produce environmental consequences that are available to exteroception, the action cannot be classified in such terms. The exteroceptive feedback stimuli used in biofeedback training, then, can function as external calibrating referents through which the interoceptive consequences are labeled in early stages of learning. In other words, Brener (1974a, 1974b, 1981) assumed that such a calibrating referent is always necessary when learning to comply with instructions to execute any novel interoaction.

On this point, the current hypothesis diverges, as we assume that ideomotor learning for voluntary interoaction can take place without a calibrating biofeedback stimulus as well, as is the case in autogenic training. Viewed through an ideomotor lens, autogenic training consists of a learning process aimed at the formation of an interoceptive response image. This learning process can be of course challenging in the absence of an exteroceptive calibrating stimulus, given the nature of this signal, as we discuss in more detail below. We predict, however, that once this response image is formed, its anticipation can be used to control the interoaction, and a biofeedback stimulus is not a necessary condition for this process to occur.

In sum, the ideomotor hypothesis proposes a central role for the quality of the feedback signal, which is impoverished in the context of interoactions. Brener's (1974a, 1974b, 1981) model stated that the interoceptive consequences of the interoaction are calibrated in terms of the biofeedback signal, which is used to create an (exteroceptive) response image. However, predictions from this model were never explicitly tested, and this model did not cover whether ideomotor theory applies to interoaction when only interoceptive feedback is available. Moreover, it should be noted that the ideomotor principle currently is not part of any theoretical discussions on the topic of voluntary control over interoactions. In the next section, we examine the nature of interoception and analyze in more detail how ideomotor theory could be applied, even in the absence of a calibrating biofeedback stimulus. Following this, we examine several ways in which such an ideomotor hypothesis could be empirically tested, inspired by such research in the domain of exteroaction.

Interoceptive Action Effects

Researchers of the human mind have become increasingly interested in the role of interoception in cognition in the past years (Allen & Friston, 2018; Berntson & Khalsa, 2021; Critchley & Garfinkel, 2018; Kunzendorf et al., 2019), but its link with voluntary interoactions has been underexplored. For our purposes, it is mostly important to determine whether interoception has a high enough resolution to detect systematic changes in the feedback signal resulting from a voluntary interoaction. At the phenomenological or experiential level, it has been argued that interoception is experienced as inaccessible, indistinct, and intermittent (Leder, 1990, 2018). Inaccessibility refers to the fact that large areas of the visceral body are insensate or unavailable to direct experience (e.g., the alveoli of the lung) or have a lower resolution compared to exteroception. Second, interoception is indistinct or spatially ambiguous, with no precise localization of events, and processes taking place in one organ can experientially radiate to different regions. In referred pain, for example, aching in the left arm may occur during a heart attack. Finally, we also experience spatiotemporal discontinuity for interoception, meaning that we only experience it intermittently and that visceral interoception reaches awareness mostly at times of demand (e.g., when we are hungry). Based on these features, it might actually be the case that conscious interoceptive experience relies more heavily on prior beliefs than the actual perception of the bottom–up signal, for which there is some evidence (e.g., Legrand et al., 2022; Ring & Brener, 2018).

As a consequence of this reduced sensory quality, consciously experiencing causal relationships between interoactions and their interoceptive feedback becomes uncertain. However, this is not necessarily problematic from an ideomotor perspective as there is no evidence that conscious awareness of such causality is actually a prerequisite for ideomotor learning (e.g., Elsner & Hommel, 2001, 2004). This becomes evident from research with infant participants, in which simple action–effect associations can already be built up and retrieved, for example, when coupling suckling a pacifier to visual and auditory feedback (e.g., Elsner, 2007; Hauf & Aschersleben, 2008; Paulus et al., 2012; Rochat & Striano, 1999; Siqueland & DeLucia, 1969). Such findings speak against the necessity of consciously experiencing the causal link between the action and its action effect, indicating that interoception might be used as an action effect for the control of interoaction.

That being said, for a signal to become a reliable action effect that can be used in the initiation and control of action, it should be accessible to the brain in a way that can be used for action–effect acquisition, even when these effects or their relationship to certain actions do not reach the level of conscious awareness. Brener (1977) summarized several aspects of the visceral afferent system to motivate that interoceptive signals can be accessed in such terms. For example, early physiological work on the visceral afferent system concluded that, both structurally and functionally, it does not differ in important ways from the exteroceptive or proprioceptive sensory systems in this light (e.g., Chernigovskiy, 1967; Newman, 1974), and both interoceptive and exteroceptive (and proprioceptive) signals can reach the higher nervous centers through specific afferent pathways. Moreover, there is evidence that interoceptive stimuli can be used to condition somatic or visceral responses, which implies that interoceptive afferents are fully involved in the intersensory processes of associative learning (e.g., Bykov, 1957), even if they might be of lower sensory resolution than exteroceptive ones. To note, this work speaks solely of the structure and function of the physiological pathways and is still compatible with a general lack of conscious awareness of these signals. Together with the theoretical assumption introduced in the previous section, that from an ideomotor perspective, the only factor is whether there is sufficient quantity and quality of a signal for learning to occur, independent of the identity of the channel (i.e., whether it is extero-, proprio-, or interoceptive) or conscious awareness; we would argue that interoception is at least a viable candidate to be used as an action effect.

Finally, it should be noted that interoceptive signals can reach the brain through pathways other than those consisting solely of interoceptive mechanoreceptors (Desmedt et al., 2023; Engelen et al., 2023; Khalsa et al., 2009). Desmedt et al. (2023) recently reviewed several existing definitions of interoception and found that there are conceptual discrepancies in the literature, as some definitions rely purely on homeostatic pathways (i.e., interoceptive mechanoreceptors; e.g., Craig, 2002; Khalsa et al., 2018) while others allow for nonhomeostatic pathways of interoception as well (e.g., Brener & Ring, 2016). For our purposes, the existence of these nonhomeostatic pathways through which interoceptive signals can be perceived are of particular interest. For example, for the cardiovascular system, there are three physiological pathways to process interoceptive information (Park & Blanke, 2019), but only two of them are purely homeostatic: the pathway that originates in the baroreceptors of the heart (Garfinkel & Critchley, 2016) and the one that involves cardiac efferent neurons at the heart wall (Tahsili-Fahadan & Geocadin, 2017). The third one, however, is exteroceptive in nature, as it involves Aβ large-diameter mechanosensitive sensory fibers (Park & Blanke, 2019). From such observations, interoception has been defined as including all the top–down and bottom–up processes through which signals from the internal body (i.e., originating from below the skin) are sensed and interpreted (Desmedt et al., 2023). Viewed this way, interoception includes, apart from the classical homeostatic pathways, afferent information that arises below the skin and travels via pathways that are usually considered to support exteroception (see also Berntson & Khalsa, 2021; Brener & Ring, 2016; Khalsa et al., 2009; Knapp-Kline et al., 2021). This insight is especially relevant for our hypothesis, which focuses on how voluntary control learning of interoaction can take place in the absence of a (calibrating, exteroceptive) biofeedback signal, as for example, in autogenic training. That is, at the start of the training, interoceptive action effects might be formed by (initially) relying on naturally existing exteroceptive pathways for interoceptive signals as well, for purposes of calibration. Following this, through a process of response specification, this reliance on exteroceptive pathways might fall away.

Taking all this into consideration, we argue that there is no a priori reason to assume that interoception cannot be used for control learning over interoaction as an action effect can, in principle, be used to form an interoceptive response image that controls the interoaction. At this stage, it remains an empirical question. In the next section, we propose several empirical research lines that are informed by this hypothesis and provide experimental blueprints, inspired by previous findings from the exteroaction literature.

Testing Ideomotor Predictions for Voluntary Interoaction

The ideomotor hypothesis of voluntary interoaction generates predictions about the learning mechanism underlying the acquisition of control that can be tested empirically. Crucially, even though it has been theorized in the past that ideomotor theory applies to voluntary control learning over interoaction in the context of biofeedback training (Brener, 1974a, 1974b, 1981), this model has never been empirically tested. Indeed, even in the domain of exteroaction, which is more amenable to experimental control, empirical tests of ideomotor theory postdate this model by several decades (e.g., Elsner & Hommel, 2001, 2004; Kunde, 2001). As a first step then, it should be tested whether ideomotor theory holds for voluntary interoaction using biofeedback training, before investigating it for purely interoceptive feedback (e.g., for autogenic training). A key prediction of ideomotor theory is that attending to the action effect activates the motor response it is associated with, especially in the context of a relevant goal. Compared to exteroactions, however, it is hard to instruct participants to passively attend to the (interoceptive) action effect of an interoaction in a well-controlled manner as the interoceptive feedback is internally generated (i.e., the experimenter does not have direct access to this action effect). This aspect can be circumvented with a biofeedback procedure, where the experimenter has access to the sensory action effect after the training (i.e., the biofeedback stimulus).

