On the structure of action representations – investigated through binding between responses

by

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Dissertation submitted in partial fulfillment of the requirements for the degree of
Doctor of natural sciences (Dr. rer. nat.) to the Faculty of Psychology,
Trier University, Germany.

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Date of Submission:
Place of Submission: Trier, Rheinland-Pfalz, Germany
Place of Publication: Trier, Rheinland-Pfalz, Germany

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Acknowledgments

Firstly, I would like to thank my supervisors, Birte Moeller and Christian Frings. Birte, thank you for all your feedback, for your guidance, and for always having a sympathetic ear. Thank you for sharing your enthusiasm about science with me, I have always left our meetings more motivated than when I entered them. Christian, thank you for your advice regarding my future path in science, for all the honest and critical feedback, and for fostering a cooperative lab environment.

I would like to thank all the people in the department of Cognitive Psychology for all the discussions and chats we had in the hallway. I feel very fortunate to be a part of this lab. Thanks to the ‘snack break’ crew for not only being the greatest colleagues I could imagine but for also being my friends. Thank you for always having the important answers, whether it is about scientific debates or where to get the best memes. Special thanks to Philip, my science buddy since the good old days in Bielefeld, where the Nussecken definitely tasted sweeter. I am not sure whether I would stand here today without all of you.

I would like to thank everyone that made this dissertation possible. Thank you to Christian Beste and Alexander Münchau, co-authors of one of the articles underlying this dissertation, for your helpful feedback and for bringing in a new perspective. Thank you to all student research assistants and students who helped with the data collection and to everyone who participated in my experiments.

A big thank you to all my friends. To my flatmates for all the cheese, pizza, and generally good times. To Cara, Rune, and Kerstin, for your bardic inspiration that helped me escape reality when I needed to. And especially to Eva and Sarah – no matter the spatial separation, you are like family to me.

Lastly, I would like to thank my family for always believing in me. My cousin Anna, thank you for all the times we have been through together, from childhood mischief to late-night conversations on the carpet. A thank you to my brother Flo, who always pushed me to dream big. And I would like to thank you, Mom, for your never-ending care and support no matter what.

Trier, February 2023

Summary

Every action we perform, no matter how simple or complex, has a cognitive representation. It is commonly assumed that these are organized hierarchically. Thus, the representation of a complex action consists of multiple simpler actions. The representation of a simple action, in turn, consists of stimulus, response, and effect features. These are integrated into one representation upon the execution of an action and can be retrieved if a feature is repeated. Depending on whether retrieved features match or only partially match the current action episode, this might benefit or impair the execution of a subsequent action. This pattern of costs and benefits results in binding effects that indicate the strength of common representation between features. Binding effects occur also in more complex actions: Multiple simple actions seem to form representations on a higher level through the integration and retrieval of sequentially given responses, resulting in so-called response-response binding effects. This dissertation aimed to investigate what factors determine whether simple actions form more complex representations. The first line of research (Articles 1-3) focused on dissecting the internal structure of simple actions. Specifically, I investigated whether the spatial relation of stimuli, responses, or effects, that are part of two different simple actions, influenced whether these simple actions are represented as one more complex action. The second line of research (Articles 2, 4, and 5) investigated the role of context on the formation and strength of more complex action representations. Results suggest that spatial separation of responses as well as context might affect the strength of more complex action representations. In sum, findings help to specify assumptions on the structure of complex action representations. However, it may be important to distinguish factors that influence the strength and structure of action representations from factors that terminate action representations.

1. Introduction

Imagine you are sitting at home when you are suddenly overcome with the desire to prove your singing skills to the world. In this moment, you would obviously conceive the plan to immediately seek out the next karaoke bar. Executing this plan is easy for you, but it is easy because we can break it up into a lot of different action steps, like leaving the house and traveling to the bar. Each step has its own set of sub-steps, like opening, closing, and locking the front door, that we can then execute in sequence. To do so, we have a cognitive representation of every step, so that our cognitive system knows what to do at any given point in time. Such cognitive representations need to contain information about what it is we are doing, what objects or people we interact with, as well as where and why we are doing it. But to date, not much is known about how information from different sub-steps is related to each other and whether it affects the representation of a superordinate action step. This dissertation investigates factors that impact how we represent increasingly complex actions, by zooming in on how the structure of such representations can be influenced and on whether different contextual factors play a role in the occurrence and strength of these representations.

2. Hierarchy in action control

Actions can take many different forms. An action can be as minute as moving your finger to push a piano key or can be as broad as deciding to go to a karaoke bar to put on a passionate performance of Queen’s Bohemian Rhapsody. Although there is much variety in the way actions are investigated, a big part of the literature would agree that an action is a behavior performed with the intention to reach a certain goal (Frings et al., 2020; Herwig et al., 2013; Hommel et al., 2001; Prinz, 1997; Zacks &

Tversky, 2001). This goal can either be directly perceivable or anticipated (Herwig et al., 2013; Herwig, 2015), in this case producing a tone or impressing people with your karaoke skills, respectively. In this, actions can differ from so-called events: While an action is characterized as an episode with intentional behavior, events can consist of, or include intentional behavior, but do not need to (Hommel et al., 2001; Zacks & Tversky, 2001). However, the term event is often used to explicitly comprise intentional behavior (e.g., Hommel, 2004; Zacks et al., 2007; see also Prinz, 1997), and as the focus of this dissertation is on intentional human action, the terms event and action will be used interchangeably, but meaning intentional actions.

The actions in the two previous examples (pushing a piano key and going to a karaoke bar) differ in their complexity. They differ in the time and space that they take up (Zacks & Tversky, 2001), with the finger pushing the key happening in seconds without leaving the proximity of the keyboard. Meanwhile, executing the plan to perform at a karaoke bar can not only take hours, but also requires you to leave the house, travel, and enter the karaoke bar. Also, they differ in the number of steps they involve: While the former action can be executed with one step, like a finger movement, the latter not only takes many steps, like leaving the house and traveling, but these steps also have sub-steps, for example, leaving the house involves walking through the door, closing the door, and locking the door.

In the research on action, there is a wide consensus that actions are represented hierarchically, meaning that complex behavior can be divided into units (Botvinick, 2008; Herwig et al., 2013; Lashley, 1951; Miller et al., 1960; Newtson, 1973; Schneider & Logan, 2006; Zacks, Tversky, & Iyer, 2001) and, importantly, that we do so automatically (Zacks, Braver, et al., 2001; Zacks & Swallow, 2007). Such division might be made based on whether partial actions are perceived as part of a more complex action, like locking the door would be part of the complex action of leaving the house (Zacks & Tversky, 2001). And/or it can be made by categorizing the type of action, calling on existing knowledge or *schemata* about actions (Rumelhart, 1980; Rumelhart & Ortony, 1977; Zacks & Tversky, 2001), for example, by categorizing locking the door as a kind of locking action. In either case, this probably leads to a hierarchically organized representation of the action (Zacks & Tversky, 2001).[1] This automatic hierarchical structuring helps the cognitive system predict further actions and make sense of what is happening around us (Kurby & Zacks, 2008). Further, hierarchical representation impacts action execution, with people who are better at segmenting observed behavior (i.e., perceiving structure) being better at executing structured actions (Bailey et al., 2013; Richmond & Zacks, 2017; Sebastian et al., 2017). Aside from the control of actions, the hierarchical structure also impacts how actions are encoded in memory, with improved memory for hierarchically encoded actions (Flores et al., 2017; Gold et al., 2017; Lassiter et al., 1988; Zacks, Speer, et al., 2006).

In sum, we tend to automatically form hierarchical representations of actions so that complex actions consist of multiple simpler actions, and this affects control of, and memory about actions (e.g., Gold et al., 2017; Richmond & Zacks, 2017). But it is unclear how our cognitive system decides whether two actions stick together into a hierarchical representation, or conversely, what makes us *cut* (or segment) behavior into individual actions. To answer this, it is important to first get an understanding of

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[1] Although this is differentiated in some parts of the literature (for a discussion, see Zacks & Tversky, 2001), both principles show overlap, and probably, both apply in many cases, as we use both perception and existing knowledge to build representations of our actions (e.g., Kurby & Zacks, 2008; Zacks & Tversky, 2001).

how action representations at different levels of complexity are structured, to then identify factors that might influence this structure.

