



Ideomotor learning: Time to generalize a longstanding principle

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ARTICLE INFO

Keywords:

Ideomotor learning
Action control
Response-response association
Stimulus-stimulus association

ABSTRACT

The ideomotor principle holds that anticipating the sensory consequences of a movement triggers an associated motor response. Even though this framework dates back to the 19th century, it continues to lie at the heart of many contemporary approaches to human action control. Here we specifically focus on the ideomotor learning mechanism that has to precede action initiation via effect anticipation. Traditional approaches to this learning mechanism focused on establishing novel action-effect (or response-effect) associations. Here we apply the theoretical concept of common coding for action and perception to argue that the same learning principle should result in response-response and stimulus-stimulus associations just as well. Generalizing ideomotor learning in such a way results in a powerful and general framework of ideomotor action control, and it allows for integrating the two seemingly separate fields of ideomotor approaches and hierarchical learning.

1. Roots of the ideomotor principle

The notion that the mere anticipation – that is: the idea – of upcoming sensory consequences can trigger a motor response is known as the *ideomotor principle*. This concept emerged in philosophical and physiological studies of the 19th century (Herbart, 1825; Lotze, 1852; Harleß, 1861; see also Pfister and Janczyk, 2012; Stock and Stock, 2004), and it rose to prominence after William James (1890) had popularized this theoretical approach in his Principles of Psychology. It also traditionally came with close ties to neuroscientific theorizing (Carpenter, 1852) and applications to animal learning alike (Washburn, 1908), before the field went on hiatus during the behaviorist era of the 20th century. When the ideomotor principle regained popularity (Greenwald, 1970), the assumption that actions are triggered primarily by mental states marked a radical change in the analysis of human behavior, as many theoretical accounts had often highlighted external stimulus conditions as the primary trigger for overt actions (see also Prinz, 1998).

Even though the ideomotor approach dates back about 200 years, it continues to lie at the heart of many contemporary approaches to human action control (Greenwald, 1970; Hommel et al., 2001; Shin et al., 2010). In the meantime, the approach has been applied to various fields within (e.g., Frings et al., 2020; Janczyk and Kunde, 2020) and also beyond the immediate control of motor action (e.g., Badets et al., 2016;

Badets and Osiurak, 2017). This state of affairs suggests that the basic theoretical assumptions of the ideomotor principle capture critical mechanisms for action control and beyond. But what exactly are these assumptions? Firstly, and central for the following argument, ideomotor approaches highlight the role of learning processes that lead to the formation of bi-directional action-effect associations. That is, after repeated occurrences of a certain action-effect combination, not only the action becomes associated (and can activate) the effect's representation, but also the perception or anticipation of the effect can activate the action's representation. Secondly, ideomotor approaches hold that acquired action-effect associations enable voluntary actions because motor behavior can be re-activated by mentally recollecting – i.e., anticipating –, potential action effects (Hoffmann, 1993; Kunde, 2001, 2006). We will focus on the first of these assumptions in the following and further propose that the learning mechanism is not specific to action-effect (or response-effect) associations. Rather, we draw on recent findings from behavioral and neuroscientific studies to argue that learning outcomes in terms of response-effect, response-response, and stimulus-stimulus associations can be achieved by one and the same learning mechanism. We propose that this mechanism can be described as ideomotor learning, generalized to all kinds of pairings of stimulus-, response-, and effect features. Following this notion has direct implications for ideomotor action control and its more general role in human action representation.

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2. What is ideomotor learning?

Classical approaches from 19th century philosophy hold that ideomotor learning should be viewed from a developmental perspective, suggesting that the capacity for voluntary action arises from early learning experience (Herbart, 1825, p. 464; cited after Stock and Stock, 2004):

“Right after the birth of a human being or an animal, certain movements in the joints develop, for merely organic reasons and independently of the soul; and each of these movements elicits a certain feeling in the soul. In the same instance, the outside senses perceive what change has come about. [...] At a later time, a desire for the change observed before arises. Thus, the feeling associated with the observation reproduces itself. [...] Hence, what has been desired actually happens; and the success is perceived. Through this, the association is reinforced [...].”

Similar concepts were put forward in physiological models (Harleß, 1861; see Pfister and Janczyk, 2012), suggesting that ideomotor learning draws on rather simple, associative mechanisms that operate already in newborns (and likely also during prenatal development). That is, repeated co-occurrence between motor activity and sensory activity builds stable, bi-directional associations between the corresponding neural ensembles. This process would nowadays be labeled Hebbian learning (Hommel, 2013) and it enables re-activation of one part of the association to spill over to the second part (Hommel, 2009; Kunde, 2006). In this way, if an infant repeatedly experiences the sight and proprioception that his or her leg is stretching after certain muscle movements, he or she learns the association between the motor activity and its resulting sensory changes, i.e., the action effect. Anticipating the effect later on elicits the response: After the infant has learned the association, anticipation of the outstretched leg would initiate the movements.