For exteroactions, this ideomotor prediction has been tested extensively using action–effect induction paradigms (e.g., Elsner & Hommel, 2001, 2004), which we have described above. To shortly recapture the structure of such paradigms, participants first go through an acquisition phase, during which a certain action is paired with a random action effect (e.g., left key press—high tone; right key press—low tone). During the following test phase, this action effect is used as the cue to inform participants which of the two actions they need to perform. In the nonreversal condition, the action effect that was previously associated with the action is used as cue (e.g., high tone—left key press), but in the reversal condition, the opposite action needs to be performed (e.g., high tone—right key press). Participants are slower in the reversal condition, indicating that a bidirectional association between the action and the action effect was learned and that the response image is used to control the action. We propose here that a similar "induction" procedure can be applied to voluntary control over interoactions.

To give an example of what such a study might look like conceptually, we can imagine a situation in which a visual biofeedback stimulus is presented that changes its color contingent on alterations in skin temperature. We use the example of skin temperature as this remains close to the physiological responses targeted in autogenic training (see below). During training, participants can be taught to increase and decrease their skin temperature by controlling a biofeedback stimulus, which changes its color contingently on these alteration in the skin temperature of the participant (e.g., turning yellow vs. blue, respectively). Participants should receive such training until they can reliably change their skin temperature in the desired direction. It is relatively straightforward, after training, to use this biofeedback stimulus to test for action–effect acquisition for interoactions with a similar nonreversal and reversal condition as has been used for exteroactions. In the nonreversal condition, participants would again be instructed to increase or decrease skin temperature while passively observing the color stimulus that was used during training (i.e., yellow—increase; blue—decrease). In the reversal condition, participants would be given the same instruction but while passively viewing the incompatible stimulus color (i.e., yellow—decrease; blue—increase). If the biofeedback stimulus is indeed used to create a response image through a calibration process (Brener, 1974a, 1974b, 1981), participants should be more effective in controlling skin temperature in the nonreversal condition.

As a caveat, the experimental design conceptualized above does differ somewhat from the classical action–effect induction paradigms (e.g., Elsner & Hommel, 2001, 2004) due to the ordinarily self-regulated and continuous nature of the intended response: First, during biofeedback training (i.e., the acquisition phase), participants are required to use the action effect in a more deliberate manner to modulate a continuous response over which they otherwise have no control as interoactions are self-regulated in their natural state. In the classical action–effect induction paradigm, in contrast, the action effect simply appears after the action has been correctly executed. It is possible that this more deliberate use of the action effect results in stronger action–effect acquisition, but this is an open question. Second, during the test phase, the biofeedback stimulus would not just be used as a cue but would remain present while participants attempt to modulate a continuous response. That is, the targeted response (e.g., decreasing or increasing skin temperature) is temporally extended, and the action effect has to stay present throughout the test to investigate its effect. In the sense that this action–effect stimulus is present during action execution, rather than merely used as cue, the logic during the test phase is somewhat more akin to the one used in priming studies inspired by ideomotor theory (e.g., Brass et al., 2000, 2001). Finally, it is potentially not necessary to explicitly instruct participants to produce the interoaction when the stimulus representing the action effect is presented. That is, it might suffice to present this action effect and investigate whether it controls the interoaction by observing whether the interoaction is modulated in the expected direction. The situation is different for exteroaction because perceiving action effects (e.g., social priming) will not automatically induce an overt exteroaction, as we often have several different exteroactive goals activated and inhibit irrelevant ones. This might not be the case for interoaction, as in natural settings, there are no goals associated with interoaction, and the response might be more automatically modulated after action–effect acquisition. This remains an empirical question at this point. Keeping these caveats in mind then, the study design proposed here for biofeedback training is logically similar to classical action–effect acquisition paradigms. As such, if ideomotor theory indeed holds for interoactions, we would expect a similar modulation of the action and, thus, evidence for the action–effect acquisition.

Second, once this action–effect acquisition has been established for biofeedback training, it should be investigated whether a purely internally generated interoceptive action effect can be used. Autogenic training provides such a technique, but as we have reviewed above, its mechanism of operation is currently not well understood. To reiterate, in autogenic training, practitioners focus attention on a mental image of the interoceptive consequences of an interoaction related relaxation, for example, a feeling a warmth in their limbs to increase skin temperature (Kanji, 1997). The actual evidence on whether this training results in relevant and direct physiological changes is currently inconsistent (e.g., Ernst & Kanji, 2000; Kanji et al., 2006a, 2006b; Stetter & Kupper, 2002). Given this inconsistency, it is possible that autogenic training simply operates through a nonspecific general relaxation response that mostly affects self-report measure (Benson et al., 1974; Keefe et al., 1980; but see Mishima et al., 1999). However, as this practice places a central role on the anticipation of interoceptive consequences, it can be readily understood in terms of ideomotor learning. To provide clarity in this respect and to determine whether autogenic training can be explained through an ideomotor mechanism, a similar study can be set up as the proposed biofeedback study described above. Participants would go through a training phase, where they are instructed to acquire control over a relevant interoaction. The instruction sentences can be adapted so that participants are trained both in the original relaxation response (e.g., "my arm feels warm") and the opposite one (e.g., "my arm feels cold"). If an ideomotor mechanism can account for the processes underlying autogenic training rather than a general relaxation response, then the changes should be specific for the actual interoaction that is being targeted, and both directions of control should be equally achievable. That is, demonstrating that such changes in physiological parameters can be learned in specific ways would be predicted by an ideomotor learning mechanism that is based on the use of an action effect (e.g., a feeling of warmth or of cold).

Finally, this hypothesis raises the question how effectively interoceptive compared to exteroceptive feedback can be used in voluntary control learning over interoactions, as is the case for autogenic training and biofeedback training, respectively, or in other words, whether body-related or environment-related action effects would be more effective to acquire voluntary control over interoaction. When we introduced ideomotor theory, we reviewed several studies that provided evidence for the existence of body-related action effects (e.g., Janczyk et al., 2009; Pfister & Kunde, 2013; Wirth et al., 2016). Whereas these studies have provided evidence that actions can be represented in terms of body-related action effects, they also revealed that such effects could be less strong than environment-related ones (e.g., Pfister & Kunde, 2013) or only emerge under specific conditions (e.g., Wirth et al., 2016). This raises the question under which circumstances action effects might be represented primarily in reference to the body or in reference to the environment (see also Pfister, 2019). For example, theoretical models assume that the weighting of different feature codes—which could be environment- or body-related—depends in part on the current intentions of the agent (e.g., Hommel et al., 2001; Memelink & Hommel, 2013). Along these lines, it has been argued that environment-related effects would mostly be used to represent and control higher level and more abstract decision making while body-related effects would be primarily involved in more concrete action initiation (Hofmann et al., 2009; Prinz, 1987; see also James, 1890). From this, one might assume that body-related action effects would be preferentially used in the context of the studies described above, which represent simple and concrete action initiations, and that autogenic training, which relies on body-related action effects, thus would provide a more effective means to acquire voluntary control over interoaction.

That being said, this discussion is further complicated in the context of interoaction. We introduced the ideomotor hypothesis by stating that interoceptive signals are generally less accessible than exteroceptive ones, which makes them harder to use for control learning. When exteroceptive feedback is used, on the other hand, as for example, in biofeedback training, the interoceptive signals are presented exteroceptively. This provides a precise exteroceptive feedback signal in a modality with which we are generally more familiar when learning to control our behavior, as we voluntarily control exteroactions during most of our waking hours. However, this exteroceptive feedback signal is indirect and divorced from the body (e.g., a visual stimulus compared to the actual feeling warmth), meaning that mapping the exteroceptive information to the body has to be learned. When interoceptive feedback is used, as in autogenic training, a weak association between the interoaction and its interoceptive feedback might already exist (e.g., the feeling of a racing heart and the interoaction of increasing heart rate), making it easy to form an action effect. Moreover, in biofeedback training, participants have to switch attention between external (biofeedback signal) and internal (interoaction and/or interoception) information, which results in a switch cost (Gresch et al., 2024; Hautekiet et al., 2023; Verschooren et al., 2020; Verschooren, Liefooghe, et al., 2019; Verschooren, Schindler, et al., 2019). Such bottlenecks have also been reported for simultaneous interoceptive and exteroceptive processing, which compete for our limited attentional bandwidth (Ren et al., 2022). In other words, it is possible that having to attend toward external signals makes it actually more difficult to develop awareness and control of internal signals. In autogenic training, in contrast, all the necessary information is internally generated, so attention can be completely focused on strengthening this action effect.

Taken together, there are arguments for and against body- and environment-related action effects being more effective for voluntary interoaction. Empirically, this question has not been conclusively tackled, but it can be straightforwardly investigated by comparing biofeedback and autogenic training when an identical protocol is used for both (see also Kanji et al., 2006b). Discovering the circumstances under which these techniques work best would be an interesting avenue for future research, which can be guided by ideomotor theorizing.