2.1 Binding – looking for structure of actions

One approach to understanding the structure of actions is by investigating the very elements that make up the simplest of actions. Binding accounts zoom in on features of actions at a very elemental level and make assumptions on the structure of individual actions, or as we will see later, compounds of individual actions. Thus, they allow a thorough investigation of hierarchical actions, focusing on the question of what is the *glue* that makes individual features stick together (Treisman, 1992; Treisman & Gelade, 1980). Historically, modern binding theories are a derivative of the *ideomotor principle* (Greenwald, 1970; James, 1890), assuming that sensory and motor information is represented in a *common code* format, without the need to translate between them in order to act, so that the mere anticipation of the action's outcome can elicit a response (Prinz, 1992, 1997). The *theory of event coding* (TEC; Hommel et al., 2001) assumes that through this common coding, associations between sensory information (namely features of stimuli or action effects) and motor information (features of a response) are stored in a short-term memory representation called *event file* (Hommel, 1998; Hommel et al., 2001). Event files are short-lived and decay in the frame of a few seconds (Frings, 2011; Hommel & Frings, 2020). Upon execution of an action, stimulus, response, and effect features become integrated into an event file, and can, upon repetition of one of those features, retrieve the other features (Frings et al., 2020; Hommel et al., 2001). If all features repeat at a subsequent event, this usually leads to benefits for action performance, whereas a partial repetition, that is, some features repeat, but others change, can lead to costs (Hommel et al., 2001).[2] If no features repeat at a subsequent event, nothing is retrieved that can affect action performance (Hommel et al., 2001). The influence of full, partial, and no feature repetitions on action performance can be expressed as a *binding effect*. Experimentally, binding effects are measured in a sequential prime-probe paradigm, consisting of a *prime*, where features are integrated, and a *probe*, where all, some, or no features (of interest) from the prime can repeat, affecting response times and error rates of the probe response. As formulated more recently in the *Binding and Retrieval in Action Control* Framework (BRAC; Frings et al., 2020), integration and retrieval of features constitute separate processes, that can be modulated individually and as such, can explain a variety of findings across different action control paradigms.

Regarding the structure of event files, it is assumed that features are stored there in the form of multiple binary bindings (Hommel, 2004), which includes bindings between stimulus features (*stimulus-stimulus bindings*; cf. *object files*, Treisman, 1992; see also van Dam & Hommel, 2010), bindings between stimulus and response features (*stimulus-response bindings)*, as well as between response and effect features (*response-effect bindings)*, while there seem to be no bindings between stimulus and effect features or bindings between all three (Moeller et al., 2019). It is tacitly assumed that such event files span a singular response, (that is, response features that are planned together) of undefined complexity (e.g., Frings et al., 2020; Hommel, 1998; Hommel et al., 2001), but can contain multiple task-relevant and even irrelevant stimuli

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[2] Performance costs due to partial repetitions occur because either we have to disassemble the retrieved action plan to "free" the repeated feature so that we can integrate the feature again in this new plan (Hommel et al., 2001; Stoet & Hommel, 1999); or because the retrieved action plan and the newly formed one compete for execution (Geissler et al., 2023; see also Mattson & Fournier, 2008).

(cf. *distractor-response bindings*, Frings et al., 2007; Frings & Rothermund, 2011) and effects (e.g., Frings et al., 2020; Hommel et al., 2001).

While the focus of binding accounts, especially in an experimental context, is on such simple actions, it was theorized even in early formulations of the TEC that the idea of bindings can scale up to explain the control of more complex, hierarchical actions (Hommel et al., 2001). Recent findings show that there are bindings between the responses of multiple simple actions, across what we understand as event files, which might be taken as an indicator for hierarchical bindings (Moeller & Frings, 2019b). Such *response-response bindings* consist of two (Moeller & Frings, 2019b) or more (Moeller & Frings, 2019a) separately planned and sequentially executed responses that are integrated into a representation of one more complex action, while their individual action representations (i.e., event files)[3] remain intact (Moeller & Frings, 2022). If one of these responses is repeated shortly thereafter, the other integrated responses are retrieved and can be more readily executed. This results in performance benefits if they match the next required response but can lead to costs if they do not match, which can be expressed in so-called *response-response binding effects*, indicating the strength of common representation of the responses. Like other binding effects, they are measured with a sequential prime-probe paradigm, but every prime and every probe consists of two consecutively given responses (R1 and R2) that each can repeat or change between prime and probe.[4]

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[3] For the sake of clarity, I will refer to representations of individual actions on the presumed lowest level of hierarchy as event files. For a discussion of the term event file, see chapter 5.1.1.

[4] Leading to four different conditions: $R1_{repetition}R2_{repetition}$, $R1_{repetition}R2_{change}$, $R1_{change}R2_{repetition}$, $R1_{change}R2_{change}$. Response-response binding effects are calculated as the advantage of probe R1 repetition (vs. probe R1 change) in probe R2 repetition trials minus the advantage of probe R1 repetition (vs. probe R1 change) in probe R2 change trials.

Response-response bindings usually last longer than bindings on the level of a single event file level (Geissler et al., 2021; Moeller & Frings, 2021), and are formed even between responses that are not contiguous: Moeller and Frings (2019a) found that if three responses (R1, R2, and R3) are executed sequentially, there were not only bindings between directly adjacent responses (R1-R2 and R2-R3) but also bindings between the non-adjacent responses (R1-R3), indicating a network-like structure of binary bindings on the level of responses rather than a structure where contiguity of responses is necessary for them to form bindings. Further support for such a network-like structure comes from the findings that response-response bindings do not contain information about the temporal order of responses (Moeller & Frings, 2019a, 2019c) and that responses can be bound to multiple other responses at the same time (Geissler et al., 2023). Overall, findings to date suggest that bindings assume a hierarchical structure, with stimulus-response and response-effect bindings at a lower level (the level of individual event files), and response-response bindings at a higher level of representation.

2.2 Event segmentation – where to *cut* and the case for space

The hierarchical structure of action representations was also investigated with a focus on more complex, everyday actions: The *Event Segmentation Theory* is concerned with the question of where to *cut* continuous behavior into parts (Zacks et al., 2007; Zacks & Swallow, 2007). The theory assumes that we have a transient internal representation of what is happening around us, called an event model, that guides sensory and perceptual processing to predict what might happen next. If the prediction spontaneously diverts too much from the perception of what is actually happening (i.e., the prediction error rises) the internal representation is updated, leading to event segmentation, that is, the perception of event boundaries (Kurby & Zacks, 2008; Zacks et al., 2007; Zacks et al., 2011) and disruption of control processes (Zacks, 2004). When the event model is updated, it uses both bottom-up, that is, sensory and perceptual information, and top-down information like previously acquired knowledge about events (Zacks et al., 2007).

Event segmentation research focuses on the segmentation of observed behavior in complex environments, typically researched by letting participants watch movies of everyday activities (e.g., Kurby & Zacks, 2022; Newtson et al., 1977; Sebastian et al., 2017; Zacks, Tversky, & Iyer, 2001; but see Zacks, 2004, for an exception) and instructing them to segment this behavior into events by pressing a button whenever they perceived the end of a meaningful action, (i.e., an event boundary). Segmentation occurs on different grain sizes (Zacks & Tversky, 2001), leading to events of different complexity. Fine and coarse-grained event boundaries coincide temporally, indicating the hierarchical structuring of events (e.g., Radvansky & Zacks, 2014). Whether the grain size is fine or coarse can depend on the current focus of the observer and can be manipulated via instructions (Newtson, 1973; Zacks, 2004).

