I Binding/Retrieval in Action Production

I.1 Binding and Retrieval of Action Effects

Bernhard Hommel, Wilfried Kunde, & Klaus Rothermund

The role of action effects in action control

Humans are generally assumed to carry out intentional actions, at least most of the time. Intentional actions are defined as movements that serve to realize particular outcomes, which means that intentional agents need to have some idea about what outcomes a particular movement can achieve. How do they acquire such knowledge? This has been the main question of so-called ideomotor approaches since Lotze (1852), Harless (1861), or James (1890). Ideomotor theories assume that the newborn or the novice begin by moving in a more or less random fashion but learn to associate each movement with the sensory consequences it generates. For instance, newborns might first be driven by very simple reflexes, like the grasping reflex, but slowly learn that most grasping actions are successful in getting hold of particular objects or even body parts of their parents. The same is true for novices, as learning to ski will involve the building of associations between leaning to the left or right, say, and steering in a particular direction. If ideomotor learning consists in associating particular action patterns with the cognitive representation of its sensory consequences, so the idea, the emerging association can be used the other way around: the newborn or novice can reactivate the cognitive representation of the intended sensory consequences (by "thinking of them"), which would prime and reactivate the associated motor pattern. Hence, people can learn to act intentionally by binding motor codes to representations of the sensory consequences that using the corresponding motor patterns has been learned to generate.

More recent theories, like the Theory of Event Coding (TEC; Hommel, et al., 2001), have modernized ideomotor thinking by assuming that ideomotor learning consists in acquiring event files (Hommel, 2004) that integrate pointers to motor patterns with codes of the features of the sensory consequences that carrying out these motor patterns were

Commented [RP1]: I never quite understood the focus on newborns that we have basically inherited from Herbart if I see correctly. By the time a newborn spawns it has already had months worth of intrauterine athletic experiences to work out some action-effect associations.

Commented [BH2R1]: This focus does not invalidate what is being said. Prenatal experience and learning is possible, but we do not really know whether reflexes are already in place and how much learning has been achieved.

Commented [WK3R1]: Your basically right Roland. The bad thing with birth, however, is that most of what the fetus has acquired in the cosy intrauterine environment arguably becomes useless when gravitation kicks in at birth. This point has been nicely worked out by Tal Ravid-Roth, a PhD student of Baruch, in one or two papers that should appear soon. She argues that at birth action-effect learning more or less starts from scratch, and it does so with so with eye movements and corresponding visual experiences. But I guess we need not dig into this at this point.

experienced to produce. As we will see later in this chapter, these event files are likely to also include other information, like to be expected reward, affective consequences, and task conditions, but the basic ingredients that are driving the acquisition of intentional action consist of pointers to motor patterns and codes of sensory consequences (aka action effects). In the following, we will first explain whether and how the binding of pointers to motor patterns and sensory codes into event files works, how the binding process and its consequences can be experimentally analyzed, and what basic empirical effects can be observed in the different paradigms. We then turn to neuroscientific studies that have begun to reveal the physiological underpinnings of action-effect binding, and we will briefly touch the methodological approaches of the studies and key findings. Next, we will expand the discussion to include other ingredients of event files, like the affective consequences of actions and to be expected reward or punishment that actions have been experienced to come with. Finally, we will present a brief overview of important moderators of action-effect binding, like development, task instructions, attention, and more.

Experimental analyses of binding and retrieval of action effects

It is a common challenge in the Cognitive Sciences that the cognitive representations and mechanisms proposed to be behind behavior cannot be observed directly. This holds true as well for the idea that motor activities become linked to their perceptual consequences (i.e., effects), and are retrieved through codes of these effects. Consequently, we need some behavioral indications for such linkages (i.e., action-effect bindings) and their retrieval.

Induction paradigms. A first approach to provide such evidence can be termed induction logic (Greenwald, 1970; Prinz, 1997). If pointers to motor activities become bound to codes of perceptual consequences, then after such bindings have been established, the perception of such consequences should to some extent ‘induce’ or prime the motor activities to which they had become bound previously. Imitation, thus the tendency to repeat the movements we observe in others might be explained that way. The visual experience of a

body movement of another person resembles the visual experience of own body movements and thus primes exactly these body movements (Heyes, 2011).