In sum, the ideomotor hypothesis proposed here generates predictions and further open questions that can guide future research. In the next section, we highlight the theoretical value of our hypothesis by comparing its explanatory power to other theoretical accounts in the literature, after which we focus on the applied value of our hypothesis.

Ideomotor Control of Interoaction in the Context of Predictive Coding

To better highlight the added theoretical value of the ideomotor hypothesis of voluntary interoaction, it is useful to position it in relationship to other theoretical work in the literature. As we stated in the introduction, this hypothesis occupies a novel theoretical space on the intersection between voluntary control learning of action and the functional interpretation of interoception. We have thoroughly examined ideomotor theory as an explanation of voluntary action, which revealed that it was primarily focused on exteroaction in the past. That is, our contribution to theoretical work on voluntary action control is that we propose explicitly to expand this previous work on exteroaction to the domain of interoaction. We have not in detail discussed theoretical work on the functional interpretation of interoception for interoaction, however. In this section, we examine how the ideomotor hypothesis of voluntary interoaction relates to that work.

Previous theoretical work on interoception has mainly focused on how it is used to maintain bodily homeostasis in health and disease (see Brewer et al., 2021, for a recent review). A prominent theoretical framework explaining how interoception supports homeostasis is (interoceptive) active inference (Allen et al., 2022; Pezzulo et al., 2018; Seth, 2013; Seth et al., 2011; Seth & Friston, 2016; Smith et al., 2017; Tschantz et al., 2020, 2022). The primary focus of interoceptive active interference is explaining how the body maintains homeostasis in a reflexive way as this is its usual mode of operation. Interoceptive active inference explains this process from a predictive coding perspective (Seth, 2013). Predictive coding accounts, in general, attempt to explain how the brain makes sense of the world outside of it, which not only includes the external environment (Clark, 2013) but also the body itself. The brain does not have direct access to these realities but only to sensory input that is compatible to different degrees with various generative models or states of the external environment and the body. According to predictive coding accounts, the brain makes sense of this confusion by comparing the actual incoming sensory bottom–up data to the predictions from these underlying generative models. In other words, bottom–up signals are not just passively registered as they come in, but the brain is a predictive system that compares these bottom–up signals with hierarchical, top–down predictive signals. The goal of such a predictive system is to minimize prediction errors between the top–down predictions and bottom–up signals. Applied to interoceptive bottom–up signals, this model explains the regulation of homeostasis by assuming that internal (generative) models of interoceptive signals are constructed, which predict the current state of the internal body (Seth, 2013; Tschantz et al., 2022). When interoceptive prediction errors occur between these internal models and interoceptive input, autonomic reflexes are activated to return to homeostasis (Gu et al., 2013).

In such an interoceptive active inference model, no voluntary input is required, and these models are also not geared specifically toward explaining voluntary control. Ideomotor theory provides more explanatory power here by emphasizing that, after an association has been learned between an action and its action effect, the anticipation of this action effect can be used for voluntarily controlling it. It should nonetheless be noted that ideomotor theory, which proposes that a top–down anticipation (or prediction) is used to control a response, is compatible with predictive coding in general and interoceptive inference specifically. In fact, the predictive coding framework can be seen as a broader interpretation of ideomotor theory, which predates it (James, 1890; von Holst & Mittelstaedt, 1950). The difference between both frameworks currently lies in what they are trying explain, that is, reflexive interoaction for interoceptive inference and voluntary interoaction for ideomotor theory. In future work, attempts should be made to integrate both approaches within the same framework.

Moreover, at the experimental level, it is challenging to provide clear evidence or even an idealized experiment for or against one theory over the other. It has been argued that predictive coding approaches, of which active inference is an instantiation, can be formulated in ways that are compatible with almost any empirical finding, which makes it hard to falsify them or empirically adjudicate them against other accounts (e.g., Bowman et al., 2023; Hodson et al., 2024; Miłkowski & Litwin, 2022). Of note, similar arguments have been made concerning ideomotor theory: Specifically, it has been argued that ideomotor approaches should be seen as broad theoretical frameworks without clear predictions for empirical tests (e.g., Pfister, 2019; see also Hommel et al., 2001). That is, negative findings in ideomotor experiments can always be explained by referring to different (body- or environment-related) action effects that were not explicitly tested, as ideomotor theory is compatible with any type of action effect. In that sense, ideomotor theory is also not easily falsifiable (see also Oriet et al., 2001).

That being said, Pfister (2019) has argued that ideomotor theory still contributes to our understanding of voluntary control as it provides inspiration for designing informative experiments that would not be conceived against the background of alternative frameworks, such as predictive coding. Indeed, ideomotor theory for exteroaction has been empirically very successful in the past decades (e.g., Elsner & Hommel, 2001; Kunde, 2001). We fully agree with this interpretation, and the current hypothesis and proposed blueprint for empirical research step firmly into that tradition. The empirical research proposed could only be formulated in a specific ideomotor context and is inspired directly by existing ideomotor research on exteroaction. In this light, it should be noted that this work is not about testing or proving ideomotor theory in itself, which would be beyond the scope of this article, but about using this theory to test specific predictions about voluntary control for interoaction. We would add that, specifically in comparison to predictive coding, ideomotor theory specifies what kinds of effects are used for motor control and the specific format of these signals.

In sum, while it is difficult to dissociate ideomotor theory from interoceptive active inference at the empirical level, it is still sensible to frame voluntary interoaction in an ideomotor framework. As ideomotor approaches have been successful in the domain of exteroaction, the ideomotor hypothesis proposed here can help stimulate research into this underexplored area of voluntary action control and guide the development of theoretically and practically interesting experiments, for which we provide a blueprint.

Clinical Applications

Investigating and pushing the boundaries of naturally occurring voluntary control over interoactions is not just of theoretical value, but it has several clinical applications as well. It has been argued, for example, in Damasio et al.'s (1991) somatic marker hypothesis, that interoceptive feedback plays a fundamental role in the formation and experience of emotions (see also James–Lange theory of emotion; Dewey, 1894). The somatic marker hypothesis states that our emotions result from the interpretation of our bodily responses to external (e.g., a threatening visual stimulus) and internal (e.g., an aversive thought) events (Damasio et al., 1991). Given this tight link between interoception and our emotional experience, interoception has been implicated in mental illness as well (e.g., Brewer et al., 2021; Khalsa et al., 2018). It follows that, if we are able to modulate this feedback (e.g., voluntarily inducing a steady and calm heartbeat), we can in principle get some control over our emotional state.

Regulating arousal is very challenging, and pharmacological agents often have to be used to achieve it, which can have negative side effects (see also Meissner et al., 2024). Techniques such as biofeedback training and, even more so, autogenic training provide safe and cost-efficient alternatives to such approaches. As we have discussed in the previous sections, there is evidence that autogenic and biofeedback training can relieve clinical symptoms of stress-related disorders (e.g., P. Lehrer et al., 2020; Lim & Kim, 2014; Pizzoli et al., 2021). Indeed, Kanji (1997) explicitly stated that the goal of autogenic training is to achieve emotional balance and control over the body's stress response. Similarly, in a seminal article on biofeedback training, Glueck and Stroebel (1975) argued that in our "hyper" Western culture, there is "too much emergency response too much of the time" (p. 319), from which biofeedback training can provide relief. In this sense, the techniques discussed here are closely related to yoga and meditation training. In yoga and meditation too, an increased heart rate variability are observed (e.g., Bernardi et al., 2001; Phongsuphap et al., 2008), which are often targeted by autogenic and biofeedback training. Among other things, these techniques have been shown to reduce mind wandering (e.g., Nashiro et al., 2022), which means attention is drawn less to potentially negative internal thoughts that play a role in psychopathology (see also Verschooren & Egner, 2023). Moreover, these techniques could provide targeted relief for other more specific medical conditions. One example is postural orthostatic tachycardia syndrome, a form of dysregulation of the autonomic nervous system (Benarroch, 2012). Postural orthostatic tachycardia syndrome is characterized by a large and irregular increase of heart rate when standing in an upright position, either sitting or standing. Interestingly, patients also often report coldness, pain, numbness, or tingling in the extremities. These latter symptoms are especially prominent when the underlying cause for postural orthostatic tachycardia syndrome is small fiber neuropathy or autonomic peripheral neuropathy, which consists of damage to the small fiber nerves, especially in the extremities (Freeman, 2005). Taken together, these symptoms, including the irregular increase in heart rate and unpleasant sensations within the extremities under the skin, can be targeted by voluntarily controlling the associated interoactions. The ideomotor hypothesis put forward here predicts that such patients could find relief by using the desired response image of the state they want their body to be in, for example, anticipating a lower heart rate or increased temperature in the extremities. That being said, given the inconsistent findings in the literature (Lim & Kim, 2014; Stetter & Kupper, 2002), these procedures for gaining control over the internal body need to be further developed and optimized. An enhanced theoretical understanding of the learning mechanism through which they are controlled is an important step forward in that regard.