Event Segmentation Theory sees actions as defined in time and space (Zacks & Tversky, 2001). However, space was mostly researched in the sense of a general context, such as having an event unfold at a specific location, like a kitchen or living room (e.g., Kurby & Zacks, 2008; relatedly, see also Magliano et al., 2001). Locations can provide knowledge that can be used to predict what is likely to happen (Zacks et al., 2007). And changes in location such as leaving a room are also likely to indicate that a new event starts, through knowledge about the location as well as through feature changes that a location change likely entails – in line with this, location changes were found to affect short- and long-term memory of events (Horner et al., 2016; Radvansky & Copeland, 2006). However, space can also be understood in the sense of the composition of spatial features, like the positions of objects or movements that one perceives. Whether these factors influence event segmentation was investigated in two studies on moving objects (Zacks, 2004; Zacks, Swallow, et al., 2006). When watching a movie of simple shapes moving on the screen, different movement features of these shapes influenced segmentation, among them the distance between objects, which correlated negatively with segmentation, indicating that spatially separated objects are associated with segmentation (Zacks, 2004; Zacks, Swallow, et al., 2006). While this suggests that space plays a role in event segmentation, it is unclear how it might affect different elements of an event. For example, does the spatial distance between objects have the same influence on event segmentation as the distance between an actor's individual movements that are executed during an event? The rationale used in the event segmentation literature leaves open how event representations are structured, in other words, in which way individual responses, stimuli, or even effects of our actions are related to each other. Additionally, the focus is on observing rather than producing behavior. While there are similarities between observation and production of behavior – for example, they lead to similar brain activity (Dinstein et al., 2007; Rizzolatti et al., 1996) – observation of behavior might be less informative of actions on a very fine grain. Consider, for example, fine-grained actions like the consecutive pressing of piano keys. These keypresses coincide in time and space to some degree, and whether all key presses are considered as one event or each as their own event may in an experimental context depend on instruction or the focus of the observer (Newtson, 1973; Zacks, 2004), but is anyway difficult to measure by mere observation. However, it can be measured quite precisely by using paradigms focusing on action control via the production of behavior, such as binding paradigms (e.g., Frings et al., 2007; Hommel, 1998; Moeller & Frings, 2019b).

3. Bringing together segmentation & structure

Research to date suggests that actions are represented hierarchically. Event Segmentation Theory (Zacks & Swallow, 2007) focuses on where to cut complex behavior into segments, while the binding literature (e.g., Frings et al., 2020; Hommel et al., 2001; Moeller & Frings, 2019b) focuses on what makes features, simple actions, or even short action sequences stick together into one representation. While these approaches differ in their methods and in the grain size of actions that are investigated, they share the similarity that both are interested in how we represent actions and what makes actions being represented as one. Results from the event segmentation literature suggest that space might play a role in whether events get segmented (Zacks, 2004), but further investigation is necessary, especially regarding the role of space between different components of actions. The way a trial is structured in the response-response binding paradigm allows to investigate the influence of space between different action (event file) components (stimuli, responses, and effects) separately within a response-response-binding episode, as well as changes between response-response binding episodes.

The role of space has been addressed for stimulus-stimulus and stimulus-response bindings, where it was found that spatial separation of stimuli influenced whether they were perceived, and thus represented as part of the same representation or not: Binding between two stimuli only occurred if they were spatially connected, but not if they were separated (van Dam & Hommel, 2010). If additional distractor stimuli were spatially connected or close to a target stimulus, this resulted in stronger distractor-response binding effects than when they were separated or far apart, indicating that the spatial relation between target and distractor affected whether and how strongly they become part of the same event file (Frings & Rothermund, 2011; Moeller et al., 2012; Schmalbrock, Kiesel, & Frings, 2022). More specifically, the influence of stimulus relation differed for integration and retrieval processes, so that spatially connected stimuli did not affect the integration of distractors and responses, but furthered retrieval (Schmalbrock, Kiesel, & Frings, 2022). However, this is contrasted by findings manipulating the perceived stimulus relation by color similarity, showing an opposite effect, where similar stimuli benefited the integration of distractors and responses, while dissimilarity benefited retrieval (Laub et al., 2018). While directions of effects might differ depending on the modulation that was used, findings provide evidence that manipulating the perceived spatial separation of stimuli, be it through their distance, connectedness, or similarity, influences whether they are represented in the same event file.

Event segmentation research suggests that space may affect the segmentation of complex actions. Binding research shows that space is relevant at the level of single event files, where it affects binding between stimuli and between stimuli and responses. Whether spatial separation also affects bindings on a higher level (i.e., response-response bindings) is investigated in the first three articles (chapters 4.1, 4.2, and 4.3) of this dissertation. Here we manipulated the three event file components stimuli, responses, and effects separately and looked at how varying the relation of these components across event files – by spatially separating them within each prime and each probe – influenced their representation as an overarching event, and thus the formation of response-response bindings.

The most obvious choice to test the influence of space on response-response binding effects was to manipulate the spatial separation between responses. As we assume the same underlying binding mechanism for response-response bindings as for bindings between stimuli or stimuli and responses (Moeller & Frings, 2019b), manipulating the spatial relation of two responses should, similarly to manipulating the spatial relation of two stimuli, affect binding between the two. Related findings show that making responses more dissimilar by switching effector sets (responding via hands vs. hands or feet) affected the strength of response-response binding effects with overall weaker bindings between responses from different effectors (Moeller & Frings, 2019d). The influence of space on binding between responses is investigated in Article 1 (chapter 4.1), where we introduced a spatial separation between to-be-bound responses by the placement of a physical barrier.

Following the rationale of the first article, Article 2 (chapter 4.2) investigated the role of spatial stimulus separation on the representation of two event files as one overarching event. We manipulated the distance between two targets that participants responded to sequentially within both the prime and the probe and looked at whether it influenced the binding between their respective responses. If the space between stimuli is relevant for the representation of two partial actions as one overarching event, we expected it to influence the strength of integration and/or retrieval between responses.

Given that the ideomotor principle assumes a special role for action effects, up to the point where both actions and their effects are represented by the same code (Prinz, 1992, 1997), we also applied a distance manipulation to this third event file component in Article 3 (chapter 4.3). Within each prime and each probe, responses elicited visible effects that either occurred close together or far apart. Again, we were interested in whether their spatial distance had an influence on binding between responses.

Because changes in space also seem to be an important factor in the study of more complex and natural actions (Zacks, 2004; Zacks, Swallow, et al., 2006), Article 2 further looked at how changes in spatial stimulus layout between prime and probe affect response-response binding effects. To somewhat anticipate findings, not only did changes in spatial layout reduce binding effects, but in light of previous research (e.g., Chao, 2009; Laub & Frings, 2020; Mayr et al., 2018; Qiu et al., 2022a), the results suggest that the spatial stimulus layout was represented in the response-response binding episode as a context.

Contexts can be external and internal, with external context referring to all sensations outside the individual (e.g., the spatial layout of stimuli), while internal context refers to internal states (e.g., an individual’s motivation or focus of attention) that are present during the execution of a task (e.g., Egner, 2014; Mayr et al., 2018). Until now, contextual influences on response-response binding have not been investigated. Based on the finding that context might be relevant in response-response binding episodes (Article 2), the last two articles (chapters 4.4 and 4.5) investigate the influence of different contexts further. Article 4 (chapter 4.4) investigated the role of an internal context that is induced via instructions. Experimental instructions regarding speed and accuracy are usually ambivalent, meaning that both aspects are stressed to achieve the best performance. This leaves the prioritization of both to the participants, probably contributing to interindividual variance. In Article 4 we manipulated experimental instructions and feedback to focus selectively on accuracy, speed, or both. We theorize that this manipulation leads to speed sets, accuracy sets, or ambivalent speed-accuracy sets, which might influence the occurrence of response-response binding effects.