However, induction extends far beyond the observation of body movements and can be demonstrated for arbitrary novel visual or auditory action consequences. In a typical induction experiment participants first experience that certain motor activities, such as two different keypresses, consistently produce two different effects (e.g., two different tones). Then, in a subsequent test phase, the presentation of these tones as stimuli creates a bias toward producing the keypress that had produced these effects in the preceding learning phase when freely choosing between keypresses (e.g., Elsner & Hommel, 2001; Janczyk et al., 2023).

In another version of the paradigm response times (RTs) are shortened if participants are required to respond to these effects in a manner that is consistent rather than inconsistent to the previous response-effect mapping of the learning phase (Elsner & Hommel, 2001). Moreover, RTs of responses to imperative stimuli in the test phase are lower if these imperative stimuli are accompanied by nominally irrelevant effects of the preceding learning phase that match rather than mismatch the required response (Hommel, 1996).

With versions of this induction paradigm several characteristics of induction have been studied, such as the role of awareness for such induction (Kunde, 2004; Le Bars et al., 2016; Schreiner & Kunde, 2025), the dependency on dual task-load (e.g., Janczyk & Kunde, 2020; Weller et al., 2017), or amount of learning experience required (Ruge & Wolfensteller, 2011). Regarding the latter point, it seems that contrary to the original idea of association building, even single encounters of action-effect episodes can result in the formation of action-effect bindings and create subsequent induction (Dutzi & Hommel, 2009; Moeller et al., 2019).

Anticipation paradigms. Induction paradigms strongly support the assumption that bindings between pointers to motor activities and perceptual consequences are acquired and that perceiving such consequences activates the motor activities to which they are bound. Induction phenomena obtained in behavioral studies leave it open, though, whether codes of

Commented [RP4]: Maybe cite the multi-lab replication by Markus et al.?

Janczyk, M., Giesen, C. G., Moeller, B., Dignath, D., & Pfister, R. (2023). Perception and action as viewed from the Theory of Event Coding: A multi-lab replication and effect size estimation of common experimental designs. Psychological Research, 87, 1012-1042. doi: 10.1007/s00426-022-01705-8

Commented [BH5R4]: done

consequences really precede motor generation in cases where such consequences are not already perceivable prior to acting, as is the case in induction paradigms. This is crucial, as we barely reproduce what we perceive already. Rather, humans mostly aim at actively generating perceptual consequences (i.e., goals) that are intended but not yet present.

Here all kinds of anticipation paradigms come into play (Rosenbaum & Krist, 1996). In these paradigms it is typically observed that features of foreseeable perceptual consequences of motor activities shape the production of these motor activities in one way or another. For example, it takes longer to produce a motor activity if the foreseeable environment-related consequences of the activity mismatch the body-related consequences of the required motor activity (Chen & Proctor, 2013; Hommel, 1993; Kunde et al., 2004; Pfister & Kunde, 2013). Also, responses like a keypress last longer if this keypress foreseeably produces a short rather than long auditory effect (Tonn et al., 2023). In all these situations the perceptual consequences are not yet physically present as a stimulus while the motor activity is generated. Hence, such observations show that some representation of the anticipated perceptual consequences must be active while the motor activity is generated, presumably because they serve as internal retrieval cues for that very motor activity as proposed by ideomotor theory.

Research with these kinds of paradigms has revealed many aspects of the anticipation process, such that it codes dynamical changes of stimulation from before the body movement to stimulation after that movement (Schaaf et al., in press). Moreover, even reactions of other people to our own behavior can serve as retrieval cues for that behavior if these reactions occur in a sufficiently foreseeable manner (Kunde et al., 2018; Paulus, 2025).

Dual action. A related approach relies on dual actions, hence situations in which two motor activities are required in close temporal proximity. For example, if motor activities are actually retrieved through codes of their perceptual consequences, then the overlap of perceptual consequences of a required and concurrently planned action should leave a trace in behavior. In fact, such influences have been observed. If the body-related (Stoet &

Hommel, 1999) or environment-related (Mocke et al., 2020) consequences of a required motor activity overlap partly, but not fully, with the consequences of another planned activity, there is a performance decrement as compared to no such overlap. The likely reason behind this finding is that the perceptual consequences that mediate the production and planning of motor activities are represented in a distributed, feature-based manner, such that the use of a feature for one purpose renders this feature less accessible for generating another motor activity. We refer the reader to the chapter on action planning (see chapter II.2), in which research along these lines is discussed in more detail.