To this point, the ideomotor hypothesis proposed here suggests ways to optimize the properties of the feedback signal used in control learning. For example, the notion of ideomotor compatibility entails that stimuli that resemble the sensory feedback of the response enable automatic response selection (Greenwald, 1972; Greenwald & Shulman, 1973; Maquestiaux et al., 2020). That is, ideomotor theory predicts that voluntary control learning should develop most efficiently for biofeedback signals that mimic the relevant interoceptive properties as closely as possible. For example, it might also be more effective to change the color temperature of a visual stimulus to facilitate ideomotor control over blood circulation, rather than working with an auditory stimulus, while the opposite might be found for controlling the heart rate, as these stimuli most closely resemble the actual feedback one receives from the respective interoaction (e.g., Greenwald, 1972). This assumption is speculative at this point, however. By investigating different kinds of interoceptive response images to be used for biofeedback learning, it will be possible to triangulate these most efficient properties. This way, ideomotor theory can guide the development of efficient techniques for the acquisition of voluntary interoaction that can be applied in the context of different pathologies.

Finally, our hypothesis can also shed light on the mechanism underlying neurofeedback training, which is a noninvasive brain-training technique that involves real-time monitoring and feedback of brain activity, typically using electroencephalography (Hammond, 2011; Marzbani et al., 2016; Sitaram et al., 2017, for a review). In this sense, it is a specific case of biofeedback training but one where the exact mechanism is even more opaque as we cannot directly sense our brain activity or voluntarily up- or downregulate it. Despite this lack of clear understanding (Marzbani et al., 2016), neurofeedback training has been used to optimize cognitive performance (Gruzelier, 2014) and to alleviate symptoms of various neurological disorders, such as attention deficit hyperactivity disorder (Arns et al., 2009), anxiety and depression (Lee et al., 2019), and autism spectrum disorder (Pineda et al., 2014). Ideomotor theory can straightforwardly explain neurofeedback training by positing that the specific brain activity (e.g., a certain frequency band) becomes associated with the feedback signal. This question could be tested with a similar approach as the one proposed above, which could lead to further developments of this application.

In general, on top of providing avenues for optimizing these techniques, we hope that this hypothesis and the empirical work it will generate can help make mind–body practices less esoteric and more acceptable to the broader public. Techniques such as autogenic training seem to be mostly underused but, at face value at least, can provide relief for a wide range of disorders of the body and the mind. The most important step forward will be to start testing these applications in a theoretically grounded way as this can inspire novel ways of optimizing them.

Final Caveats and Alternative Mechanisms

To begin with, our hypothesis attributes the lack of interoactive control primarily to an input issue (i.e., impoverished interoceptive feedback signals) as opposed to an output issue (i.e., a potential lack of dedicated voluntary control mechanisms for internal organs). In the case of exteroactions, the motor system contains dedicated and detailed mechanisms for fine-tuned control of, for example, hand movements, which is its primary function (Schieber, 2009). On the other hand, while some brain mechanisms seem to exist to control internal activity, they may be far less detailed and fine-tuned. Several biofeedback studies have been carried out in the scanner to uncover the neural mechanism underlying voluntary interoaction (Critchley et al., 2001, 2002, 2011; Jones et al., 2015; Quadt et al., 2022; Yoshimoto et al., 2024). In these studies, activation has been found in the left anterior cingulate and parietal cortex for intentional modulation of bodily arousal, in the insular cortex for the integration of interoceptive and exteroceptive information, and in the ventromedial cortex for the representation of the physiological state of the body. The anterior insula specifically has been shown to be active in all interoceptive signaling (Craig, 2009), including in autogenic (Schlamann et al., 2010) and biofeedback training (Critchley et al., 2001, 2002), and seems to be involved in increasing bodily awareness by switching attention from exteroceptive to interoceptive information processing (Menon & Uddin, 2010). Based on current available evidence, we expect that the anterior insular cortex, rostral cingulate zone, medial prefrontal cortex, and visual regions play a role in voluntary control of interoactions (Critchley et al., 2002; Krieghoff et al., 2011), but this needs to be confirmed in further studies. All in all, however, this neural mechanism is less fine-grained and dedicated than in the case of exteroactions. Thus, it is possible that even when highly detailed interoceptive feedback could be provided, an average human might still lack the ability to control internal organs. It is at this stage indeed an open question, and we acknowledge that it is somewhat speculative to state that our lack of interoactive ability primarily or solely stems from the lack of feedback sensitivity. That being said, it is interesting in this context to consider the case of neurofeedback, discussed in this article above. Under normal circumstances, we have no direct control to up- or downregulate our brain processes themselves, and there exist no dedicated neural mechanisms for this control. However, we can do so after receiving relevant feedback, which again emphasizes the crucial role that sensory feedback plays in the voluntary control of actions of any type as ideomotor theory would predict.

A second caveat we should note is that when investigating the acquisition of voluntary control learning over interoaction, it is important to consider "exteroactive mediation." Exteroactive mediation can be defined as any form of (constitutive) involvement of the somatomotor system during voluntary interoaction. For example, when instructed to lower the heart rate, people can use voluntary control over the breath to achieve the desired change (see also Brener, 1974b). As such, controlling for these effects is important when investigating direct voluntary interoactive control. At the same time, it should be noted that an initial lack of specificity is a general fact of control learning, and responses only become more differentiated over time (e.g., when learning a novel fine-tuned exteroaction), so in principle the presence of nonspecific processes during the learning phase do not pose an issue. In fact, the argument has been made in the past that such somatomotor mediation might ultimately be irrelevant (Brener, 1981), and the only question we as researchers should be interested in is whether participants can or cannot comply with the instruction to perform a certain interoaction, be it direct or indirect (e.g., by modulating respiration rate). The current ideomotor hypothesis of voluntary interoaction predicts, however, that interoaction without exteroactive mediation will become possible over time as the response image and its action effects are refined. To see how such specificity might evolve over time, several measures of exteroaction should be obtained while testing the ideomotor hypothesis of interoaction (e.g., collecting the measurement of respiration rate as well).

In a similar vein, one should consider the process of "cognitive/mental mediation," meaning that people might primarily change their thoughts and/or feelings which, as a secondary effect, then has an influence on internal bodily states. If this were indeed the process underlying voluntary interoactions, as for example, those targeted in autogenic and biofeedback training, we should conclude that this mechanism is quite different from how we control our motor actions. In biofeedback training studies, such mediations are indeed used and sometimes actively encouraged by experimenters (e.g., Meissner et al., 2024). In autogenic training, the instruction to imagine a "calm and steady heartbeat" could also be understood as an instruction to imagine a peaceful situation. Thus, one major strategy to achieve interoactive control might be via emotion regulation or mental imagery, which would again be a rather indirect route (similar to how some stage actors might try to induce the production of tears by voluntarily remembering sad events of their own life). This explanation indeed fits well with the observation that some studies employing autogenetic training find effects on subjective states rather than physiological changes (e.g., Ernst & Kanji, 2000; Kanji et al., 2006a, 2006b; Stetter & Kupper, 2002). Here again, it should be empirically investigated whether direct and specific interoactive control is possible (e.g., increasing and decreasing skin temperature), rather than general, nondirected relaxation responses.

Last, we introduced the examples of individuals capable of high degrees of voluntary interoaction to emphasize that this type of control can indeed be learned. The caveat that should be made here is that these might actually be unique individuals that potentially represent an exception to the rule of "average humans." Thus, similar to individuals who show far-from-average memory capacity or exceptional physical abilities, it is possible that these exceptional individuals represent cases of neurodiversity, whose impressive abilities simply could not be reached by most humans even after extensive training. Here again, the sole answer lies in further empirical research into this topic, which we hope this provocative hypothesis can help motivate.

Conclusions

Research on the voluntary control of action has primarily focused on the domain of exteroaction. We apply ideomotor theory in this article to the learning process underlying the (acquisition of) voluntary control over interoactions and propose several ways in which this ideomotor hypothesis of voluntary interoaction can be tested. This hypothesis provides a unifying framework for extero- and interoaction and accounts for their ostensible differences in terms of the quality of the feedback that they produce. We hope this proposal will guide future research investigating the naturally occurring limits of interoaction and that the ideomotor principle can be used to push these limits.