Another factor that can serve as an external context is the stimulus modality (Grant et al., 2020; Yang et al., 2017). Many theories assume that representations of events are multimodal (Zacks et al., 2007; Zmigrod et al., 2009; for a review, see Zmigrod & Hommel, 2013). However, a lot of research on the representation and control of actions is conducted using visual stimulus material. Even approaches focusing on natural behavior, for example, the movie-watching tasks used in research on Event Segmentation Theory, often overlook the influence of other stimulus modalities. For binding effects, it is generally assumed that they are modality unspecific (Hommel et al., 2001) and they were shown to include other stimulus modalities than the visual (e.g., Schöpper et al., 2020; Wesslein et al., 2019; Zmigrod et al., 2009). However, some findings indicate that binding effects might also differ between modalities (Möller et al., 2016; Schöpper & Frings, 2022). Until now, response-response bindings were only investigated when responding to visual stimuli. Thus, Article 5 (chapter 4.5) aims to extend findings on response-response bindings to the auditory modality.

4. Original Manuscripts

Of the five presented original manuscripts, one has been published in a peer-reviewed journal (chapter 4.3), three are submitted for publication (chapters 4.1, 4.2, and 4.4), and one is in preparation for publication (chapter 4.5) in a peer-reviewed journal. The manuscripts are not ordered chronologically. Please note that the pagination in the next sections corresponds to the one in the manuscripts.

4.1 Article 1. Separated hands further response-response binding effects

This manuscript has been submitted for publication as:

Selimi, S., Frings, C., & Moeller, B. (2022). *Separated hands further response-response binding effects.* Manuscript submitted for publication.

Separated hands further response-response binding effects

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Word count: 2277 (main text without methods)

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Funding Information: The research reported in this article was supported by a grant of the Deutsche Forschungsgemeinschaft to Birte Moeller (MO 2839/2-2).

Acknowledgments: We would like to thank Rosemarie Kirmse for helping with the design of the experimental setup and data collection.

Abstract

Action control is hierarchically organized. Multiple consecutive responses can be integrated into an event representation of higher order and can retrieve each other upon repetition, resulting in so-called response-response binding effects. Previous research indicates that the spatial separation of responses can affect how easily they can be cognitively separated. In this study, we introduced a barrier between the responding hands to investigate whether the spatial separation of two responses also influences response-response binding effects. In line with previous research on stimulus-response binding, we expected an increased separability of responses to result in stronger response-response binding effects when responding hands were separated by a barrier. We indeed found stronger response-response binding effects with separated hands. Results indicate that a more distinct representation of individual actions through increased separability might benefit the control of hierarchical actions.

Introduction

Everyday actions can be as simple as pressing a button and as complex as preparing a burger menu ordered in a fast-food restaurant. Yet, it is widely assumed that action control is hierarchically organized (e.g., Botvinick, 2008; Lashley, 1951; Zacks & Swallow, 2007; Zacks & Tversky, 2001), meaning that complex actions can be segmented into simpler actions. For example, preparing a burger consists of adding multiple ingredients, preparing the burger menu consists of preparing a burger, fries, and a drink, and fulfilling the order involves preparing, billing, and passing out the food. Although in everyday action control, we do not consciously name every simple action that makes up a more complex action, we are still able to segment them, i.e. to perceive them individually, if we need to (Newtson et al., 1977; for a review, see Zacks & Tversky, 2001). This segmentation of complex actions into simpler ones, or conversely, the combination of simpler actions into bigger events, is substantial for action control, as it makes it easier for our cognitive system to anticipate future actions (Kurby & Zacks, 2008; Lashley, 1951).

One growing area of the literature examines the control of simple actions and their interrelations via the investigation of feature integration and retrieval (see Frings et al., 2020). Here, simple actions like adding a slice of tomato to a burger are defined as short-term events, where stimulus-, response-, and effect features are integrated into a common representational format, so-called event files (Hommel, 1998; Hommel et al., 2001). If one of the integrated features is repeated at a subsequent event, the other integrated features are retrieved, affecting the execution of the current action. However, integration and retrieval do not only occur in simple actions but are also found in action sequences, where consecutive responses are integrated into the same event representation and can retrieve each other, resulting in so-called response-response binding effects (Moeller & Frings, 2019a, 2019b).

Here, sequentially executed responses are integrated into one event representation. If one of the responses now repeats at a next event, the other responses are retrieved. If the next required response matches one of the retrieved ones, executing this next response is facilitated. If they do not match, executing a response is impaired. With that, response-response bindings do not only follow the idea of hierarchical action control that more complex actions can be segmented into simpler actions, but they also allow for a more detailed view of the interrelations of simple actions. Moreover, response-response bindings are not limited to contiguous responses, but can also occur between non-contiguous responses and are not reliant on the temporal order of responses (Moeller & Frings, 2019a, 2019c). In addition, response-response bindings seem to be quite robust over time, without significant decay six seconds after integration (Geissler et al., 2021; Moeller & Frings, 2021). With these characteristics, the concept of response-response bindings may apply to a broad range of complex actions.

In the context of response-response binding, looking at the segmentation between events means looking at the relation between responses. While we know that responses do not need to be temporally contiguous to be bound, it is still largely unknown how the spatial relation between responses influences response-response binding. Going back to the example of preparing a burger, all burger toppings are likely to be spatially separated in their containers rather than in one big pot to avoid confusion, which makes the preparation process more efficient. Likewise, the action to reach for a slice of tomato or cucumber follows this spatial separation, which might also add to efficiency. A look at the literature seems to indicate that the spatial separation between responses can indeed affect how they are cognitively represented.

In a variation of the Stroop task, spatially separating responses by increasing the distance between the responding hands facilitated responding (Lakens et al., 2011). When participants had to categorize the ink colors of letter strings (either color words or neutral strings, like *XXXX*) by button press, while ignoring the word meaning, responding correctly despite incongruent stimuli (e.g., the color word *blue* in red ink) became easier with more separation of response keys (Lakens et al., 2011; Nett & Frings, 2014). Lakens et al. (2011) argue that spatially structuring responses facilitates categorizations and that such structures can indeed affect cognitive processes. In other words, more distance between responses helped keep their representations apart (but see Schäfer & Frings, 2021).

Spatial separation between hands can also be induced via the placement of a barrier. Adding a barrier between two hands that received concurrent stimulation, helped to separate the processing of the interfering stimulation (Wesslein et al., 2015). Interestingly, this was the case even if the barrier was transparent, indicating that it is rather the perceived separation between hands than an obstructed vision that produced the effect (Wesslein et al., 2015).

Together, past findings seem to indicate that spatial separation of responding hands can affect response representation. Whether separated response representation, in turn, can affect binding between responses is so far unclear. With regard to the direction in which it might influence binding, previous findings by Laub et al. (2018) on simple actions suggest that separation might further binding effects: Increased separability between a target and a distractor stimulus had beneficial effects on distractor-based retrieval, resulting in stronger distractor-response binding effects. This was likely because a distractor that was separated from the target was more salient and thus received more attention, which generally benefits distractor based retrieval (Moeller & Frings, 2014). Transferring this to response-response binding, we would expect that an increased separability of responses and thus more separated response representations might make the individual responses more distinct. This, in turn, may facilitate retrieval of responses, resulting in overall larger response-response binding effects when responses are perceived as spatially separated.

In the present study, we examine whether the spatial relation of two responses affects their integration and retrieval in a response-response binding paradigm. Participants responded twice in the prime and twice in the probe. Here it can be assumed that the prime responses are integrated, so that repetition of one of them as the first probe response retrieves the other. Importantly, the two prime responses (and also the two probe responses) were given with different hands. Hence, we were able to measure integration and retrieval between two responses that were executed by different hands. We either placed a barrier between the hands giving these two responses, to induce separation, or did not separate the hands. In each trial, participants gave responses (one with the left and one with the right hand) to two consecutive stimuli in both a prime and a probe. If a barrier was placed between the hands, the responses should have been more clearly perceived as separate. We expected this to result in stronger response-response binding effects in the condition where hands were separated by a barrier. To anticipate results, we did find larger response-response binding effects with separated hands, indicating that hierarchical action control might benefit from the spatial separation between individual actions.