Neuroscientific analyses of binding and retrieval of action effects

While the available findings from behavioral studies provide strong support for the assumption that people are picking up the contingencies between their movements and the sensory consequences these movements generate, and that they are using this knowledge for planning and selecting intentional actions, many theoretical claims are hard to test with behavioral studies alone. For instance, how do we know that people are using the same representations to code events that they perceive and the events that they generate? How do we know how much sensory detail is being used to code action effect and intended action outcomes? How do we know that perceiving action effects really activates motor codes that are related to these effects? The available behavioral evidence might be taken to suggest some answers, but how close they are to the truth is hard to tell. Fortunately, however, various neuroscientific methods are available to provide converging evidence and additional testing opportunities. Most of the available studies on action-effect integration and the use of the integrated information for planning intentional actions are using EEG and fMRI.

For instance, Band et al. (2009) used EEG to test whether and under which circumstances people pick up self-generated sensory effects. Participants were presented with task-relevant (i.e., informative) feedback and other, task-irrelevant (i.e., uninformative) action-contingent stimuli. As expected, task-relevant feedback induced the so-called feedback-related negativity—an electrophysiological component that is known to come with

Commented [RP6]: At least a nod towards Kunde et al. 2002 seems warranted here

Commented [WK7R6]: Thank you for pointing into the history of psychology, Roland. But that paper tells a slightly more complicated story, as there were partial overlap benefits only. The reasons have later been resolved by Viola (task-relevance of action effects matters), but I think this story is better hosted in the chapter on action planning.

Commented [RP8]: To me, this section felt the least developped in terms of what it adds to your theoretical argument, especially considering the number of words spent on discussing these studies relative to the work in the preceding section.

[And, as a minor observation: This section reads very different from the previous parts in that it singles out specific studies by highly detailed in-text citations throughout. I am personally not a big fan of this style in any case, but here it felt particularly strange. Take this statement for instance: „These basic findings were later replicated in an fMRI study by Melcher, Weidema, Eenshuistra, Hommel, and Gruber (2008)." It only seems to say that Tobias did some fMRI stuff in the past. I do love Tobias - he introduced me to the incredible Sambesi restaurant in Göttingen, among other things - but I don't see how this type of storytelling actually builds a strong storyline]

Commented [BH9R8]: I did not really understand these comments. They seem to imply quite some degree of unfamiliarity with how mechanisms are being discussed in the cognitive neurosciences. Especially the comments on Melcher et al. reveals that: PET is often taken as low-tech with limited resolution, so that replication in the much better resolved fMRI is particularly relevant for many readers with stronger neuroscience expertise.

KR: Again, maybe highlight this point explicitly?

Commented [RP10]: It would be good to spell out what claims you have in mind here

Commented [BH11R10]: done

performance-related feedback. Interestingly, however, the same component was also induced by task-irrelevant action-contingent stimuli. This shows that people apparently learn contingencies between their actions and the sensory effects thereof spontaneously and actively predict the occurrence of the latter when carrying out the former. This is also suggested by another EEG study of Dignath, et al. (2020). They presented action effects that were flickering in a particular frequency and demonstrated that, during action planning, this particular frequency was dominant in entraining neural activity.

Other studies tested the prediction of ideomotor theories, including TEC, that the activation of action-effect representations primes neural structures which are arguably involved in generating the motor pattern which previously was experienced to produce these action effects. Elsner et al. (2002) used PET in a study where participants were first exposed to action-contingent sensory stimuli and then later were presented with the stimuli while passively waiting for another stimulus event. As ideomotor theory predicts, activated areas in the supplementary motor cortex, which is known to underlie intentional action planning, and areas in the hippocampus, which presumably held the link between actions and sensory consequences. These basic findings were later replicated in an fMRI study by Melcher et al. (2008), which provides an even more detailed picture of the involved neural structures than PET.