References

Allen, M., & Friston, K. J. (2018). From cognitivism to autopoiesis: Towards a computational framework for the embodied mind. *Synthese*, *195*(6), 2459–2482. https://doi.org/10.1007/s11229-016-1288-5

Allen, M., Levy, A., Parr, T., & Friston, K. J. (2022). In the body's eye: The computational anatomy of interoceptive inference. *PLOS Computational Biology*, *18*(9), Article e1010490. https://doi.org/10.1371/journal.pcbi.1010490

Ansorge, U. (2002). Spatial intention-response compatibility. *Acta Psychologica*, *109*(3), 285–299. https://doi.org/10.1016/S0001-6918(01)00062-2

Arns, M., de Ridder, S., Strehl, U., Breteler, M., & Coenen, A. (2009). Efficacy of neurofeedback treatment in ADHD: The effects on inattention, impulsivity and hyperactivity: A meta-analysis. *Clinical EEG and Neuroscience*, *40*(3), 180–189. https://doi.org/10.1177/155005940904000311

Benarroch, E. E. (2012). Postural tachycardia syndrome: A heterogeneous and multifactorial disorder. *Mayo Clinic Proceedings*, *87*(12), 1214–1225. https://doi.org/10.1016/j.mayocp.2012.08.013

Benson, H., Beary, J. F., & Carol, M. P. (1974). The relaxation response. *Psychiatry: Journal for the Study of Interpersonal Processes*, *37*(1), 37–46. https://doi.org/10.1080/00332747.1974.11023785

Benson, H., Lehmann, J. W., Malhotra, M. S., Goldman, R. F., Hopkins, J., & Epstein, M. D. (1982). Body temperature changes during the practice of g Tum-mo yoga. *Nature*, *295*(5846), 234–236. https://doi.org/10.1038/295234a0

Benson, H., Malhotra, M. S., Goldman, R. F., Jacobs, G. D., & Hopkins, P. J. (1990). Three case reports of the metabolic and electroencephalographic changes during advanced Buddhist meditation techniques. *Behavioral Medicine*, *16*(2), 90–95. https://doi.org/10.1080/08964289.1990.9934596

Bernardi, L., Sleight, P., Bandinelli, G., Cencetti, S., Fattorini, L., Wdowczyc-Szulc, J., & Lagi, A. (2001). Effect of rosary prayer and yoga mantras on autonomic cardiovascular rhythms: Comparative study. *BMJ: British Medical Journal*, *323*(7327), 1446–1449. https://doi.org/10.1136/bmj.323.7327.1446

Berntson, G. G., & Khalsa, S. S. (2021). Neural circuits of interoception. *Trends in Neurosciences*, *44*(1), 17–28. https://doi.org/10.1016/j.tins.2020.09.011

Bornemann, B., Kovacs, P., & Singer, T. (2019). Voluntary upregulation of heart rate variability through biofeedback is improved by mental contemplative training. *Scientific Reports*, *9*(1), Article 7860. https://doi.org/10.1038/s41598-019-44201-7

Borthwick, K., & Brindle, R. (2023). No relationship between proprioception and interoception in university athletes and non-athletes. *BIOS*, *94*(2), 94–101. https://doi.org/10.1893/BIOS-D-21-00009

Bowman, H., Collins, D. J., Nayak, A. K., & Cruse, D. (2023). Is predictive coding falsifiable? *Neuroscience and Biobehavioral Reviews*, *154*, Article 105404. https://doi.org/10.1016/j.neubiorev.2023.105404

Brass, M., Bekkering, H., & Prinz, W. (2001). Movement observation affects movement execution in a simple response task. *Acta Psychologica*, *106*(1–2), 3–22. https://doi.org/10.1016/S0001-6918(00)00024-X

Brass, M., Bekkering, H., Wohlschläger, A., & Prinz, W. (2000). Compatibility between observed and executed finger movements: Comparing symbolic, spatial, and imitative cues. *Brain and Cognition*, *44*(2), 124–143. https://doi.org/10.1006/brcg.2000.1225

Brener, J. (1974a). A general model of voluntary control applied to the phenomena of learned cardiovascular change. In P. A. Obrist, A. H. Black, J. Brener, & L. V. DiCara (Eds.), *Cardiovascular psychophysiology: Current issues in response mechanisms, biofeedback and methodology* (pp. 365–391). AldineTransaction.

Brener, J. (1974b). Factors influencing the specificity of voluntary cardiovascular control. In L. V. DiCara (Ed.), *Limbic and autonomic nervous systems research* (pp. 335–368). Springer. https://doi.org/10.1007/978-1-4613-4407-0_10

Brener, J. (1977). Visceral perception. In J. Beatty & H. Legewie (Eds.), *Biofeedback and behavior. NATO conference series* (Vol. 2, pp. 235–259). Springer. https://doi.org/10.1007/978-1-4684-2526-0_15

Brener, J. (1981). Control of internal activities. *British Medical Bulletin*, *37*(2), 169–174. https://doi.org/10.1093/oxfordjournals.bmb.a071696

Brener, J., & Ring, C. (2016). Towards a psychophysics of interoceptive processes: The measurement of heartbeat detection. *Philosophical Transactions of the Royal Society B: Biological Sciences*, *371*(1708), Article 20160015. https://doi.org/10.1098/rstb.2016.0015

Brewer, R., Murphy, J., & Bird, G. (2021). Atypical interoception as a common risk factor for psychopathology: A review. *Neuroscience and Biobehavioral Reviews*, *130*, 470–508. https://doi.org/10.1016/j.neubiorev.2021.07.036

Bykov, K. M. (1957). *The cerebral cortex and the internal organs*. Chemical Publishing.

Ceunen, E., Vlaeyen, J. W. S., & Van Diest, I. (2016). On the origin of interoception. *Frontiers in Psychology*, *7*, Article 743. https://doi.org/10.3389/fpsyg.2016.00743

Chen, J., & Proctor, R. W. (2013). Response-effect compatibility defines the natural scrolling direction. *Human Factors*, *55*(6), 1112–1129. https://doi.org/10.1177/0018720813482329

Chernigovskiy, V. N. (1967). Interoceptors and the physiological mechanism of artificial pneumothorax. In V. N. Chernigovskiy, D. B. Lindsley (Ed.) & G. Onischenko (Trans.), *Interoceptors* (pp. 462–480). American Psychological Association. https://doi.org/10.1037/10531-019

Clark, A. (2013). Whatever next? Predictive brains, situated agents, and the future of cognitive science. *Behavioral and Brain Sciences*, *36*(3), 181–204. https://doi.org/10.1017/S0140525X12000477

Craig, A. D. (2002). How do you feel? Interoception: The sense of the physiological condition of the body. *Nature Reviews Neuroscience*, *3*(8), 655–666. https://doi.org/10.1038/nrn894

Craig, A. D. (2009). How do you feel—Now? The anterior insula and human awareness. *Nature Reviews Neuroscience*, *10*(1), 59–70. https://doi.org/10.1038/nrn2555

Critchley, H. D., & Garfinkel, S. N. (2018). The influence of physiological signals on cognition. *Current Opinion in Behavioral Sciences*, *19*, 13–18. https://doi.org/10.1016/j.cobeha.2017.08.014

Critchley, H. D., Melmed, R. N., Featherstone, E., Mathias, C. J., & Dolan, R. J. (2001). Brain activity during biofeedback relaxation: A functional neuroimaging investigation. *Brain: A Journal of Neurology*, *124*(5), 1003–1012. https://doi.org/10.1093/brain/124.5.1003

Critchley, H. D., Melmed, R. N., Featherstone, E., Mathias, C. J., & Dolan, R. J. (2002). Volitional control of autonomic arousal: A functional magnetic resonance study. *NeuroImage*, *16*(4), 909–919. https://doi.org/10.1006/nimg.2002.1147

Critchley, H. D., Nagai, Y., Gray, M. A., & Mathias, C. J. (2011). Dissecting axes of autonomic control in humans: Insights from neuroimaging. *Autonomic Neuroscience*, *161*(1–2), 34–42. https://doi.org/10.1016/j.autneu.2010.09.005

Damasio, A. R., Tranel, D., & Damasio, H. C. (1991). Somatic markers and the guidance of behavior: Theory and preliminary testing. In H. S. Levin, H. M. Eisenberg, & A. L. Benton (Eds.), *Frontal lobe function and dysfunction* (pp. 217–229). Oxford University Press. https://doi.org/10.1093/oso/9780195062847.003.0011

Desmedt, O., Luminet, O., Walentynowicz, M., & Corneille, O. (2023). The new measures of interoceptive accuracy: A systematic review and assessment. *Neuroscience and Biobehavioral Reviews*, *153*, Article 105388. https://doi.org/10.1016/j.neubiorev.2023.105388

Dewey, J. (1894). The theory of emotion: I: Emotional attitudes. *Psychological Review*, *1*(6), 553–569. https://doi.org/10.1037/h0069054

Dignath, D., Pfister, R., Eder, A. B., Kiesel, A., & Kunde, W. (2014). Representing the hyphen in action-effect associations: Automatic acquisition and bidirectional retrieval of action-effect intervals. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, *40*(6), 1701–1712. https://doi.org/10.1037/xlm0000022

Eder, A. B. (2023). A perceptual control theory of emotional action. *Cognition and Emotion*, *37*(7), 1167–1184. https://doi.org/10.1080/02699931.2023.2265234

Elsner, B. (2007). Infants' imitation of goal-directed actions: The role of movements and action effects. *Acta Psychologica*, *124*(1), 44–59. https://doi.org/10.1016/j.actpsy.2006.09.006