EXPERIMENT

Method

Participants. Effect sizes in former studies on RR-binding (computed as t/sqrt(n)) were large (*d* = 0.88) on average (Moeller & Frings, 2019b, 2019c, 2019d). A power analysis with the program G*Power assuming α = .05 and a power of 1–β = .80 suggests that at least 44 participants were necessary (Faul et al., 2007). The data was collected in a period from April – August 2021 and from October 2021 – January 2022, after recruitment was halted due to the covid-19 pandemic. Forty-seven students (39 women) from Trier University participated in the experiment. The samples' mean age was 22.8 years (*SD* = 3.4). All participants reported normal or corrected-to-normal vision and were rewarded with partial course credit or monetary compensation. Three additional participants had to be excluded: One participant due to a high number of incorrect trials (181 out of 192), one due to outlier RTs (more errors than three times the interquartile range), and one due to outlier RTs and error rates (more than 20% errors, more than three times the interquartile range in both RTs and errors).

Design. The design comprised two within-subjects factors, namely, response A relation (response repetition vs. response change from prime to probe) and response B relation (response repetition vs. response change from prime to probe), and one between-subjects factor, namely barrier (barrier vs. no barrier).

Materials. The experiment was conducted using E-Prime 3.0. Instructions were presented in white on a black background on a standard liquid crystal display (TFT) screen. The viewing distance was approximately 60 cm. The list of possible stimuli consisted of eight different shapes with a height of 3.7° and a width of 4.0° of visual angle and made up of four overlapping lines of different lengths. The shapes could be presented in eight different colors (blue, green, red, yellow, purple, brown, and orange). In each display, two shapes were presented simultaneously 1.2° of visual angle to the left and right of the screen center. Participants responded via two out of four keys on a computer keyboard.

Procedure. Before the experiment, participants gave informed consent regarding the recording of personal data and responses during the experiment and indicated their age and gender. Instructions were given on the screen. Participants were instructed to place their middle and index fingers on the keys A, S, 5 (number pad), and 6 (number pad) of a standard computer keyboard. They were told that they would always see two line patterns that would be either identical or different in shape and identical or different in color. Their task was to first categorize the shapes (Response A) and then the colors (Response B) of these patterns as identical or different, by successively pressing two keys with the corresponding fingers. The left index and middle fingers were used for the shape classification. For identical shapes, participants were instructed to press the key with the left index finger (S) and for different shapes, they were supposed to press the key with the left middle finger (A). To classify the colors, the index and middle fingers of the right hand were used, respectively. For identical colors, a key was pressed with the right index finger (5), and for different colors, a key was pressed with the right middle finger (6).

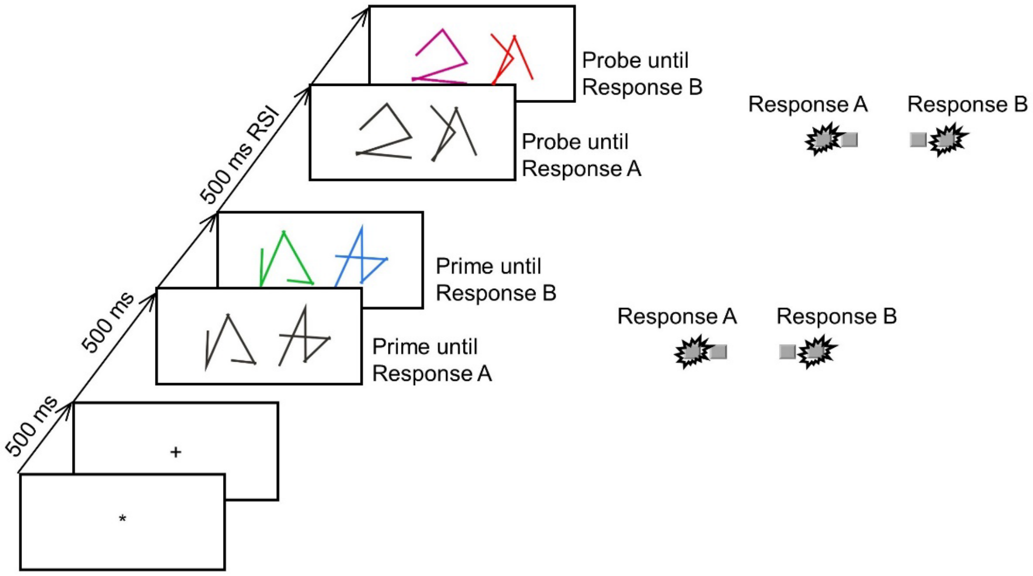

Figure 1. Sequence of events in one example trial. Participants decided for each prime and each probe whether the presented stimuli had identical or different shapes (Response A) and identical or different colors (Response B). This is an example of a Response A repetition and Response B repetition trial. The stimuli are not drawn to scale, black is depicted as white and white as black.

An asterisk that was presented for 500 ms in the middle of the screen indicated the beginning of each trial (see **Figure 1**). Then a plus sign appeared for 500 ms, followed by the prime line patterns. These were presented in white for the shape comparison and, in the case of a correct response, changed color upon Response A execution (via the left hand). The colored shapes remained on the screen until Response B (via the right hand) was given. During training trials, a feedback message appeared on screen for 600 ms immediately following the response, indicating whether the given response was correct or not. Afterward, a blank screen appeared for 500 ms and was followed by the probe line patterns. The procedure in the probe was identical to that in the prime. Every 40 trials participants were allowed to take a short break, after which they resumed the task in their own time. In Response A repetition trials (Ar), the same response was required to the shapes of the prime and probe line patterns (e.g., the prime shapes differed, and the probe shapes differed). In Response A change trials (Ac), different responses were required for the categorization of the prime and probe line patterns (e.g., the prime shapes were identical, and the probe shapes differed). In Response B repetition trials (Br), the same response was required to the colors of the prime and probe line patterns (e.g., the prime colors were identical, and the probe colors were also identical). In Response B change trials (Bc), different responses were required to the prime and probe colors (e.g., the prime colors differed, and the probe colors were identical). These relations resulted in the four conditions Response A repetition with Response B repetition (ArBr), Response A repetition with Response B change (ArBc), Response A change with Response B repetition (AcBr), and Response A change with Response B change (AcBc). Each of these conditions was presented 12 times with each of the four possible combinations of identical/different shapes and colors in the probe, resulting in 192 experimental trials total. Shapes and colors were randomly assigned to the different positions/displays while restricting that neither could repeat between prime and probe of one trial. In the beginning, participants practiced their task for 16 trials (subsample of the experimental trials). Half of the sample completed the experiment with a barrier separating both hands (see **Figure 2**), placed there before the start of the experiment (barrier condition). The other half completed the experiment without separation by a barrier (no barrier condition).[1]

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[1] This data was collected as part of a larger experiment. There were other conditions with different participants that are not relevant to the question of the current study.