While these studies provided first proof of principle, later research revealed more details about the underlying processes. For instance, Kühn, Keizer, Colzato et al. (2011) used fMRI to trace the activation of neural stimulus and action codes over time and conditions. Stimuli consisted of pictures of faces and places, as they are known to be coded in the fusiform face area and the parahippocampal place area, respectively. After these areas were located in every participant, it was possible to trace the relative activation induced by face or place pictures, in addition to the activation of the motor cortex due to pressing the response keys. As it turned out, repeating a stimulus reactivated the action that it accompanied in the previous trial, and repeating an action reactivated the representation of the stimulus that it was previously accompanied by. This provides strong evidence that the

Commented [RP12]: Are these studies meant to showcase evidence for claims that cannot be addressed by behavioral work? I don't think they make particularly good examples for this case, at least if the conclusion is „This shows that people apparently learn contingencies between their actions and the sensory effects thereof spontaneously and actively predict the occurrence of the latter when carrying out the former. " -> this seems to be exactly the conclusion that you had also drawn from Anticipation paradigms above.

I'd suggest fielding other studies that actually make a unique case (if there are such studies) or instead discuss this work as converging rather than qualitatively different evidence.

Commented [BH13R12]: Again, a comment that is not particularly well informed by discussions in the cognitive neurosciences. Demonstrating that an EEG component that is considered to be sensitive to intentionally process feedback in tasks that rely on feedback is just as sensitive to task-irrelevant action effects has a strong impact on the theoretical and functional interpretation of this component.

KR: Well, if that's the point, maybe you can make it more explicit?

Commented [RP14]: This seems to be a claim that behavioral Induction paradigms also test

Commented [BH15R14]: This comment ignores two issues: first, it assumes that knowing which brain areas are busy with ideomotor processing is entirely irrelevant, which I think is a questionable assumption, because these areas provide constraints for theoretical interpretations. Second, it ignores the possibility that behavioral research cannot exclude that the same outcome is generated by entirely different mechanisms, whereas finding that the exact same brain areas are involved reduces this possibility.

Commented [WK16R14]: I've changed a bit the first sentence to make clearer that we are now going beyond purely behavioral observations.

mere co-occurrence of stimuli and actions induces the binding of the neural representations of the two, and that encountering either of the components another time tends to retrieve the other—as the ideomotor principle requires. Along these lines, Kühn, Keizer, Rombouts, and Hommel (2011) tested whether action-effect representations are actively involved in intentional action planning. They had participants respond to color stimuli by means of a hand action (pressing a left or right key) or a facial action (smiling or kissing). Interestingly, planning a hand action activated the extrastriate body area, which is known to code for perceived non-facial body parts, whereas planning a facial action activated the fusiform face area, which is known to code for perceived faces. A later study revealed that the preparation of hand or face actions also increases the precision of neural activation patterns in the extrastriate body area and the fusiform face area, respectively (van Steenbergen et al., 2017). Thus, people do seem to anticipate the perception of the sensory consequences of their actions (as the extrastriate body area and the fusiform face area are housing perceptual representations), and they do so during the action-planning process—as ideomotor theorizing claims.

Taken altogether, the available neuroscientific evidence provides strong support for the ideomotor approach to intentional action and the particular role of action-effect binding this approach suggests. Moreover, it provides a first view into the mechanics underlying ideomotor action control and into the processes that are involved in the binding and retrieval of the integrated event files that underlie human action control.

Commented [RP17]: Not sure how this follows from the studies that you discuss above

Commented [BH18R17]: See above

Acquisition of affective action effects

In 1884, William James published an article on what one may consider an ideomotor approach to human emotion. He basically claimed that emotions emerge from self-perception: if an emotional stimulus, like a snake, say, is registered, it is assumed to induce a particular action tendency, like running away, and it is the perception of one's own action or action tendency that creates the emotion. In other words, we are afraid because we are escaping, and we are sad because we cry. This theoretical approach was more recently

rediscovered and revived by Damasio (1994), who also assumed that emotions are strongly tied to actions and action tendencies. More specifically, he claimed that people create so-called somatic markers that represent the affective consequences of one's actions. It may often be these somatic markers that are guiding action selection, in the sense that one tends to pick actions that are expected to induce positive affect (Eder, 2023; Eder & Rothermund, 2013; Eder et al., 2015).