Elsner, B., & Hommel, B. (2001). Effect anticipation and action control. *Journal of Experimental Psychology: Human Perception and Performance*, *27*(1), 229–240. https://doi.org/10.1037/0096-1523.27.1.229

Elsner, B., & Hommel, B. (2004). Contiguity and contingency in action-effect learning. *Psychological Research*, *68*(2–3), 138–154. https://doi.org/10.1007/s00426-003-0151-8

Elsner, B., Hommel, B., Mentschel, C., Drzezga, A., Prinz, W., Conrad, B., & Siebner, H. (2002). Linking actions and their perceivable consequences in the human brain. *NeuroImage*, *17*(1), 364–372. https://doi.org/10.1006/nimg.2002.1162

Engelen, T., Solcà, M., & Tallon-Baudry, C. (2023). Interoceptive rhythms in the brain. *Nature Neuroscience*, *26*(10), 1670–1684. https://doi.org/10.1038/s41593-023-01425-1

Ernst, E., & Kanji, N. (2000). Autogenic training for stress and anxiety: A systematic review. *Complementary Therapies in Medicine*, *8*(2), 106–110. https://doi.org/10.1054/ctim.2000.0354

Földes, N., Philipp, A. M., Badets, A., & Koch, I. (2017). Exploring modality compatibility in the response-effect compatibility paradigm. *Advances in Cognitive Psychology*, *13*(1), 97–104. https://doi.org/10.5709/acp-0210-1

Freeman, R. (2005). Autonomic peripheral neuropathy. *Lancet*, *365*(9466), 1259–1270. https://doi.org/10.1016/S0140-6736(05)74815-7

Garfinkel, S. N., & Critchley, H. D. (2016). Threat and the body: How the heart supports fear processing. *Trends in Cognitive Sciences*, *20*(1), 34–46. https://doi.org/10.1016/j.tics.2015.10.005

Glueck, B. C., & Stroebel, C. F. (1975). Biofeedback and meditation in the treatment of psychiatric illnesses. *Comprehensive Psychiatry*, *16*(4), 303–321. https://doi.org/10.1016/S0010-440X(75)80001-0

Green, E., & Green, A. (1977). *Beyond biofeedback*. Delacorte.

Greenwald, A. G. (1970). Sensory feedback mechanisms in performance control: With special reference to the ideo-motor mechanism. *Psychological Review*, *77*(2), 73–99. https://doi.org/10.1037/h0028689

Greenwald, A. G. (1972). On doing two things at once: Time sharing as a function of ideomotor compatibility. *Journal of Experimental Psychology*, *94*(1), 52–57. https://doi.org/10.1037/h0032762

Greenwald, A. G., & Shulman, H. G. (1973). On doing two things at once. II. Elimination of the psychological refractory period effect. *Journal of Experimental Psychology*, *101*(1), 70–76. https://doi.org/10.1037/h0035451

Gresch, D., Boettcher, S. E. P., van Ede, F., & Nobre, A. C. (2024). Shifting attention between perception and working memory. *Cognition*, *245*, Article 105731. https://doi.org/10.1016/j.cognition.2024.105731

Gruzelier, J. H. (2014). EEG-neurofeedback for optimising performance. I: A review of cognitive and affective outcome in healthy participants. *Neuroscience and Biobehavioral Reviews*, *44*, 124–141. https://doi.org/10.1016/j.neubiorev.2013.09.015

Gu, X., Hof, P. R., Friston, K. J., & Fan, J. (2013). Anterior insular cortex and emotional awareness. *The Journal of Comparative Neurology*, *521*(15), 3371–3388. https://doi.org/10.1002/cne.23368

Hammond, D. (2011). What is neurofeedback: An update. *Journal of Neurotherapy*, *15*(4), 305–336. https://doi.org/10.1080/10874208.2011.623090

Hauf, P., & Aschersleben, G. (2008). Action-effect anticipation in infant action control. *Psychological Research*, *72*(2), 203–210. https://doi.org/10.1007/s00426-006-0101-3

Hautekiet, C., Verschooren, S., Langerock, N., & Vergauwe, E. (2023). Attentional switching between perception and memory: Examining asymmetrical switch costs. *Attention, Perception, & Psychophysics*, *85*(5), 1398–1408. https://doi.org/10.3758/s13414-023-02665-w

Hodson, R., Mehta, M., & Smith, R. (2024). The empirical status of predictive coding and active inference. *Neuroscience and Biobehavioral Reviews*, *157*, Article 105473. https://doi.org/10.1016/j.neubiorev.2023.105473

Hofmann, W., Friese, M., & Strack, F. (2009). Impulse and self-control from a dual-systems perspective. *Perspectives on Psychological Science: A Journal of the Association for Psychological Science*, *4*(2), 162–176. https://doi.org/10.1111/j.1745-6924.2009.01116.x

Hommel, B., Müsseler, J., Aschersleben, G., & Prinz, W. (2001). The theory of event coding (TEC): A framework for perception and action planning. *Behavioral and Brain Sciences*, *24*(5), 849–878. https://doi.org/10.1017/S0140525X01000103

James, W. (1890). *The principles of psychology*, Vol. I. Henry Holt. https://doi.org/10.1037/10538-000

Janczyk, M., Skirde, S., Weigelt, M., & Kunde, W. (2009). Visual and tactile action effects determine bimanual coordination performance. *Human Movement Science*, *28*(4), 437–449. https://doi.org/10.1016/j.humov.2009.02.006

Jones, C. L., Minati, L., Nagai, Y., Medford, N., Harrison, N. A., Gray, M., Ward, J., & Critchley, H. D. (2015). Neuroanatomical substrates for the volitional regulation of heart rate. *Frontiers in Psychology*, *6*, Article 300. https://doi.org/10.3389/fpsyg.2015.00300

Kanji, N. (1997). Autogenic training. *Complementary Therapies in Medicine*, *5*(3), 162–167. https://doi.org/10.1016/S0965-2299(97)80060-X

Kanji, N., White, A., & Ernst, E. (2006a). Autogenic training to reduce anxiety in nursing students: Randomized controlled trial. *Journal of Advanced Nursing*, *53*(6), 729–735. https://doi.org/10.1111/j.1365-2648.2006.03779.x

Kanji, N., White, A. R., & Ernst, E. (2006b). Autogenic training for tension type headaches: A systematic review of controlled trials. *Complementary Therapies in Medicine*, *14*(2), 144–150. https://doi.org/10.1016/j.ctim.2006.03.001

Keefe, F. J., Surwit, R. S., & Pilon, R. N. (1980). Biofeedback, autogenic training, and progressive relaxation in the treatment of Raynaud's disease: A comparative study. *Journal of Applied Behavior Analysis*, *13*(1), 3–11. https://doi.org/10.1901/jaba.1980.13-3

Khalsa, S. S., Adolphs, R., Cameron, O. G., Critchley, H. D., Davenport, P. W., Feinstein, J. S., Feusner, J. D., Garfinkel, S. N., Lane, R. D., Mehling, W. E., Meuret, A. E., Nemeroff, C. B., Oppenheimer, S., Petzschner, F. H., Pollatos, O., Rhudy, J. L., Schramm, L. P., Simmons, W. K., Stein, M. B., … the Interoception Summit 2016 participants. (2018). Interoception and mental health: A roadmap. *Biological Psychiatry: Cognitive Neuroscience and Neuroimaging*, *3*(6), 501–513. https://doi.org/10.1016/j.bpsc.2017.12.004

Khalsa, S. S., Rudrauf, D., Feinstein, J. S., & Tranel, D. (2009). The pathways of interoceptive awareness. *Nature Neuroscience*, *12*(12), 1494–1496. https://doi.org/10.1038/nn.2411

Kimmel, H. D., & Hill, F. A. (1960). Operant conditioning of the GSR. *Psychological Reports*, *7*(3), 555–562. https://doi.org/10.2466/pr0.1960.7.3.555

Knapp-Kline, K., Ring, C., Emmerich, D., & Brener, J. (2021). The effects of vibrotactile masking on heartbeat detection: Evidence that somatosensory mechanoreceptors transduce heartbeat sensations. *Psychophysiology*, *58*(6), Article e13817. https://doi.org/10.1111/psyp.13817

Kox, M., van Eijk, L. T., Zwaag, J., van den Wildenberg, J., Sweep, F. C. G. J., van der Hoeven, J. G., & Pickkers, P. (2014). Voluntary activation of the sympathetic nervous system and attenuation of the innate immune response in humans. *Proceedings of the National Academy of Sciences of the United States of America*, *111*(20), 7379–7384. https://doi.org/10.1073/pnas.1322174111

Kozhevnikov, M., Elliott, J., Shephard, J., & Gramann, K. (2013). Neurocognitive and somatic components of temperature increases during g-tummo meditation: Legend and reality. *PLOS ONE*, *8*(3), Article e58244. https://doi.org/10.1371/journal.pone.0058244