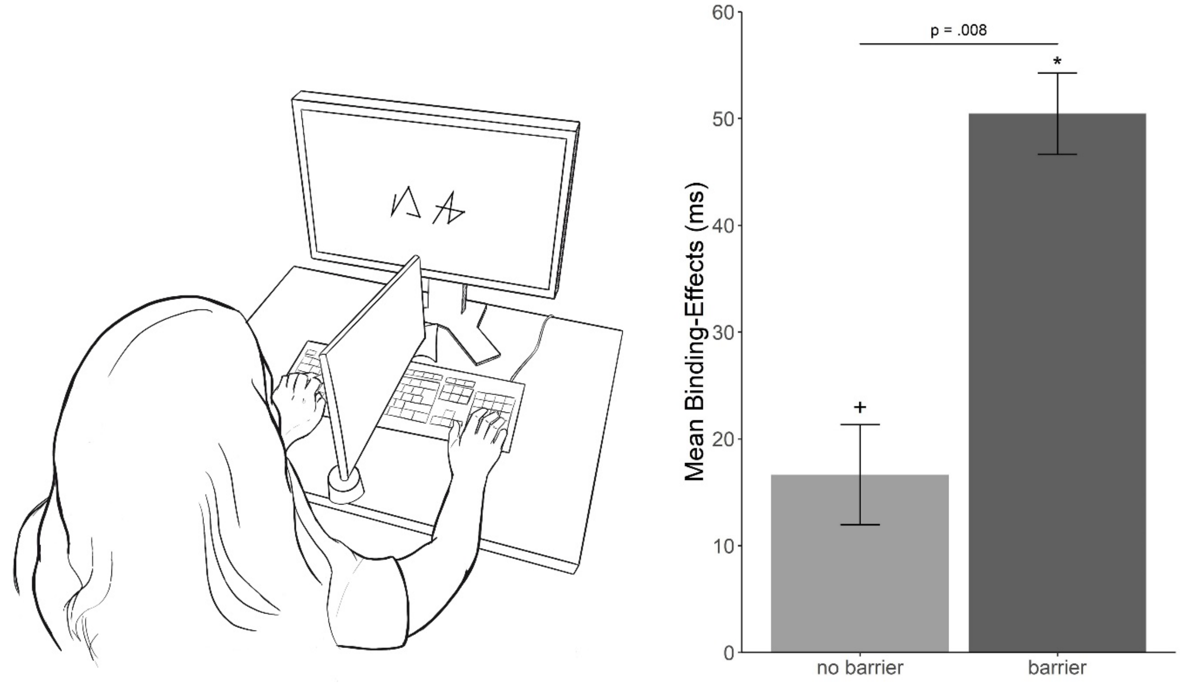

Figure 2. *Left:* Schematic depiction of the experimental setup. The participants' hands were placed on the response keys at the respective ends of the keyboard. In the barrier condition, a black and opaque barrier was placed in the middle of the keyboard and lining up with the screen center, visually separating both halves of the keyboard, but not the view of the screen. *Right:* Mean response-response binding effects for response times as a function of barrier (no barrier vs. barrier). Binding effects are calculated as the advantage of probe Response A repetition (vs. probe Response A change) in probe Response B repetition trials minus the advantage of probe Response A repetition (vs. probe Response A change) in probe Response B change trials: [AcBr - ArBr] - [AcBc - ArBc]
* $p < .05$ and + $p < .1$ indicate whether binding effects differ significantly from zero.

Results

The dependent variable of interest was probe Response B performance. Regarding the analysis of response times (RTs), only trials with correct responses A and B in both prime and probe were considered. The error rate for prime responses (A or B) was 6.2%. The probe error rates were 2.7% for Response A and 4.4% for Response B (only including trials with correct previous responses). We excluded RTs of more than 1.5 interquartile ranges above the third quartile of the probe Response

B RT distribution of the participant (Tukey, 1977) and RTs shorter than 200 ms from the analysis. Due to these constraints, 17.0% of the trials were excluded from the RT analyses. For the mean RTs and error rates, see **Table 1**.

Table 1. Mean response times (in milliseconds) and mean error rates (in percentages) for probe Response B, as a function of Response A relation between prime and probe, Response B relation and barrier.

	No barrier		Barrier	
	B repetition	*B change*	*B repetition*	*B change*
A change	570 (6.6)	551 (2.5)	601 (4.9)	577 (2.2)
A repetition	556 (4.6)	553 (5.7)	565 (3.5)	591 (5.9)

In a 2 (Response A relation: repetition vs. change) × 2 (Response B relation: repetition vs. change) × 2 (barrier: no barrier vs. barrier) analysis of variance (ANOVA) on probe Response B RTs, the main effect for Response A relation was significant, $F(1, 45) = 6.51$, $p = .014$, $\eta_p^2 = .13$, while the main effects for Response B relation, $F(1, 45) = 1.09$, $p = .301$, $\eta_p^2 = .02$, and barrier, $F(1, 45) = 1.07$, $p = .306$, $\eta_p^2 = .02$, were not. The interaction of Response A and Response B relation was significant, $F(1, 45) = 32.53$, $p < .001$, $\eta_p^2 = .42$, indicating binding between responses. Importantly, this was further modulated by barrier, $F(1, 45) = 7.72$, $p =.008$, $\eta_p^2 = .15$. Follow up analyses revealed a larger binding effect in the barrier condition, $t(24)= 6.51$, $p <.001$, than in the no barrier condition, $t(21)= 1.75$, $p =.096$. For a summary of mean binding effects, see **Figure 2**.

The same analysis on error rates revealed no significant main effects for Response A relation, $F(1, 45) = 3.99$, $p = .052$, $\eta_p^2 = .08$, Response B relation, $F(1, 45) = 1.85$, $p = .181$, $\eta_p^2 = .04$, or barrier, $F(1, 45) = .68$, $p = .41$, $\eta_p^2 = .01$. Again, the interaction of Response A and Response B relation was significant, $F(1, 45) = 25.58$,

$p < .001$, $\eta_p^2 = .36$. However, this relation was not further modulated by barrier, $F(1, 45) = 0.01$, $p = .939$, $\eta_p^2 < .01$.

Discussion

In the present study, we investigated the influence of hand separation on response-response binding effects. Every trial consisted of a prime and a probe, each with two consecutive responses A and B that were given with alternating hands. Replicating earlier studies (e.g., Moeller & Frings, 2019b; Selimi et al., 2022), we found a significant response-response binding effect. Importantly, this effect was modulated by the presence/absence of a barrier between the hands. Separation of the hands through the placement of a barrier led to significantly larger binding effects than without a barrier. Binding effects can be interpreted to indicate what becomes part of a common action representation (Hommel, 2009; Moeller & Frings, 2019b). Apparently, the placement of a barrier between the spatial positions of individual responses affects to what extent these responses are integrated into a higher-order representation.

Binding effects are the result of two processes, namely integration (during the prime) and retrieval (during the probe), working together (Frings et al., 2020). In our study, the manipulation of response separation might have affected either response integration, response retrieval, or both processes. Even though we cannot pinpoint the exact process with this study, it is reasonable to assume that it was the retrieval process that was affected by the separation manipulation. For one, there is growing evidence that retrieval is more easily and more often influenced by modulations than integration (Hommel et al., 2014; Hommel, 2022; Moeller & Frings, 2014). In addition, the same pattern of beneficial effects due to separability of features during retrieval was reported in the past: While feature integration is largely unaffected by separation, this separation makes it easier to tell features apart, which facilitates retrieval of one feature by another (Laub et al., 2018). To get definite evidence as to whether integration or retrieval was affected in the present study, the separation manipulation would have to be applied to the prime (associated with integration) and probe (associated with retrieval) separately (see Laub et al., 2018; Schmalbrock et al., 2022). Although not the focus of this study, it might be interesting to tackle this aspect in future research.

In response-response binding, two individual responses are represented as one higher-order representation (Moeller & Frings, 2019b). Our results indicate that the separation of responding hands affects the representation of such response sequences, with stronger response-response binding with increased separability. An explanation might be that separation helps to structure events cognitively: Although an overarching event is formed around the two responses, it is reasonable to assume that these responses also include smaller event representations, i.e., event files containing a single response (Moeller & Frings, 2019b, 2022). Thus, binding effects seem to have a hierarchical structure, but importantly, individual parts of larger-scale events still seem to retain their individual representation to some degree. The separation of responses induced by the barrier apparently helped to cognitively separate responses and could have thus led to more distinct individual representations of each response. Such more distinct cognitive representations of individual responses might then facilitate piecing them together into an action sequence.

The beneficial effects of distinct representations of individual actions seem to be in line with other research on hierarchical actions. Findings in the event segmentation literature indicate that we naturally segment actions of different complexity in time, i.e. we set temporal borders between events. This happens on the level of complex everyday actions (e.g., Newtson et al., 1977; Zacks, Braver, et al., 2001; Zacks, Tversky, & Iyer, 2001), but also on the level of individual or few responses (Fournier & Gallimore, 2013). Borders seem to be similar across different participants (e.g., Zacks, Tversky, & Iyer, 2001) and individuals who are better at segmenting larger-scale events, are also better at remembering them later on (Zacks et al., 2006). Thus, even if it is not specifically instructed, our cognitive system uses segmentation to make sense of the world and predict future actions (Kurby & Zacks, 2008; Lashley, 1951). In our study, the spatial separation of individual actions by a barrier probably induced more distinct representations of individual actions and might have thus supported the natural tendency to segment events.

