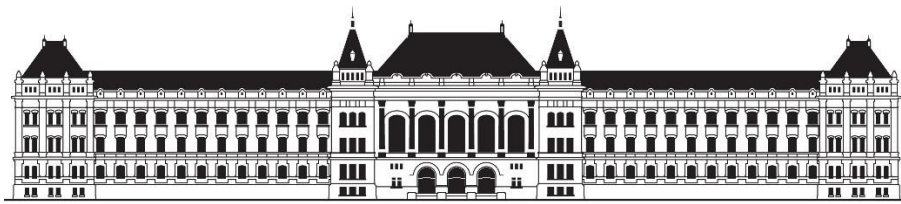


THE ROLE OF STIMULI AND MOTOR FEATURES IN THE REPRESENTATION AND OPTIMISATION OF ACTIONS

PhD Thesis booklet



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Introduction and aims

We are in constant interaction with our modern environment. For example, we press buttons when handling kitchen appliances, and we click with a mouse when operating a computer. These basic interactions rely heavily on the sensory consequences of our actions, in more than one way. Sensory action effects are not only used for learning (Wolpert et al., 2011), but they are also considered to be the means by which we gain access to our motor system. This latter idea has been around since the middle of the 19th century in the form of the *ideomotor theory* (Herbart, 1816; Lotze, 1852; Harless, 1861; James, 1890). The basic proposal of the theory was that our actions and their sensory consequences become coupled through regular use, suggesting the following, seemingly radical claim: by imagining sensory effects we can produce movements that actually bring about those effects (hence the term *ideo-motor*). Recent theories and approaches that build upon the ideomotor principle, such as the Theory of Event Coding (TEC; Hommel et al., 2001; Hommel, 2019) and the Binding and Retrieval in Action Control (BRAC; Frings et al., 2020) assume the existence of two processes, feature binding and retrieval. As its name suggests, feature binding states that features of stimuli, responses to these stimuli and following effects are bound together into shared representations called event files. Conversely, the retrieval of one of these features (be it stimulus, response or effect-related) retrieves all other associated features, and these can impact performance.

A different role of sensory action effects can be seen in action-effect-related motor adaptation (Neszmélyi & Horváth, 2017, 2018, 2019; Horváth et al., 2018). This term denotes a process in which incidentally occurring action effects are not ignored by the cognitive system but are used in action optimisation. Specifically, in tasks in which actions elicit tones, actions are

carried out with less force compared to a setting in which actions do not produce such effects. It is also the case that in a block of tone-eliciting actions, the exerted force continually decreases, possibly until an optimum is reached.

These processes, binding/retrieval and action-effect-related motor adaptation are the subjects of this thesis. Starting with the former, studies that report binding and retrieval effects typically use tasks in which more than one categorical action option is available (such as left/right-handed keypresses). Furthermore, the studied features are commonly relevant to the task at hand (e.g. participants have to maintain a similar distribution of left- and right-handed actions). In our studies, we investigated whether features of actual movements (action properties that are task-irrelevant and continuous), like force and duration, also become bound to and retrieved by salient stimuli.

Turning to the topic of action-effect-related motor adaptation, in our study, we investigated the question of action-effect predictability. Because previous studies used a blocked design in which actions either always or never elicited tone effects, it remained an open question whether motor adaptation can arise if the arrival of action effects is unpredictable. Because motor adaptation is considered to be a somewhat automatic process, we hypothesised that it ought to arise even in a context where the action outcome is unreliable.

Thesis points

Thesis point 1: Task-irrelevant, continuous properties of actions can become bound to and retrieved by auditory action effects

Studies on binding and retrieval typically pair discrete actions with following sensory effects on a prime trial and then observe specific behavioural changes on a probe trial where the previously encountered stimulus either repeats or changes (e.g. Dutzi & Hommel, 2009; Herwig & Waszak, 2012; Janczyk et al., 2012). In a free-choice setting, participants can have two response options (such as a left- or right-handed keypress), and response changes can manifest themselves in a tendency to repeat the previous action (if the stimulus repeats from prime to probe). In a forced-choice setting, behavioural changes can be observed in response time differences (Moeller et al., 2016, 2019).