These predictions receive empirical support by research on the acquisition of novel action-effect associations. With infant participants, several findings have documented that coupling visual or auditory effects to simple motor actions (e.g., sucking on a pacifier) increases the frequency of these actions which is consistent with the idea that action-effect associations are built up and retrieved (Elsner, 2007; Hauf et al., 2004; Rochat and Striano, 1999; Siqueland and DeLucia, 1969). Even more stringent tests have been reported in studies with adult participants. This research also coupled simple actions (e.g., keypresses) with arbitrary effects in the agent’s environment (e.g., tones of distinct frequencies), while ideomotor learning was probed in two-stage learning paradigms (Elsner and Hommel, 2001; see also Eder et al., 2015; Hommel et al., 2003, Janczyk et al., 2022). In an initial acquisition phase, participants typically perform a series of actions and experience the ensuing action effect. In a subsequent test phase, action effects of the preceding learning phase are now presented before each action. Following the above predictions, the presentation of a former action effect has been observed to facilitate selection and performance of associated actions whereas it interfered with selecting and performing actions that had not been associated with the effect in the acquisition phase. These findings emerged from different experimental designs including performance-based measures such as response times in forced-choice tasks as well as choice frequencies in free-choice settings (Pfister et al., 2011). The learning process further builds reliable and stable associations after relatively little experience with an action-effect pairing. Empirical evidence suggests that as little as 12 instances of experiencing an action-effect relation are sufficient to forge lasting associations between the two representations (Wolfensteller and Ruge, 2011).

Neuroscientific findings mirror these observations by showing that re-encountering a previous action effect activates brain areas that are closely connected to motor control. Early findings from positron emission tomography (PET) for instance revolved around a learning task in which participants learned action-effect associations in a series of

learning trials. When these action effects were used as stimuli in a subsequent test phase, PET data suggested conjoint activation of the supplementary motor area and the hippocampus upon re-encountering stimuli that previously had been action effects in the learning phase. The strength of this activation further scaled with the frequency of previous action effects relative to neutral stimuli that had not been associated with a particular action in the learning phase. These observations are consistent with the idea of instilling action tendencies by retrieving previous action-effect associations from memory. Later work with functional magnetic resonance imaging (fMRI) extended this pattern to premotor and somatosensory cortices while pointing towards potential asymmetries between action effects associated with left-hand and right-hand actions (Melcher et al., 2008, 2013). Converging findings were further sought in fMRI work on neurophysiological activity that is triggered by anticipating upcoming action effects rather than re-encountering effect stimuli from a previous learning phase (Pfister et al., 2014). This work highlighted and additional contribution of parietal areas and particularly the temporo-parietal junction. A further key area emerging from such research is the anterior insular cortex that showed increased activation during perception of a stimulus that was previously self-produced (Mutschler et al., 2007), and is a region that is currently discussed as an important relay center for motivated behavior (Gogolla, 2017; Mutschler et al., 2009; Wu et al., 2019).

Evidence for associations between an action and a following effect can even be observed for single couplings, if the association (or: binding) is probed right after encountering an action-effect pairing (Dutzi and Hommel, 2009; Janczyk et al., 2012; Moeller, Pfister et al., 2016, 2019). Yet, note that it is still debated whether or not action-effect associations after a single encounter are actually comparable to those established by prolonged learning (Herwig and Waszak, 2012; see also Colzato et al., 2006; Logan, 1988, 1990; Moeller and Frings, 2017). On the one hand, many authors have assumed that feature binding is an early learning instance in a longer lasting learning process, i.e., that binding is learning (e.g., Dutzi and Hommel, 2009; Frings and Rothermund, 2011; Giesen, Frings, and Rothermund, 2012; Giesen and Rothermund, 2014; Hommel, 1998; Hommel and Elsner, 2009; Moeller and Frings, 2014; Waszak and Pholulandeth, 2009). And indeed retrieval after multiple and just a single coupling is virtually identical (Boronat and Logan, 1997; Frings and Moeller, 2012; Hommel, 2004). On the other hand, it has been suggested that processes of ad hoc bindings for new stimuli can be differentiated from conjunction detection of familiar stimuli (Hommel and Colzato, 2009; VanRullen, 2009), and variations in response pacing and stimulus setup can influence short-term binding and longer-term learning effects independently (Moeller and Frings, 2017).