In sum, the separation of responses through a barrier furthers response-response binding. This finding underlines the relevance of spatial separability in hierarchical action control: When representing two smaller events as one, it might be important that their individual representations do not get lost.

Declarations

Author notes

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Funding Information

The research reported in this article was supported by a grant of the Deutsche Forschungsgemeinschaft to Birte Moeller (MO 2839/2-2).

Data Accessibility Statement

The datasets and analysis code of the current study are available in the Psycharchives repository under http://dx.doi.org/10.23668/psycharchives.7961 (dataset) and http://dx.doi.org/10.23668/psycharchives.7960 (analysis code). The experiment was not preregistered.

Ethics and consent

All procedures performed involving human participants were in accordance with the ethical standards at the psychology institute in Trier and with the 1964 Helsinki declaration and its later amendments. Informed consent was obtained from all individual participants included in the study.

Competing interests

The authors have no competing interests to declare.

References

Botvinick, M. M. (2008). Hierarchical models of behavior and prefrontal function. *Trends in Cognitive Sciences*, *12*(5), 201–208. https://doi.org/10.1016/j.tics.2008.02.009

Faul, F., Erdfelder, E., Lang, A.-G., & Buchner, A. (2007). G*power 3: A flexible statistical power analysis program for the social, behavioral, and biomedical sciences. *Behavior Research Methods*, *39*(2), 175–191. https://doi.org/10.3758/BF03193146

Fournier, L. R., & Gallimore, J. M. (2013). What makes an event: Temporal integration of stimuli or actions? *Attention, Perception & Psychophysics*, *75*(6), 1293–1305. https://doi.org/10.3758/s13414-013-0461-x

Frings, C., Hommel, B., Koch, I., Rothermund, K., Dignath, D., Giesen, C., Kiesel, A., Kunde, W., Mayr, S., Moeller, B., Möller, M., Pfister, R., & Philipp, A. (2020). Binding and Retrieval in Action Control (BRAC). *Trends in Cognitive Sciences*, *24*(5), 375–387. https://doi.org/10.1016/j.tics.2020.02.004

Geissler, C. F., Frings, C., & Moeller, B. (2021). Illuminating the prefrontal neural correlates of action sequence disassembling in response-response binding. *Scientific Reports*, *11*(1), 22856. https://doi.org/10.1038/s41598-021-02247-6

Hommel, B. (1998). Event Files: Evidence for Automatic Integration of Stimulus-Response Episodes. *Visual Cognition*, *5*(1-2), 183–216. https://doi.org/10.1080/713756773

Hommel, B. (2009). Action control according to TEC (theory of event coding). *Psychological Research*, *73*(4), 512–526. https://doi.org/10.1007/s00426-009-0234-2

Hommel, B. (2022). The Control of Event-File Management. *Journal of Cognition*, *5*(1), Article 1. https://doi.org/10.5334/joc.187

Hommel, B., Memelink, J., Zmigrod, S., & Colzato, L. S. (2014). Attentional control of the creation and retrieval of stimulus-response bindings. *Psychological Research*, *78*(4), 520–538. https://doi.org/10.1007/s00426-013-0503-y

Hommel, B., Müsseler, J., Aschersleben, G., & Prinz, W. (2001). The Theory of Event Coding (TEC): A framework for perception and action planning. *The Behavioral and Brain Sciences*, *24*(5), 849-78; discussion 878-937. https://doi.org/10.1017/S0140525X01000103

Kurby, C. A., & Zacks, J. M. (2008). Segmentation in the perception and memory of events. *Trends in Cognitive Sciences*, *12*(2), 72–79. https://doi.org/10.1016/j.tics.2007.11.004

Lakens, D., Schneider, I. K., Jostmann, N. B., & Schubert, T. W. (2011). Telling things apart: The distance between response keys influences categorization times. *Psychological Science*, *22*(7), 887–890. https://doi.org/10.1177/0956797611412391

Lashley, K. S. (1951). The problem of serial order in behavior. In L. A. Jeffress (Ed.), *Cerebral mechanisms in behavior* (pp. 112–147).

Laub, R., Frings, C., & Moeller, B. (2018). Dissecting stimulus-response binding effects: Grouping by color separately impacts integration and retrieval processes. *Attention, Perception & Psychophysics*, *80*(6), 1474–1488. https://doi.org/10.3758/s13414-018-1526-7

Moeller, B., & Frings, C. (2014). Attention meets binding: Only attended distractors are used for the retrieval of event files. *Attention, Perception & Psychophysics*, *76*(4), 959–978. https://doi.org/10.3758/s13414-014-0648-9

Moeller, B., & Frings, C. (2019a). Binding processes in the control of nonroutine action sequences. *Journal of Experimental Psychology: Human Perception and Performance*, *45*(9), 1135–1145. https://doi.org/10.1037/xhp0000665

Moeller, B., & Frings, C. (2019b). From simple to complex actions: Response-response bindings as a new approach to action sequences. *Journal of Experimental Psychology: General*, *148*(1), 174–183. https://doi.org/10.1037/xge0000483

Moeller, B., & Frings, C. (2019c). Lost time: Bindings do not represent temporal order information. *Psychonomic Bulletin & Review*, *26*(1), 325–331. https://doi.org/10.3758/s13423-018-1493-y

Moeller, B., & Frings, C. (2019d). Response-response binding across effector-set switches. *Psychonomic Bulletin & Review*, *26*(6), 1974–1979. https://doi.org/10.3758/s13423-019-01669-8

Moeller, B., & Frings, C. (2021). Response-response bindings do not decay for 6 seconds after integration: A case for bindings' relevance in hierarchical action control. *Journal of Experimental Psychology: Human Perception and Performance*, *47*(4), 508–517. https://doi.org/10.1037/xhp0000897

Moeller, B., & Frings, C. (2022). All together now: Simultaneous feature integration and feature retrieval in action control. *Psychonomic Bulletin & Review*, *29*(2), 512–520. https://doi.org/10.3758/s13423-021-01999-6

Nett, N., & Frings, C. (2014). Things can be told apart: No influence of response categories and labels on the distance effect in Stroop tasks. *Experimental Psychology*, *61*(2), 142–148. https://doi.org/10.1027/1618-3169/a000234

Newtson, D., Engquist, G. A., & Bois, J. (1977). The objective basis of behavior units. *Journal of Personality and Social Psychology*, *35*(12), 847–862. https://doi.org/10.1037/0022-3514.35.12.847

Schäfer, S., & Frings, C. (2021). Different effects of spatial separation in action and perception. *Psychonomic Bulletin & Review*, *28*(3), 845–852. https://doi.org/10.3758/s13423-020-01867-9

Schmalbrock, P., Kiesel, A., & Frings, C. (2022). What Belongs Together Retrieves Together – The Role of Perceptual Grouping in Stimulus-Response Binding and Retrieval. *Journal of Cognition*, *5*(1), Article 28. https://doi.org/10.5334/joc.217

Selimi, S., Frings, C., & Moeller, B. (2022). Binding between Responses Is Not Modulated by Grouping of Response Effects. *Journal of Cognition*, *5*(1), Article 42. https://doi.org/10.5334/joc.233

Tukey, J. W. (1977). *Exploratory data analysis* (Vol. 2). Reading, MA.