But what about the retrieval of actual movement features? Even simple actions can be characterised by a multitude of metric, task-irrelevant properties that may become bound to and retrieved by sensory effects. Furthermore, as opposed to the previously mentioned decision categories, these properties are present and can be studied even if a single interaction option is present.

To investigate these questions, we devised a modified action-effect binding paradigm, in which participants had a single response option, the pinching of a force-sensitive device. In two separate experiments, actions on the prime elicited either high- or low-pitched tones that either repeated (congruent trials) or changed (incongruent trials) from prime to probe. On the probe, tones served as a go signal, requiring a quick response. We studied action force, duration and

reaction times to the probe. We hypothesised that actions would be more similar to each other (between prime and probe), and they would be initiated faster on the probe in congruent trials compared to incongruent trials.

Results showed some evidence of binding and retrieval, especially when it comes to correlations of action duration and response time differences. Other measures, such as peak force and impulse, while pointing to the same general direction, did not result in significant differences. We argued that the difference in measures may be partly attributed to accessibility, with action duration being more readily observable and perhaps weighted differently than action force. It might also be the case that task-irrelevant action features might not be retrieved to the same extent as task-relevant features. I return to the question of task-relevance in Thesis point 3.

Relevant study for this thesis point: Study 1

Varga, S., Pfister, R., Neszemlyi, B., Kunde, W., & Horváth, J. (2022). Binding of Task-Irrelevant Action Features and Auditory Action Effects. *Journal of Cognition*, 5(1), 35.

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Thesis point 2: A difference in change detection cannot explain results attributed to feature binding and retrieval

The binding studies described in this thesis naturally interpret results in prime-probe paradigms as evidence of binding and retrieval. However, there may be a few confounds that can question these interpretations. In the case of studies using two response options, one such potential confound could be an underlying strategy. Simply put, a stimulus change may signal

participants to change their response, while the repetition of the stimulus may be interpreted as a signal for response repetition. Evidence of the existence of such a signalling heuristic indicates that binding and signalling can both contribute to a pattern of results typically attributed to binding and retrieval (Weissman et al., 2023). However, this may not be the only potential confound. When a stimulus repeats, its sensory processing may be reduced (Näätänen, & Picton, 1987). This suggests that stimuli in congruent and incongruent trials may be processed differently, with the stimulus change receiving amplified processing, thus possibly leading to differences in arousal or attentional allocation. If such an effect was indeed present, it would lead to the alternative explanation stating that differences in reaction times (such as the one described in Study 1) do not reflect binding and retrieval but a difference in change perception and processing. This would be especially problematic in a task where a single interaction option is present (such as in our experiments).

To test an alternative explanation based on change detection, we repeated Experiment 1 from Study 1 along a control condition in which participants had to react to the second tone of a pair of repeating or changing tones. We hypothesised that if binding and retrieval are indeed the better explanation, there would be an interaction between condition and congruency, with a difference in reaction times being observable in the experimental condition, but not in the control condition.

Reaction time comparisons showed results favouring an explanation based on binding and retrieval, with increased reaction times in incongruent trials compared to congruent trials in the experimental condition, but not in the control condition. This suggests that a difference in change detection is not enough to produce the results attributed to binding and retrieval.

Relevant study for this thesis point: Study 2

Varga, S., Pfister, R., Neszmeélyi, B., Kunde, W., & Horváth, J. (2024). Task-relevance and change detection in action-effect binding. *Acta Psychologica*, 243:104147.