From this perspective, it would make sense to assume that the event files that are representing one's action repertoire also include information about affective states, and about action-contingent affective states in particular. To test this prediction, researchers have used several of the above-mentioned behavioral paradigms, but replaced the typical non-affective, sensory action effects by more emotional material. For instance, Eder and Klauer (2009, 2010) found that carrying out responses that are emotionally charged (e.g., by systematically carrying them out to indicate, or approach or avoid, positive or negative events) make it more difficult to perceive affectively compatible stimuli. Hence, carrying out an avoidance action induces more errors in perceiving a masked negative stimulus than perceiving a masked positive stimulus, and vice versa. This suggests that the features "positive" and "negative" can be bound to responses and are thus less available for coding temporarily close visual stimuli (Eder et al., 2012).

Lavender and Hommel (2007) reported that people are faster in moving a doll towards a positive picture and away from a negative picture than moving it towards a negative and away from a positive picture. This suggests that the action's goal of approaching or avoiding charged the action in positive or negative terms, and that the affective value these terms imply became part of the action representation (Eder & Rothermund, 2008). In other words, the affective consequences of actions are integrated into the event file representing these actions. This is also suggested by observations from Coll and Grandjean (2016), that affectively neutral responses can be emotionally charged by presenting pictures of faces with angry or fearful expressions as action effects. If event files can integrate codes of positive and negative affect, one would expect that they tend to be

reactivated in the presence of positive or negative stimuli or, more specifically, in the presence of stimuli that arouse positive or negative affect. Indeed, stimuli that are sufficiently equivocal to induce stimulus conflict were found to facilitate avoidance behavior (Dignath & Eder, 2015).

The role of reinforcement

Basic principles of learning suggest that behavior is not just a function of the frequency of previous Stimulus-Response (S-R) or Response-Effect (R-E) pairings ("law of exercise"; Thorndike, 1898), but is also governed by reinforcement, that is, by the affective quality of the consequences that are produced by an action ("law of effect"; Thorndike, 1898). To account for these effects of instrumental learning it is key to investigate the affective quality of action effects (reward vs. punishment) and its moderating influence on basic mechanisms of action control (see also chapter IV.1 on Binding and Retrieval and Pavlovian and Instrumental Learning). These questions have been addressed in several studies, using different paradigms.

A study by Eder et al. (2013; see also Muhle-Karbe & Krebs, 2012) used a standard action-effect learning (i.e., induction) paradigm, in which simple keypresses were linked to distinct but neutral auditory sounds in a training phase. A subset of these responses was additionally predictive of either monetary gains (reward) or losses (punishment). Presenting the sounds as response cues in a later test phase generally facilitated responding with the key that had produced this sound during training, replicating the standard induction effect. Furthermore, this effect was stronger for responses that had been rewarded during training, but was not weakened for punished responses.

While this finding seems to suggest a modulating role of reward for the strength of action-effect learning, other studies paint a different picture. A study by Eder et al. (2015) showed that both positive *and* negative cues facilitated responses that predictably produced effects of the same valence. Similarly, Mocke et al. (2025) found that anticipating a positive/negative outcome facilitates responses that had produced a consequence of the

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Commented [RP21]: Induction?

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same valence in the preceding trial. While these results are generally in line with principles of ideomotor theory in that cues activate responses that produce these cues, the lack of a modulating role of valence for these effects suggests that the ideomotor principle is immune to reinforcement, and simply operates on the basis of code similarity. Accordingly, valence (both positive and negative) is just one sensory feature among others that can trigger responses that produce corresponding sensory codes as outcomes.

In this regard, it is instructive to note that Eder et al. (2015) did find an influence of effect valence on response selection in a free choice paradigm, with responses producing positive outcomes being generally chosen more often than responses that were linked to negative effects. In sum, these findings suggest that automatic processes of response activation operate independently of reinforcement, with both positive and negative consequences triggering actions that produce effects of corresponding valence (directive influence of affective consequences), whereas strategic processes of action selection are influenced by propositional beliefs regarding the valence of response outcomes (incentive function of outcomes on strategic choice and propositional learning; De Houwer, 2009).