Krieghoff, V., Waszak, F., Prinz, W., & Brass, M. (2011). Neural and behavioral correlates of intentional actions. *Neuropsychologia*, *49*(5), 767–776. https://doi.org/10.1016/j.neuropsychologia.2011.01.025

Kunde, W. (2001). Response-effect compatibility in manual choice reaction tasks. *Journal of Experimental Psychology: Human Perception and Performance*, *27*(2), 387–394. https://doi.org/10.1037/0096-1523.27.2.387

Kunzendorf, S., Klotzsche, F., Akbal, M., Villringer, A., Ohl, S., & Gaebler, M. (2019). Active information sampling varies across the cardiac cycle. *Psychophysiology*, *56*(5), Article e13322. https://doi.org/10.1111/psyp.13322

Leder, D. (1990). *The absent body*. University of Chicago Press. https://press.uchicago.edu/ucp/books/book/chicago/A/bo3622735.html

Leder, D. (2018). Inside insights: A phenomenology of interoception. In M. Tsakiris & H. De Preester (Eds.), *The interoceptive mind: From homeostasis to awareness* (pp. 307–322). Oxford University Press. https://doi.org/10.1093/oso/9780198811930.003.0017

Lee, Y.-J., Lee, G.-W., Seo, W.-S., Koo, B.-H., Kim, H.-G., & Cheon, E.-J. (2019). Neurofeedback treatment on depressive symptoms and functional recovery in treatment-resistant patients with major depressive disorder: An open-label pilot study. *Journal of Korean Medical Science*, *34*(42), Article e287. https://doi.org/10.3346/jkms.2019.34.e287

Legrand, N., Nikolova, N., Correa, C., Brændholt, M., Stuckert, A., Kildahl, N., Vejlø, M., Fardo, F., & Allen, M. (2022). The heart rate discrimination task: A psychophysical method to estimate the accuracy and precision of interoceptive beliefs. *Biological Psychology*, *168*, Article 108239. https://doi.org/10.1016/j.biopsycho.2021.108239

Lehrer, P., Kaur, K., Sharma, A., Shah, K., Huseby, R., Bhavsar, J., Sgobba, P., & Zhang, Y. (2020). Heart rate variability biofeedback improves emotional and physical health and performance: A systematic review and meta analysis. *Applied Psychophysiology and Biofeedback*, *45*(3), 109–129. https://doi.org/10.1007/s10484-020-09466-z

Lehrer, P. M., & Gevirtz, R. (2014). Heart rate variability biofeedback: How and why does it work? *Frontiers in Psychology*, *5*, Article 756. https://doi.org/10.3389/fpsyg.2014.00756

Lehrer, P. M., Vaschillo, E., & Vaschillo, B. (2000). Resonant frequency biofeedback training to increase cardiac variability: Rationale and manual for training. *Applied Psychophysiology and Biofeedback*, *25*(3), 177–191. https://doi.org/10.1023/A:1009554825745

Lim, S.-J., & Kim, C. (2014). Effects of autogenic training on stress response and heart rate variability in nursing students. *Asian Nursing Research*, *8*(4), 286–292. https://doi.org/10.1016/j.anr.2014.06.003

Linden, W. (1994). Autogenic training: A narrative and quantitative review of clinical outcome. *Biofeedback & Self Regulation*, *19*(3), 227–264. https://doi.org/10.1007/BF01721069

Maquestiaux, F., Lyphout-Spitz, M., Ruthruff, E., & Arexis, M. (2020). Ideomotor compatibility enables automatic response selection. *Psychonomic Bulletin & Review*, *27*(4), 742–750. https://doi.org/10.3758/s13423-020-01735-6

Marzbani, H., Marateb, H. R., & Mansourian, M. (2016). Neurofeedback: A comprehensive review on system design, methodology and clinical applications. *Basic and Clinical Neuroscience*, *7*(2), 143–158. https://doi.org/10.15412/J.BCN.03070208

Meissner, S. N., Bächinger, M., Kikkert, S., Imhof, J., Missura, S., Carro Dominguez, M., & Wenderoth, N. (2024). Self-regulating arousal via pupil-based biofeedback. *Nature Human Behaviour*, *8*(1), 43–62. https://doi.org/10.1038/s41562-023-01729-z

Memelink, J., & Hommel, B. (2013). Intentional weighting: A basic principle in cognitive control. *Psychological Research*, *77*(3), 249–259. https://doi.org/10.1007/s00426-012-0435-y

Menon, V., & Uddin, L. Q. (2010). Saliency, switching, attention and control: A network model of insula function. *Brain Structure & Function*, *214*(5–6), 655–667. https://doi.org/10.1007/s00429-010-0262-0

Miłkowski, M., & Litwin, P. (2022). Testable or bust: Theoretical lessons for predictive processing. *Synthese*, *200*(6), Article 462. https://doi.org/10.1007/s11229-022-03891-9

Mishima, N., Kubota, S., & Nagata, S. (1999). Psychophysiological correlates of relaxation induced by standard autogenic training. *Psychotherapy and Psychosomatics*, *68*(4), 207–213. https://doi.org/10.1159/000012334

Mitani, S., Fujita, M., Sakamoto, S., & Shirakawa, T. (2006). Effect of autogenic training on cardiac autonomic nervous activity in high-risk fire service workers for posttraumatic stress disorder. *Journal of Psychosomatic Research*, *60*(5), 439–444. https://doi.org/10.1016/j.jpsychores.2005.09.005

Muzik, O., Reilly, K. T., & Diwadkar, V. A. (2018). "Brain over body"-A study on the willful regulation of autonomic function during cold exposure. *NeuroImage*, *172*, 632–641. https://doi.org/10.1016/j.neuroimage.2018.01.067

Nashiro, K., Yoo, H. J., Min, J., Cho, C., Nasseri, P., Zhang, Y., Lehrer, P., Thayer, J. F., & Mather, M. (2022). Effects of a randomised trial of 5-week heart rate variability biofeedback intervention on mind wandering and associated brain function. *Cognitive, Affective & Behavioral Neuroscience*, *22*(6), 1349–1357. https://doi.org/10.3758/s13415-022-01019-7

Newman, P. P. (1974). *Visceral afferent functions of the nervous system*. Edward Arnold.

Oriet, C., Stevanovski, B., & Jolicoeur, P. (2001). Theory of event coding: Interesting, but underspecified. *Behavioral and Brain Sciences*, *24*(5), 897–898. https://doi.org/10.1017/S0140525X01400100

Park, H.-D., & Blanke, O. (2019). Coupling inner and outer body for self-consciousness. *Trends in Cognitive Sciences*, *23*(5), 377–388. https://doi.org/10.1016/j.tics.2019.02.002

Paulus, M., Hunnius, S., van Elk, M., & Bekkering, H. (2012). How learning to shake a rattle affects 8-month-old infants' perception of the rattle's sound: Electrophysiological evidence for action-effect binding in infancy. *Developmental Cognitive Neuroscience*, *2*(1), 90–96. https://doi.org/10.1016/j.dcn.2011.05.006

Petzschner, F. H., Weber, L. A. E., Gard, T., & Stephan, K. E. (2017). Computational psychosomatics and computational psychiatry: Toward a joint framework for differential diagnosis. *Biological Psychiatry*, *82*(6), 421–430. https://doi.org/10.1016/j.biopsych.2017.05.012

Pezzulo, G., Rigoli, F., & Friston, K. J. (2018). Hierarchical active inference: A theory of motivated control. *Trends in Cognitive Sciences*, *22*(4), 294–306. https://doi.org/10.1016/j.tics.2018.01.009

Pfister, R. (2019). Effect-based action control with body-related effects: Implications for empirical approaches to ideomotor action control. *Psychological Review*, *126*(1), 153–161. https://doi.org/10.1037/rev0000140

Pfister, R., Janczyk, M., Gressmann, M., Fournier, L. R., & Kunde, W. (2014). Good vibrations? Vibrotactile self-stimulation reveals anticipation of body-related action effects in motor control. *Experimental Brain Research*, *232*, 847–854. https://doi.org/10.1007/s00221-013-3796-6

Pfister, R., & Kunde, W. (2013). Dissecting the response in response-effect compatibility. *Experimental Brain Research*, *224*(4), 647–655. https://doi.org/10.1007/s00221-012-3343-x

Phongsuphap, S., Pongsupap, Y., Chandanamattha, P., & Lursinsap, C. (2008). Changes in heart rate variability during concentration meditation. *International Journal of Cardiology*, *130*(3), 481–484. https://doi.org/10.1016/j.ijcard.2007.06.103

Piaget, J. (1954). *The construction of reality in the child*. Basic Books. https://doi.org/10.1037/11168-000

Pineda, J. A., Carrasco, K., Datko, M., Pillen, S., & Schalles, M. (2014). Neurofeedback training produces normalization in behavioural and electrophysiological measures of high-functioning autism. *Philosophical Transactions of the Royal Society of London. Series B, Biological Sciences*, *369*(1644), Article 20130183. https://doi.org/10.1098/rstb.2013.0183

Pizzoli, S. F. M., Marzorati, C., Gatti, D., Monzani, D., Mazzocco, K., & Pravettoni, G. (2021). A meta-analysis on heart rate variability biofeedback and depressive symptoms. *Scientific Reports*, *11*(1), Article 6650. https://doi.org/10.1038/s41598-021-86149-7

Prinz, W. (1987). Ideo-motor action. In H. Heuer & A. F. Sanders (Eds.), *Perspectives on perception and action* (pp. 47–76). Lawrence Erlbaum Associates.