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Thesis point 3: Task-relevance can influence the binding and retrieval of continuous properties of actions, possibly mediated by relevance-induced variance

The force and duration comparisons presented in Study 1 and Experiment 1 of Study 2 gave inconclusive results. Some task-irrelevant, continuous properties of actions (most notably action duration) did seem to get bound to and retrieved by auditory stimuli in some experiments, but not in others. When it comes to force, actions were more similar to each other in congruent than in incongruent trials, but this difference was not significant. What could explain the inconsistency of the effect when it comes to these motor features? In Study 1 we argued that task-relevance may be a key factor. It could be that task-irrelevant properties are not retrieved to the same extent as task-relevant features. As a related point, it could also be that throughout the experiment, participants settle into a level of force that is comfortable, without having a reason to vary responses, consequently leading to the variability of actions being too low.

To mitigate this, in a modified experiment, we asked participants to spontaneously carry out weak and forceful actions on a prime trial, while trying to maintain an overall similar distribution of weak and forceful actions throughout the experiment. The second action on the probe was a quick reaction to the tone (as in previous experiments), with its force being irrelevant

and freely chosen. This simple change in instruction made force task-relevant on the prime (but importantly, not on the probe), and it also increased its variability.

Our results showed that actions on the prime and probe were more similar to each other when it comes to both force and duration in congruent trials, compared to incongruent trials, suggesting that continuous action features do become bound to and retrieved by auditory stimuli.

The manipulation of instruction may suggest that task-relevance per se is the key factor that results in the congruency effect in force and duration. While this may be the case, there are arguments to prefer an explanation based on increased variance. Most notably, while binding is considered to be the more non-selective and automatic process (Kiesel et al., 2023), in the case of retrieval, attention and other top-down factors can play important roles in determining what gets retrieved (Moeller and Frings, 2014). In our experiment, action force was still irrelevant on the probe, suggesting that the result may be attributed to increased variability.

Relevant study for this thesis point: Study 2

Varga, S., Pfister, R., Neszmeleyi, B., Kunde, W., & Horváth, J. (2024). Task-relevance and change

detection in action-effect binding. *Acta Psychologica*, 243:104147.

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Thesis point 4: Unpredictable sensory action effects are used in the optimisation of ongoing and upcoming actions

The research I presented on the topic of action-effect-related motor adaptation demonstrates that simple, repetitive actions, such as pinches, taps and button presses are carried out with smaller force when they elicit salient and predictable sensory effects. This seems to reflect a certain adaptation phenomenon, in which participants reduce the exerted force until an optimum is reached, possibly striking a balance between effort (energy conservation) on the one hand, and maintaining a high probability of action success on the other hand. Because of the blocked design of these studies, the action-effect relationship was highly predictable in all experiments. Furthermore, while in one of the studies presented, self-initiated tones were intermixed with externally generated ones (Neszmélyi and Horváth, 2019), the physical link between action and effect was intact.

This leaves open the question of how action-effect-related motor adaptation arises and changes from trial to trial when the link between action and effect is unpredictable. To investigate this question, we asked participants to carry out pinches with a constant between-pinch interval of 3 seconds. Half of the actions elicited a salient tone, while the other half did not. The order of tone-producing and tone-absent trials was random. We collected sequences of four actions with different histories of tone-elicitation patterns and compared the last action of each sequence. We found that actions that were preceded by tone-eliciting actions were softer than pinches preceded by sequences of tone-absent actions. Interestingly, contrary to our pre-experiment expectations, actions were also modulated on the fly, suggesting that participants

modified the force of ongoing actions as a reaction to the tone. This indicated that pinches were not entirely ballistic actions.

To study the phenomenon without on-the-fly adjustments, we repeated the experiment but changed the required response. The force-sensitive device was glued to the surface of a table and instead of pinching, the required action was to tap it. Because tapping has two well-distinguishable force peaks and is usually briefer than pinching, we expected this change would allow us to better control for the possibility of online adjustments. As expected, the modification eliminated the presence of on-the-fly adjustments, while maintaining the effect of offline adjustments. As in Experiment 1, actions preceded by tone-eliciting actions were softer than taps preceded by silent actions. The two experiments demonstrate that action-effect-related motor adaptation can arise even when the tone effect is unpredictable, and in the case of longer actions, such as pinches, this can even happen on an on-the-fly basis.