At least for repeated co-occurrences of action-effect episodes, current theorizing suggests that novel, arbitrary effects as used in studies on action-effect learning actually become part of the action representation in the cognitive system (Hommel and Wiers, 2017). The technical label of “action-effect” learning may thus be misleading in that it suggests learning to result in the motor action and its following effects being represented as two connected but separable entities, an “action” and its “effects”. Ideomotor reasoning goes far beyond such associations of separate entities: The effects elicited as part of the experimental task should actually become part of how the action is represented in the cognitive system (see Kunde, 2006; Mechsner, 2004; Mechsner et al., 2001, Prinz, 1997). Following this reasoning, the effect will gain the power to generate a certain motor action just as other effects that were already linked to this particular motor activity before. These other effects will often relate to the agent’s moving body and they comprise kinesthetic reafferences as well as visual and auditory consequences of perceiving the body in action (Pfister, 2019). The action representation will thus comprise a large number of effects that relate to the agent’s body and the agent’s environment alike.

Notably, even though effect representations gain the power to generate a motor action through ideomotor learning, this does not mean that thinking of or perceiving any previous effect inevitably triggers the

action once learning has resulted in action-effect associations. If this were the case, we would constantly be caught in a never-ending cycle of action, effect, action, effect, and action. In an early proposal, James (1890) noted that only effects that “feel good” lead to action activation, while displeasure seems to dampen activity. Modern approaches explicitly include motivational modulation of the actual motor activation (e.g., De Wit & Dickinson (2009); Watson et al., 2018). Crucially, evidence suggests that perceiving or anticipating corresponding effects needs to activate sufficiently many distinctive features of an action to a sufficiently strong degree to trigger eventual execution (Colton et al., 2018; Kunde et al., 2004; Sun et al., 2020).

Turning back to the learning mechanism and following the accumulating evidence for action-effect learning in the above research tradition, several studies have attempted to provide evidence for the hypothesized associative nature of the underlying learning mechanism. A major prediction of an associative account would be that statistical action-effect contingency and temporo-spatial action-effect contiguity should have a profound moderating role for ideomotor learning (Hoffmann, 1993; Grice, 1948; Rescorla, 1968). In other words, for the formation of an association, actions need to predict the appearance of an effect (contingency) and action and effect need to be relatively close in time and space (contiguity; Watson, 1997). Initial evidence seemed to support this claim (Elsner and Hommel, 2004). For instance, participants showed stable signs of learning when the probability of an effect stimulus increased by 60% when performing an action as compared to not acting – $p(\text{Effect} | \text{Action}) = 0.80$ vs. $p(\text{Effect} | \text{No action}) = 0.20$ – but not when actions increased the probability of an effect stimulus by only 30% – $p(\text{Effect} | \text{Action}) = 0.80$ vs. $p(\text{Effect} | \text{No action}) = 0.50$. Because the probability of the effect following an action was the same in both of the above scenarios, these results suggest that action-effect learning is indeed driven by contingency rather than mere co-occurrence. In the same study, participants seemed to build up stable action-effect associations with action-effect delays of up to 1000 ms whereas there was no evidence for learning after 2000 ms, suggesting that contiguity also affects action-effect learning. Later findings qualified these observations by showing that action-effect learning can take place even for long action-effect intervals of 2000 ms (Dignath and Janczyk, 2017; Dignath et al., 2014). These findings also suggested, however, that the length of the interval was also integrated into action representations and retrieved when re-encountering a former effect stimulus. Consequently, retrieval of the delay – leading to variations in response times – may at times overshadow learning effects when these learning effects are assessed with time-critical measures such as response times (for converging evidence on short-term binding, see Bogon et al., 2017). The available evidence for the role of contingency and contiguity thus is at least partly compatible with the idea that action-effect learning results from an associative mechanism via the Hebbian principle that what fires together wires together (Greenwald, 1970; Hommel, 2009, 2013).

2.1. Non-ideomotor learning?

The decisive evidence in favor of ideomotor learning as the basis of associative (action-effect) learning begs the question whether there are also associative but non-ideomotor forms of learning.¹ In fact, associative learning has been investigated in many forms, beginning more than 100 years ago with Pavlovian and instrumental conditioning (e.g., Thorndike, 1898; Pavlov, 1932), including research on implicit learning

¹ Even though we acknowledge that learning can proceed via different mechanisms (see also Heyes, 2012), we restrict our analysis to associative models and do not address alternative frameworks such as propositional accounts to (De Houwer, 2009) or theories of insight learning (Köhler, 1921). The reason for this choice is that the only form of learning, ideomotor mechanisms may directly contribute to, is associative learning (see also Sun et al., 2022).

(e.g., Keele et al., 2003), learning of rhythmic responses (Badets and Blandin, 2010), and even social interaction (e.g., Heyes, 2010, 2012). Despite active discussion on the question of which association between either stimuli, responses, and/or outcomes (i.e., effects) has the largest impact on following behavior (e.g., Gilroy et al., 2014; Ostlund and Balleine, 2007), these forms of associative learning are typically discussed independently of any relation they might have with ideomotor learning.² A clear exception are De Wit and Dickinson (2009) in their discussion of ideomotor action and animal learning (see also Meck, 1985). Interestingly, these authors differentiate between goal-directed action that is based on the representation of an R-E relationship and habitual action that is based on an S-R relationship. These associations are thus assumed to result from distinct learning processes.