Prinz, W. (1997). Perception and action planning. *European Journal of Cognitive Psychology*, *9*(2), 129–154. https://doi.org/10.1080/713752551

Quadt, L., Critchley, H., & Nagai, Y. (2022). Cognition, emotion, and the central autonomic network. *Autonomic Neuroscience*, *238*, Article 102948. https://doi.org/10.1016/j.autneu.2022.102948

Ren, Q., Marshall, A. C., Kaiser, J., & Schütz-Bosbach, S. (2022). Response inhibition is disrupted by interoceptive processing at cardiac systole. *Biological Psychology*, *170*, Article 108323. https://doi.org/10.1016/j.biopsycho.2022.108323

Ring, C., & Brener, J. (2018). Heartbeat counting is unrelated to heartbeat detection: A comparison of methods to quantify interoception. *Psychophysiology*, *55*(9), Article e13084. https://doi.org/10.1111/psyp.13084

Rochat, P., & Striano, T. (1999). Social–cognitive development in the first year. In P. Rochat (Ed.), *Early social cognition: Understanding others in the first months of life* (pp. 3–34). Lawrence Erlbaum.

Schieber, M. H. (2009). Motor cortex—Hand movements and plasticity. In M. D. Binder, N. Hirokawa, & U. Windhorst (Eds.), *Encyclopedia of neuroscience* (pp. 2431–2433). Springer. https://doi.org/10.1007/978-3-540-29678-2_3586

Schlamann, M., Naglatzki, R., de Greiff, A., Forsting, M., & Gizewski, E. R. (2010). Autogenic training alters cerebral activation patterns in fMRI. *International Journal of Clinical and Experimental Hypnosis*, *58*(4), 444–456. https://doi.org/10.1080/00207144.2010.499347

Schultz, J. H., & Luthe, W. (1959). *Autogenic training: A psychophysiologic approach to psychotherapy*. Grune & Stratton.

Sennesh, E., Theriault, J., Brooks, D., van de Meent, J.-W., Barrett, L. F., & Quigley, K. S. (2022). Interoception as modeling, allostasis as control. *Biological Psychology*, *167*, Article 108242. https://doi.org/10.1016/j.biopsycho.2021.108242

Seth, A. K. (2013). Interoceptive inference, emotion, and the embodied self. *Trends in Cognitive Sciences*, *17*(11), 565–573. https://doi.org/10.1016/j.tics.2013.09.007

Seth, A. K., & Friston, K. J. (2016). Active interoceptive inference and the emotional brain. *Philosophical Transactions of the Royal Society of London. Series B, Biological Sciences*, *371*(1708), Article 20160007. https://doi.org/10.1098/rstb.2016.0007

Seth, A. K., Suzuki, K., & Critchley, H. D. (2011). An interoceptive predictive coding model of conscious presence. *Frontiers in Psychology*, *2*, Article 395. https://doi.org/10.3389/fpsyg.2011.00395

Shapiro, S., & Lehrer, P. M. (1980). Psychophysiological effects of autogenic training and progressive relaxation. *Biofeedback & Self Regulation*, *5*(2), 249–255. https://doi.org/10.1007/BF00998600

Siqueland, E. R., & DeLucia, C. A. (1969). Visual reinforcement of nonnutritive sucking in human infants. *Science*, *165*(3898), 1144–1146. https://doi.org/10.1126/science.165.3898.1144

Sitaram, R., Ros, T., Stoeckel, L., Haller, S., Scharnowski, F., Lewis-Peacock, J., Weiskopf, N., Blefari, M. L., Rana, M., Oblak, E., Birbaumer, N., & Sulzer, J. (2017). Closed-loop brain training: The science of neurofeedback. *Nature Reviews Neuroscience*, *18*(2), 86–100. https://doi.org/10.1038/nrn.2016.164

Smith, R., Thayer, J. F., Khalsa, S. S., & Lane, R. D. (2017). The hierarchical basis of neurovisceral integration. *Neuroscience and Biobehavioral Reviews*, *75*, 274–296. https://doi.org/10.1016/j.neubiorev.2017.02.003

Stephan, K. E., Manjaly, Z. M., Mathys, C. D., Weber, L. A. E., Paliwal, S., Gard, T., Tittgemeyer, M., Fleming, S. M., Haker, H., Seth, A. K., & Petzschner, F. H. (2016). Allostatic self-efficacy: A metacognitive theory of dyshomeostasis-induced fatigue and depression. *Frontiers in Human Neuroscience*, *10*, Article 550. https://doi.org/10.3389/fnhum.2016.00550

Stetter, F., & Kupper, S. (2002). Autogenic training: A meta-analysis of clinical outcome studies. *Applied Psychophysiology and Biofeedback*, *27*(1), 45–98. https://doi.org/10.1023/A:1014576505223

Tahsili-Fahadan, P., & Geocadin, R. G. (2017). Heart-brain axis: Effects of neurologic injury on cardiovascular function. *Circulation Research*, *120*(3), 559–572. https://doi.org/10.1161/CIRCRESAHA.116.308446

Tebēcis, A. K., Ohno, Y., Matsubara, H., Sugano, H., Takeya, T., Ikemi, Y., & Takasaki, M. (1976). A longitudinal study of some physiological parameters and autogenic training. *Psychotherapy and Psychosomatics*, *27*(1), 8–17. https://doi.org/10.1159/000286991

Tschantz, A., Barca, L., Maisto, D., Buckley, C. L., Seth, A. K., & Pezzulo, G. (2022). Simulating homeostatic, allostatic and goal-directed forms of interoceptive control using active inference. *Biological Psychology*, *169*, Article 108266. https://doi.org/10.1016/j.biopsycho.2022.108266

Tschantz, A., Seth, A. K., & Buckley, C. L. (2020). Learning action-oriented models through active inference. *PLOS Computational Biology*, *16*(4), Article e1007805. https://doi.org/10.1371/journal.pcbi.1007805

Verschooren, S., & Egner, T. (2023). When the mind's eye prevails: The internal dominance over external attention (IDEA) hypothesis. *Psychonomic Bulletin & Review*, *30*(5), 1668–1688. https://doi.org/10.3758/s13423-023-02272-8

Verschooren, S., Liefooghe, B., Brass, M., & Pourtois, G. (2019). Attentional flexibility is imbalanced: Asymmetric cost for switches between external and internal attention. *Journal of Experimental Psychology: Human Perception and Performance*, *45*(10), 1399–1414. https://doi.org/10.1037/xhp0000683

Verschooren, S., Pourtois, G., & Egner, T. (2020). More efficient shielding for internal than external attention? Evidence from asymmetrical switch costs. *Journal of Experimental Psychology: Human Perception and Performance*, *46*(9), 912–925. https://doi.org/10.1037/xhp0000758

Verschooren, S., Schindler, S., De Raedt, R., & Pourtois, G. (2019). Switching attention from internal to external information processing: A review of the literature and empirical support of the resource sharing account. *Psychonomic Bulletin & Review*, *26*(2), 468–490. https://doi.org/10.3758/s13423-019-01568-y

von Holst, E., & Mittelstaedt, H. (1950). Das Reafferenzprinzip [The reafference principle]. *Die Naturwissenschaften*, *37*(20), 464–476. https://doi.org/10.1007/BF00622503

Wheat, A. L., & Larkin, K. T. (2010). Biofeedback of heart rate variability and related physiology: A critical review. *Applied Psychophysiology and*

Biofeedback, *35*(3), 229–242. https://doi.org/10.1007/s10484-010-9133-y

Wirth, R., Pfister, R., Brandes, J., & Kunde, W. (2016). Stroking me softly: Body-related effects in effect-based action control. *Attention, Perception, & Psychophysics*, *78*(6), 1755–1770. https://doi.org/10.3758/s13414-016-1151-2

Wolfensteller, U., & Ruge, H. (2011). On the timescale of stimulus-based action-effect learning. *The Quarterly Journal of Experimental Psychology*, *64*(7), 1273–1289. https://doi.org/10.1080/17470218.2010.546417

Yoshimoto, A., Morikawa, S., Kato, E., Takeuchi, H., & Ikegaya, Y. (2024). Top-down brain circuits for operant bradycardia. *Science*, *384*(6702), 1361–1368. https://doi.org/10.1126/science.adl3353

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