Relevant study for this thesis point: Study 3

Varga, S., Neszmeélyi, B., Hajdú, N., & Horváth, J. (2022). The emergence of action-effect-related

motor adaptation amidst outcome unpredictability. *Journal of Experimental Psychology:*

Human Perception and Performance, 48(7), 711–723.

<https://doi.org/10.1037/xhp0001021>

General discussion and conclusion

I have argued that existing research on binding and retrieval paints a convincing picture of the importance of action effects. However, this research tended to focus on decision categories—or to put it differently: action selection—leaving the question of actual execution unanswered. In our first study on the topic, we asked the question explicitly: What gets bound in action-effect bindings? While the ‘leftness’ of a left-handed action clearly seems to be such a target, what about the features of the movements themselves?

A different commonality of previous binding studies is that most paradigms investigate two action options (hence the choice between left or right, up or down, etc.). Still, binding and retrieval ought to be reflected even when a single interaction option is available. The results of our first experiments did suggest that continuous properties of actions, like force and duration, can become bound to and retrieved by salient stimuli, but the results were inconclusive. We suspected that task relevance and/or variability might be key factors that decide whether or not an action feature is retrieved. In our follow-up study, we found more convincing evidence for the binding/retrieval of both action force and duration. Because in this particular paradigm, it is difficult to decouple task relevance and variability, the importance of relevance remains an open question for now. Nonetheless, these results do show that continuous properties of actions can reflect the presence of binding and retrieval, consequently answering the previously stated question with ‘yes’, actual movements can be the subjects of these bindings.

We also demonstrated that in a paradigm in which a single action option is present, the observed effects cannot be attributed to a difference in the perception of change. Even if the

changing stimuli (from prime to probe) were to benefit from amplified processing, perhaps leading to differences in attention or arousal, this is not enough to explain reaction time differences attributed to binding and retrieval.

Turning to the other topic of this thesis, our study on motor adaptation had as its main focus the emergence of optimisation when the presence of salient action effects was unpredictable. Having had a relatively large amount of trials allowed actions to have different histories and combinations of previous tone-eliciting and silent actions (such as a sequence of five consecutive tone-producing actions, for example). By comparing the last element of different sequences of actions, we found evidence of motor adaptation for both pinches and taps. The results suggested that motor adaptation may be an automatic process that can arise even after just a few tone-eliciting actions. Our first adaptation-related experiment also resulted in an unexpected finding. The direct comparison of tone-eliciting and silent pinches (not considering their histories) showed that the former were significantly lower in force. This finding meant that contrary to the widely held belief, on-the-fly adjustments can be possible for some fast actions, such as pinches.

While I believe these results provide important insights, many questions remain. The most pressing one for me, as related to this thesis is: what is the relationship between action-effect binding and action-effect-related motor adaptation? Is motor adaptation a phenomenon that relies on our ability to bind stimuli and motor features together? Furthermore, are participants even aware of changes in their action execution?

A related question is the issue of causality. Is causality relevant in the case of motor adaptation? Intermixed, computer-generated sounds reduce the efficiency of optimisation

(Neszmélyi and Horváth, 2019), but does this mean that causality is a precondition of action-effect-related motor adaptation, or is it enough for the effect to follow the action for force adjustments to occur?

Finally, the so often asked question of ‘real-world use’ arises. If both binding/retrieval and motor adaptation can influence force exertion, can this be used deliberately in our day-to-day interactions with our tools and environment? I am writing these words by typing on a keyboard while staring at a screen, so naturally, the design and fine-tuning of different, widely used devices (e.g. input devices such as touchscreens, keyboards, and mice) come to my mind. Additionally, research on motor phenomena may have different uses in sports and rehabilitation. One such example is the phenomenon of sonification, in which the pairing of sounds to a series of movements can lead to an increase in performance or enhanced learning (e.g. Sigrist et al, 2013; Dyer et al., 2017). Similarly to sonification, action-effect-related motor adaptation may have such positive use cases. While important questions remain, I hope our results emphasize the often-overlooked role of sensory action effects and inspire some applied use cases that could leverage the links between actions and effects.

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