Another possible separation of associative and ideomotor learning is made explicit in research on implicit serial learning. Experiments on serial learning typically expose participants to a sequence of stimuli that require certain responses while the sequence of stimuli and/or responses follows a hidden structure (Keele et al., 2003; Nissen and Bullemer, 1987; Reber, 1989; Shea and Park, 2003; Verwey, 2015). A typical observation in these experiments is that performance (as measured via response times) improves over time, suggesting that participants have acquired knowledge about the sequence. The nature of this knowledge has been subject to intense debate, however (Hoffmann and Koch, 1997; Nattkemper and Prinz, 1997). Are participants acquiring knowledge about stimulus-stimulus sequences (Cohen et al., 1990; Howard et al., 1992), about response-response sequences (Willingham et al., 1989; Ziessler, 1994, 1998), or about response-stimulus, i.e., action-effect, sequences (Hoffmann et al., 2001; Esser and Haider, 2018; Pfordresher, 2005; Stöcker et al., 2003)?

The discussion on what is learned during serial learning has led to the suggestion that there is a fundamental difference between ideomotor learning (capturing action-effect associations) and other types of learning (stimulus-stimulus learning, response-response learning; Herwig et al., 2007; Shin et al., 2010). In the following, we ask whether the difference between different learning outcomes does indeed require the assumption of separate learning mechanisms (see also Pfister, 2019; Pfister et al., 2011). That is, we discuss whether ideomotor learning should be seen as a separate form of learning (as sometimes implied) and how it relates to other types of associative learning in terms of structural or mechanistic properties. To motivate this discussion we now turn to the question of how action-effect associations are represented.

2.2. Common coding

Ideomotor accounts hold that actions are represented in terms of the sensory consequences they produce. This implies that there are no genuinely “motoric” representations as implied by several alternative accounts (e.g., motor programs; Keele, 1968); rather actions are represented in a perceptual format. This view is expressed most explicitly in the common coding framework (Prinz, 1990, 1992). Common coding refers to the idea that there are no motor or sensory codes but that action and perception are represented in one and the same format. This view predicts that there should be direct interactions from action on perception and vice versa (Prinz, 1992). One example that perception and action are such closely entwined is ideomotor movement, as in a person who has thrown a bowling ball and cannot help but twist their hand or body, as if the ball’s path was influenced by these movements, for as long as the final destination of the ball is not clear (Knuf et al.,

² Studies on either operant conditioning or ideomotor learning share surprisingly many surface features in that they pair arbitrary responses with response-contingent events. Whereas operant conditioning is mainly interested in motivational impacts of rewards and punishments on behavioral choices, studies on ideomotor learning assess how such situations affect action representations and thus the agent’s ability to control their bodily movements.

2001). Another example is the observation that performance is better if responses (e.g., a soft vs. a hard keypress) lead to compatible effects (e.g., a soft vs. loud sound) than if they are followed by incompatible effects (Kunde, 2001; Kunde et al., 2004; Pfister and Kunde, 2013). A third compelling example is the fact that ongoing action, like pressing a left or right key can influence perception of left or right pointing stimuli (Müsseler and Hommel, 1997). Such observations can be accommodated readily against the background of the common coding framework because a commensurate format of both representations does not require any additional translation processes between action and perception (“response selection”). Instead, direct overlap of common codes relating to perception and action enables combined activation.

Common coding also forms the cornerstone of *Theory of Event Coding* (Hommel et al., 2001) as the currently most influential ideomotor approach to perception and action. As such, it assumes that activating representational codes for an action effect automatically activates the action itself. This framework also makes the strong assumption that representations of perceived events and of produced actions do not differ at all (Hommel, 2009). If, however, perception and action are represented in a common (identical) code, we argue that there is no distinction of ideomotor (action-effect) learning on the one hand and stimulus-stimulus and response-response learning on the other hand. Rather, these learning outcomes can be achieved by one and the same learning mechanism.³ Fig. 1A illustrates this argument. We believe that embracing this view can motivate interesting and novel research questions as we outline in the next sections.