Association versus episodic binding and retrieval

Classical versions of ideomotor theory have assumed that extended practice is needed to form stable associative links between actions and their effects in long-term memory. This is considered as a pre-requisite for outcomes leading to an activation of the corresponding response via these associative links. In contrast, both the TEC (Hommel et al., 2001) and the Binding and Retrieval in Action Control account (BRAC, Frings et al., 2020, 202) explain effects of action control in terms of flexible episodic bindings and their retrieval (see also Schmidt et al., 2016). According to episodic accounts of action control, the simultaneous occurrence of stimuli, responses, and outcomes within a coherent action episode leads to an integrated representation of the codes of these components in episodic memory (an “event file”; Hommel, 1998, 2004). The elements of such an event file can mutually re-activate each other when one of the elements of the assembly is re-encountered.

Thus, ideomotor theory and the BRAC framework show striking similarities regarding the principles of action-effect integration, and mutual or bidirectional re-activation. However, the essential difference between the two accounts is that the latter assumes that effects are driven by a retrieval of distinct episodic bindings, while the former assumes that action control is mediated by associative links that are formed during repeated co-occurrences during an extended practice phase.

Current evidence clearly attests to the validity of episodic accounts: Several studies demonstrated the basic principles of action-effect binding and retrieval for single occurrences of action-effect combinations, that is, in the complete absence of practice or to-be-learned contingencies (e.g., Dutzi & Hommel, 2009; Mocke et al., 2025; Moeller et al., 2016, 2019), which can only be explained in terms of episodic binding and retrieval processes (e.g., TEC, Hommel et al., 2001; the BRAC model, Frings et al., 2020, or the PEP model, Schmidt et al., 2016). Furthermore, contingencies are typically confounded with episodic retrieval, since highly frequent combinations (e.g., of action and effect) have a higher chance to be retrieved because they occur more frequently and thus have been encountered with a higher likelihood during the previous episodes (“law of recency”; Giesen et al., 2020; Schmidt et al., 2020; for more details, see chapter IV.2 on Binding and Retrieval and Contingency Learning). Episodic retrieval has been shown to explain the lion’s share of S-R contingency effects, with only small effects surviving after controlling for episodic retrieval, and these residual effects typically reflecting propositional knowledge rather than associations (e.g., Giesen, Duderstadt, et al., 2025; Giesen, Rudolph, et al., 2025; Rudolph & Rothermund, 2025; Rudolph et al., 2025).

The standard way to test associative effects of contingencies that are free from episodic retrieval is to establish contingencies in a training phase, and to test the effects of action control in a later test phase in which these contingencies no longer hold (i.e., during extinction), so that recency-based episodic retrieval can no longer explain these effects (e.g., Rothermund et al., 2025). With regard to action-effect learning, it is instructive that Eder et al. (2015) found that cuing effects of valent outcomes on responding were dependent on the

responses producing their effects also during the test phase, indicating that effects were not mediated by associations that had been previously acquired during training, but most likely reflected retrieval of recent action-effect episodes during the test phase itself. Similarly, recent evidence was taken to suggest that effects of action-contingencies are mediated by propositional knowledge rather than associative links (Sun et al., 2020, 2022).

In sum then, research suggests that action-effect learning is to a large extent mediated by episodic binding and retrieval, while other modes of acquisition (associative learning, observation learning, instruction; cf. Kunde & Janczyk, 2024) can at present not be ultimately excluded. Related to this question, current research investigates whether and when transient episodic bindings can become transferred into stable representations in long-term memory (e.g., Frings et al., 2024b; Rudolph & Rothermund, in press). Addressing it also in the context of action-effect learning is a major goal for future research to better understand the underlying processes of action control.

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Glossary

Event file

Integrated representation of the components of an experience event, commonly comprising of codes of stimulus features, response features, contextual features, the task representation, possible affective codes, (pointers to) motor patterns, and more (Hommel, 2004).

Theory of Event Coding

The Theory of Event Coding (TEC) is a cognitive framework that argues for the common coding of perception and action, suggesting that both are interrelated components of human information processing represented by feature codes in event files. It claims that actions are represented by codes of their perceptual consequences (action effects), which are integrated with corresponding stimulus, contextual, and action features into event file.