3. Support for a more general learning mechanism

First, note that there is no theoretical restriction of the described ideomotor learning mechanism to only responses and effects. In his revival of the ideomotor approach, Greenwald (1970) describes that events (that are composed of Stimuli, Responses, and Effects) unfold sequentially over time and are usually contingent or causally related to each other. Learning of rather abstract RE-combinations in later experiments (e.g., Elsner and Hommel, 2001, 2004) supports the notion that contingency and not causality is the decisive characteristic. Taking the common coding assumption seriously then, there is no reason to restrict the processes in ideomotor learning to actions and following perception. If contiguity is the relevant requirement for building associations and if action and perception are represented in a common code, the same sort of learning should be possible for actions and following actions as well as perceptions and following perceptions.⁴ In other words, there is no need to differentiate between actions and perceptions for considerations of what can be integrated via the mechanism behind ideomotor learning.

Tentative empirical support for the assumption that RR- and SS-associations can be learned by the same learning mechanism as RE-associations comes from studies on episodic processing of clearly defined events (Hommel et al., 2001). These studies usually analyze short-term associations (bindings) between stimulus- and response features that evolve from individual responses (e.g., Bogon et al., 2017; Giesen and Rothermund, 2014; Hommel, 1998; Moeller, Frings et al.,

³ This learning mechanism is most likely influenced by distribution of attention, leading to faster learning with increasing attention to the contingent stimuli, responses, or effects (see Herwig et al., 2007; Memelink & Hommel, 2013).

⁴ The case for perception and following action is somewhat different, because such ‘perception’ will oftentimes be a target stimulus for which additional learning has to be assumed regarding the required stimulus classification as a covert response as well as regarding instructed stimulus-response mapping. Learning of associations between perceptions based on additional distractor stimuli and following actions should of course again rely on the same mechanisms as ideomotor learning. For the sake of simplicity, we will focus on RE-, RR-, and SS-associations in the following.

2016). For example, if a person responds with a left key press to a red letter, it is assumed that features like left, red and the shape of the letter are integrated in the representation of this event. Even though such integration explicitly occurs at a single response, the same common coding system that was proposed to mediate ideomotor action control (e.g., Prinz, 1992) lies also at the heart of theoretical explanations regarding such short term bindings. That is, both the briefly prolonged event representation for a novice pressing a key on a piano and hearing the resulting sound and the learned association of pressing a key on the computer keyboard and seeing the corresponding letter appear on screen, rely on a shared representation of action and perception. In fact, binding mechanisms seem to resemble ideomotor learning and ideomotor action control on a micro level: Responding to a stimulus at a single occasion leads to integration of response-, stimulus-, and effect features in terms of short lived bindings between features (Hommel, 2004). Notably, bindings have an intriguing similarity to a central characteristic of associations resulting from ideomotor learning: The association of two features that share a binding also runs in both directions, so that the perceived effect of a single recent action can trigger the action later on (e.g., Dutzi and Hommel, 2009). Taken together, it seems reasonable to assume that the integration of features to bindings can be interpreted as a - maybe very rudimentary - form of ideomotor learning despite the somewhat mixed database on this question (Herwig and Waszak, 2012).

Turning back to the possibility of a more general learning mechanism, there is ample evidence for binding between response-related features and also between stimulus features that resembles RE-binding. Bindings between individual responses have been observed both in action planning (e.g., Fournier, Behmer et al., 2014; Fournier, Gallimore et al., 2014) and as a result of contiguity of individually planned actions (Moeller and Frings, 2019a, 2019c, 2019d). In the latter studies, executing two responses sequentially led to integration of the responses so that repeating one of the integrated responses as the first response (in the next sequence of two responses) retrieved the other response. In turn, following performance was affected, depending on whether the retrieved response did or did not match the required one. Similarly, binding also occurs between stimuli (Giesen and Rothermund, 2014), and between task irrelevant stimulus features and responses (e.g., Frings and Rothermund, 2011). Intriguingly, different binding effects (SR- and RE-binding) have been shown to correlate, and the origin of the bound feature representations (S, R, or E) seems to be irrelevant for the observed bindings (Moeller, Pfister et al., 2016). For example, RR-bindings also mirror the bidirectional quality, observed in RE-bindings and essential in the ideomotor learning mechanism (Moeller and Frings, 2019b, 2019d). Together, the literature on event coding thus seems to support the notion that the mechanisms behind ideomotor learning apply not only to RE- but also to RR- and SS-learning. That is, the same mechanisms that lead to a common representation of pressing a piano key and hearing its sound, may also lead to common representations of pressing the clutch and moving the gearstick, or of hearing the two words “well” and “done”.

Specific indication that repeated co-occurrence of certain stimuli can lead to a combined percept comes from the field of event perception (e.g., Zacks and Swallow, 2007). Here participants tend to interpret the same sequence of perceptions as consisting of longer events (i.e., as a coarse-grained structure) if the sequence was previously viewed five times as compared to unfamiliar sequences (Hard et al., 2006). This fits well with the idea that formerly fine grained individual percepts are associated to more complex percepts over repeated common encounter.

There is also evidence that multiple responses can be represented via one common code and that a learning phase including multiple repetitions of certain response combinations can lead to this. As a first hint, temporo-spatial contiguity apparently also affects formation of action chunks: If a repeated sequence of responses is structured into automatized chunks via varying response-stimulus intervals during a learning phase, participants execute groups of responses also when no external

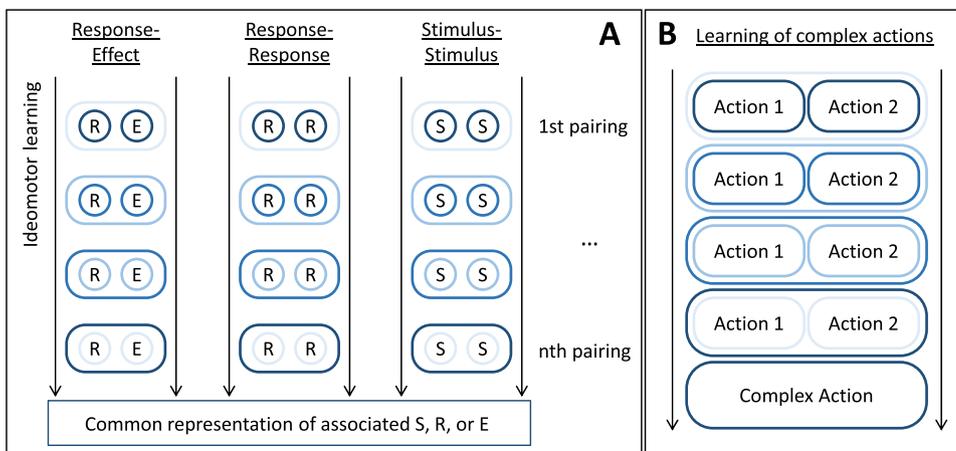


Fig. 1. Representational changes during ideomotor learning (A) Ideomotor learning process in terms of associating response and effect features. The same is proposed for SS- and RR-learning. Darker lines illustrate the activated level of representation. R = response; E = effect; S = stimulus. (B) Application of the same learning process to the representation of increasingly complex actions. Note that each individual action itself comprises a number of features and results from the learning process sketched in the left panel.

timing requires chunking (e.g., Verwey, 1996, Verwey and Dronkert, 1996). Once such chunks have been established, the whole movement sequence usually runs to completion without requiring additional control processes (Dezfouli and Balleine, 2012; Dezfouli et al., 2014). In the same vein, Schmidt (1975) describes how action evolves from controlled but jerky performance to a smooth movement in the formation of a more complex generalized motor program. Finally, action control in skilled typists can also be interpreted to show that individual actions (keystrokes) become associated with other keystrokes to form the more complex individual action of typing a word (e.g., Crump and Logan, 2010a, 2010b; Genter et al., 1988; Inhoff, 1991; Yamaguchi and Logan, 2014). For example, monitoring individual keystrokes while typing words has been observed to disrupt performance in skilled typists (Logan and Crump, 2009). The authors go on to suggest that agents tend to monitor primarily the effects of an action on the outside world rather than body-related effects of the corresponding action. Notably, in this context, the term action refers to the (one) action of typing a word, which includes multiple keystrokes. In addition, response selection for individual keystrokes in skilled typists occurs in parallel (Logan et al., 2011). This again seems to be in line with a compound representation of these keystrokes as one action. Apparently, in skilled typists, individual keypresses turn into one action that can be represented by the word appearing on the screen (for similar ideas in relation to music performance, see Keller and Koch, 2008).

Even more compelling evidence comes from studies on the role of reinforcement learning for the formation of action sequences and habits. Habitual action is at first sight very similar to sequential action, with the important difference that once started, habitual actions are completed even if later parts of the sequence become dispensable (e.g., Dezfouli et al., 2014; Graybiel, 1998). That is, in habitual action, it seems that responses, formerly represented as separable entities have come to be represented as one action, similar to the common representation of response and effect after prolonged ideomotor learning. Learning of habitual actions and of action sequences further involve similar neural circuits, suggesting that action-sequence learning is the underlying mechanism of habit formation (Dezfouli and Balleine, 2012). In line with the present argument, the authors indeed propose that learning results in previously individual goal-directed actions being represented as one more complex action as they become habitual (see also, Balleine, 2019; Dezfouli et al., 2014). A neural basis for such chunking of individual actions into one more complex action entity due to learning experience (i.e., RR-learning) might be found in the striatum (Graybiel, 1998, 2008; see also Dezfouli and Balleine, 2012). Interestingly, these same regions have also been proposed to be involved in stimulus-response and response-outcome learning (Horvitz, 2009) and have also been found to be involved in learning during the procedure that has traditionally been used to investigate ideomotor processes

(Melcher et al., 2013). In a similar vein, and even though a clear differentiation between ideomotor- and other forms of associative learning has been made in research on sequential learning (see Shin et al., 2010), the caudate nucleus was shown to contribute to sequential learning of both perceptual and motor information in a similar and gradual way (Gheysen et al., 2011, see also Forkstam et al., 2006; Gheysen and Fias, 2012; Lieberman et al., 2004; Destrebecqz et al., 2005). That is, the same neural networks are involved in RE-, SS-, and RR-learning. Finally, spike patterns of striatal output neurons as task-related activity of neural ensembles formed during learning and over-training was further shown to reverse during extinction and to reappear during reinstatement (Barnes et al., 2005). That is, representation of distinct actions before learning and their changed representation as one higher order (habitual) action after learning is also observable in neural activity. Together, these findings directly support the idea that SS-, RR-, and RE-learning rely on the same mechanisms.

4. Consequences of embracing ideomotor learning principles also for RR- and SS-associations

4.1. Consequences for the ideomotor principle

Extending the mechanisms behind ideomotor learning explicitly also to RR- and SS-associations obviously completes the notion of ideomotor learning itself. Currently ideomotor learning focuses on associations that emerge between action and effect. Yet, for a novel effect to become included into an action representation, both action and effect need to be represented as individual entities. On the one hand, 'the response' is typically a combination of a number of smaller scale actions that we must have learned to encode as one unitary action, speculatively based on a unitary, Gestalt-like property of the corresponding body-related effects (Klapp and Jagacinski, 2011; Pfister, 2019). Similarly, 'the effect' likely is a combination of individual features or possibly a series of percepts that we must have learned to encode as one unitary percept. Remember the infant and her undirected motor actions, mentioned above. Before she can learn the association between pressing a certain key on her toy and hearing a certain melody, she has to learn a combination of arm, hand, and finger movements to press the button. Similarly, to anticipate the melody, she has to learn to represent a combination of sounds as the melody. That is, before ideomotor response activation is possible, *three* associations have to be learned. First, the association of response features to one action, second, the association of stimulus features to one effect, and third, the widely recognized RE-association. Understanding ideomotor learning as reduced to action-effect learning implies that learning via different mechanisms must have taken place before most of ideomotor action control is possible – a fact that is typically not discussed in related

studies. Intriguingly, if we assume that ideomotor learning mechanisms apply more generally than typically discussed in the past, no other learning mechanism would be strictly necessary for these associations to build. Instead, if associations between contiguous codes are established regardless of whether these refer to actions or to perceptions, the same learning principle that leads to representation of an action via its effect can account for learning that results in unitary representations of complex actions and complex perceptions. Moreover, with ongoing learning, these unitary representations may be further associated with those of other complex actions or percepts (see Fig. 1B). Such pattern is indeed observed in serial reaction time tasks. Such tasks often implement a sequential structure that allows for predicting upcoming stimuli and responses ahead of time (so-called “finite state grammars”). When implementing a grammatically ordered sequence that enables predictions across multiple responses (e.g., statistical regularities enable prediction based on the past four responses), sequence learning still starts with associations between adjacent responses. Only later on can participants make use of longer response sequences to predict further responding (Cleeremans and McClelland, 1991). This same mechanism in turn allows for more complex event representations with increasing expertise (Bédard and Chi, 1992; Chase and Simon, 1973).

4.2. Consequences beyond the ideomotor principle

Applying the (ideomotor) learning principle for RE-, SS-, and RR-associations always means that the representations of two (or possibly also more) individual entities (R and/or S/E) become associated to a degree that their combination results in the representation of a new individual entity. This can be a perceived event (after SS-learning; Hard et al., 2006), a new habit (after RR-learning; Dezfouli et al., 2014), or an extended representation of one’s own action (after RE-learning; Shin et al., 2010). For each of these areas this idea is not necessarily new. Interpreting it as a general principle in the sense of ideomotor learning not only connects these different research areas, but it also integrates the entire range of events, from (the perception of) a single joint movement to (the observation of) everyday activities.

What follows from the mentioned implications, is an integration of the ideomotor principle with a hierarchical view on event perception and action control (see e.g., Balleine et al., 2015; Miller et al., 1960; Rosenbaum, . et al., 1986; Zacks and Swallow, 2007). According to this view, actions can be identified at different levels (Lashley, 1951; Logan and Crump, 2011; Vallacher and Wegner, 1987; Yamaguchi and Logan, 2014). For example, while pressing a key, one might have the goal to communicate an idea, write an essay, formulate a paragraph or sentence, type a word or one might simply want to press a key on the keyboard. With typewriting in mind, it is easily comprehensible that with increasing expertise, higher level representations become possible (e.g., from typing individual letters to typing a word). In fact, it has long been proposed that learning is hierarchical as well (Bryan and Harter, 1897; Leonard and Newman, 1964). That is, low level units of a skill are learned first, allowing formation of higher level units which in turn enable formation of even higher level units (Rosenbaum, 2010). As with the typewriting example, higher level representations oftentimes include an increasing number of lower level actions. Representation of low level units as ever larger entities (i.e., more complex actions) results in control of such complex actions as typing in a skilled typist (Yamaguchi and Logan, 2014). The formation of habits is another example (Dezfouli and Balleine, 2013; Dezfouli et al., 2014). Here, with numerous repetitions of the action sequence in question, individual actions become represented as one more complex habit that is eventually added to the list of available actions. Thus, for some of us the actions of locking one’s door and making sure it is locked by checking the handle, will turn into a habit where the action never stops before checking is completed. Dezfouli and Balleine (2012) point out that control in such a system is best described as hierarchical, with habit processes executing the decisions made by a goal-directed system. An

(ideomotor) learning mechanism that can lead to associations between responses, between stimuli, and also between responses and stimuli could be the mechanism behind such representation formation. Hence, embracing the same learning mechanism for RR- and SS- associations as for RE-associations, enables a view of the ideomotor principle as underlying action control on a much larger scale, namely as a set of mechanisms behind hierarchical action learning and representation as well as habit formation.

Note that these ideas are in line with the more general assumption that association learning is always a candidate mechanism that needs to be considered if any learning takes place (Heyes, 2012). The present suggestion is more specific in that it connects research in the tradition of ideomotor action control with associative learning and hierarchical views on human action and perception. It also goes beyond traditional association formation between stimulus and/or response features by explicitly proposing the formation of one common integrated representation of thus far individually represented stimuli, and/or responses in at least some cases of association learning. With that, it carries a notable characteristic of the ideomotor principle to different aspects of associative learning. Any combination of stimulus-, response-, and effect-features can become a new entity via repeated co-occurrence, in turn connecting various research fields such as action control, learning (also in human development), event segmentation, and expertise.

4.3. Stimuli as responses?

An increasing recognition of the ideomotor principle during the past few decades has accustomed many researchers to the idea that actions (i.e., responses) can be represented as perceptions (i.e., effects). In this last part, we would like to draw attention to the possibility that even these roles may be exchanged. Ideomotor views typically hold that actions are represented in a perceptual form, i.e., in terms of their perceivable consequences. What takes the form of a motor action from the perspective of a remote observer actually is thus represented in terms of its sensory consequences within the cognitive system of the actor. Conversely, the representation of a perceivable stimulus may also be shaped by response-related processes within the cognitive system. These processes include canonical eye movements when visually inspecting an object (Noton and Stark, 1971) as well as inner speech when processing nameable stimuli (Jones and Fernyhough, 2007; Liberman and Mattingly, 1985; Seal et al., 2004). Evidence for these ideas comes, among others, from studies that show classification performance to be affected by phonetic qualities of an object’s name even when participants work with lexical or even pictorial stimuli (Abramson and Goldinger, 1997; McKinstry et al., 2008). Hence, one can make the case that at least some forms or aspects of perception are actions themselves. In this case, ideomotor learning of a response being followed by such a perception actually reflects learning of response-response associations. Possibly, learning this kind of association even has an advantage over associations of perceptions that cannot be interpreted as action: Learning of stimulus-stimulus sequences has been shown to be especially effective if participants have to somehow act on the to-be-learned stimulus-features (e.g., counting them; Hoffmann et al., 2003; Jiménez and Méndez, 1999; note that location features seem to differ here; Koch and Hoffmann, 2000). Finally, if perception often includes action-related aspects, then another differentiation in the literature might lose some of its significance: Object-files were introduced as temporary integration of object features that enable object perception (Kahneman and Treisman, 1984). This idea of an object-file was extended to include also response features in order to accommodate event coding (*event-file*; Hommel, 2004). However, if action can be part of perception, the main difference between object- and event-files would be that the label of the former comes with a decisively perceptual focus whereas the latter makes the integration of response features explicit.

5. Conclusion

Applying the theoretical notion of common coding to ideomotor learning allows for an integrative (ideomotor) model of several associations that might look rather different at first sight. If representational codes of actions and perceptions do not differ, however, any mechanism that allows for associating representations based on contingency and contiguity will yield response-stimulus, response-response, and stimulus-stimulus associations alike. Such a more generalized learning principle can account for all learning that is necessary to apply ideomotor models also to more complex, hierarchical actions.

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Funding

The research was supported by a grant of the Deutsche Forschungsgemeinschaft to Birte Moeller (MO 2839/2–2). Correspondence concerning this article may be addressed to Birte Moeller, University of Trier, Department of Psychology, Campus I, D-54286 Trier, Germany (Email: moellerb@uni-trier.de) or Roland Pfister (roland.pfister@psychologie.uni-wuerzburg.de).

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