Wesslein, A.-K., Spence, C., & Frings, C. (2015). You can't ignore what you can't separate: The effect of visually induced target-distractor separation on tactile selection. *Psychonomic Bulletin & Review*, *22*(3), 728–736. https://doi.org/10.3758/s13423-014-0738-7

Zacks, J. M., Braver, T. S., Sheridan, M. A., Donaldson, D. I., Snyder, A. Z., Ollinger, J. M., Buckner, R. L., & Raichle, M. E. (2001). Human brain activity time-locked to perceptual event boundaries. *Nature Neuroscience*, *4*(6), 651–655. https://doi.org/10.1038/88486

Zacks, J. M., Speer, N. K., Vettel, J. M., & Jacoby, L. L. (2006). Event understanding and memory in healthy aging and dementia of the Alzheimer type. *Psychology and Aging*, *21*(3), 466–482. https://doi.org/10.1037/0882-7974.21.3.466

Zacks, J. M., & Swallow, K. M. (2007). Event Segmentation. *Current Directions in Psychological Science*, *16*(2), 80–84. https://doi.org/10.1111/j.1467-8721.2007.00480.x

Zacks, J. M., & Tversky, B. (2001). Event structure in perception and conception. *Psychological Bulletin*, *127*(1), 3–21. https://doi.org/10.1037/0033-2909.127.1.3

Zacks, J. M., Tversky, B., & Iyer, G. (2001). Perceiving, remembering, and communicating structure in events. *Journal of Experimental Psychology: General*, *130*(1), 29–58. https://doi.org/10.1037//0096-3445.130.1.29

4.2 Article 2. It's not distance but similarity of distance: Changing stimulus relations affect the control of action sequences

This manuscript has been submitted for publication as:

Selimi, S., Frings, C., Münchau, A., Beste, C., & Moeller, B. (2022). *It's not distance but similarity of distance: Changing stimulus relations affect the control of action sequences.* Manuscript submitted for publication.

It's not distance but similarity of distance: Changing stimulus relations affect the control of action sequences

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Word count: 4151 (main text)

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Abstract

Interacting with our environment happens on different levels of complexity: While there are individual and simple actions like an isolated button press, most actions are more complex and involve sequences of simpler actions. The degree to which multiple simple actions are represented as one action sequence can be measured via so-called response-response binding effects. When two or more responses are executed consecutively, they are integrated into one representation so that repetition of one response can start retrieval of the other. Executing such an action sequence typically involves interaction with multiple objects or stimuli. Here, we investigated whether the spatial relation of these stimuli affects action sequence execution. To that end, we varied the distance between response stimuli in a response-response binding task. Stimulus distance might affect response-response binding effects in one of two ways: It might directly impact the represented relation of responses, affecting whether responses are integrated and/or retrieved. Alternatively, similarity of stimulus distance during binding and retrieval might be decisive, leading to differences in response-response binding effects, depending on whether the stimulus relation changes or remains constant at the time points of integration and retrieval. We found stronger binding effects with constant than with changing stimulus relation, indicating that stimulus distance is better conceptualized as a context, in which multiple responses are represented as one sequence.

Introduction

Imagine pouring yourself a glass of water. To do so, you have to execute different actions to different objects in sequence: You have to reach for a glass, for a bottle, and then you have to open the bottle to pour. In such a sequence, we can assume that each individual response is integrated with the stimulus one reacted to, resulting in multiple short-term memory representations that have been called event files (Hommel, 1998, 2004). Importantly, there is evidence that similar bindings also occur between individual responses of such a sequence (Moeller & Frings, 2019b). That is, the individual event files seem to be held together by bindings between responses of the sequence (Moeller & Frings, 2021, 2022): When we execute multiple actions in sequence, the responses can be integrated into a higher order representation of this action sequence (Moeller & Frings, 2019a, 2019b; Selimi et al., 2022), with underlying neurophysiological processes being complex (Dilcher et al., 2021; Mielke et al., 2021; Takacs et al., 2021; Wendiggensen et al., 2022). The repetition of one of the integrated responses can then lead to the retrieval of the other responses. For example, if we grab a glass and then a bottle, both responses are integrated. If we execute a previously integrated response shortly thereafter (e.g., we again reach for the bottle), other integrated responses (e.g., grabbing the glass) can be retrieved, and their execution can thus be facilitated. If the next required response does not match the retrieved response (e.g., we want to drink from the bottle instead of grabbing a glass), we would take longer to execute the response and make more errors. Advantages from the repetition (compared to change) of the first response when the second response repeats or changes result in so-called *response-response binding effects* indicating the association of responses, i.e., how strongly they are represented as one action sequence (Moeller & Frings, 2019b), effectively extending the principle of integration and retrieval that originally targeted individual actions, to action sequences.

Presently, it is still unclear under what circumstances such higher order bindings between responses of individual events affect further action. As mentioned above, many of our actions are directed towards objects in our environment. In action sequences, individual actions can be directed to different objects, raising the question whether the relation between these objects affects action sequence representations. Here we investigate the role of distance between the response relevant stimuli of the to-be-integrated responses. Are responses more readily bound, or do they more easily retrieve each other if their response indicating stimuli follow a certain spatial setup?

To the best of our knowledge, there is no previous study in which stimulus distance in a response-response binding task was varied. Yet, binding and retrieval between stimuli and responses of individual actions was affected by stimulus set up in the past. When an individual response to a stimulus is executed, stimuli that are response irrelevant, i.e. distractor stimuli, can also become part of that event file (Frings et al., 2007), but this depends on their relation to the task-relevant stimulus. Particularly, their spatial relation was found to be relevant in several studies, with binding effects being stronger when stimuli were perceived as spatially connected (Frings & Rothermund, 2011; Schmalbrock et al., 2022) or spatially close (Moeller et al., 2012) than when they were further apart. If stimulus distance plays a similar role in action sequences (e.g., Frings & Rothermund, 2011), responses given to close stimuli should elicit stronger binding effects than responses given to far stimuli.

However, more recent findings show that integration and retrieval can be modulated separately (as emphasized in the BRAC [Binding and Retrieval in Action

Control] framework, for an overview, see Frings et al., 2020). Stimulus-response binding effects specifically benefited from close relation between stimuli at the time of integration (Laub et al., 2018), while the results were mixed for stimulus relation at the time of retrieval (Laub et al., 2018; Schmalbrock et al., 2022). If these findings transfer to stimulus distance in action sequences, close stimuli would strengthen the integration of responses, while response retrieval might benefit from either close or far stimuli.

Alternatively, the distance of stimuli might not directly affect binding between responses (with larger binding effects for one than another distance), but *repetition* of the stimulus setup, experienced during integration might be a prerequisite for retrieval to start. That is, not stimulus setup during integration or retrieval per se, but similarity of stimulus setup at those two points in time would affect binding effects. Again, such a pattern has been observed in bindings between stimuli and responses: For example, stimulus-response binding effects were larger if an additional task irrelevant sound was repeated from integration to retrieval than if the sound changed (Mayr et al., 2018; Qiu et al., 2022a, 2022b; for visual stimuli, see also Frings et al., 2007). This has been interpreted as an effect of context similarity. Any present but task irrelevant (internal and external) sensations are here defined as context. Changes in these lead to a perceived context change which hinders retrieval of previously bound features. Furthermore, such modulation of binding effects is possible via the mere configuration of stimuli (e.g., the number of distractors, Laub & Frings, 2020). In line with these findings, response-response binding effects would be larger for similar stimulus distances during integration and retrieval than for different distances.

To investigate whether the relation of stimuli that we respond to sequentially influences the representation of the respective response sequence, i.e., how it affects response-response binding effects, we manipulated the distance between stimuli in a response-response binding paradigm (Moeller & Frings, 2019b). In each trial, two prime (and two probe) responses were given consecutively to two response stimuli appearing on screen. These response stimuli appeared next to each other (close) or on opposite sides of the screen (far). Upon execution, responses were integrated into one event representation. If one of the responses was repeated as a probe response, the other integrated response was retrieved and influenced further responding. If the distance between response stimuli becomes part of the cognitive representation of the action sequence, response-response binding effects should differ depending on the stimulus distance conditions. We manipulated stimulus distance during integration (in the prime) and retrieval (in the probe) orthogonally, resulting in four conditions: Prime close – probe close, prime far – probe far, prime close – probe far, and prime far – probe close, with the former having similar stimulus relations between prime and probe and the latter having dissimilar stimulus relations.

If stimulus distance directly affects how responses are represented as a sequence, we expected that close prime stimuli facilitate integration of responses, leading to stronger response-response binding effects than with far prime stimuli. Statistically, this would be indicated by an interaction of the binding effect with prime stimulus distance. If the distance of stimuli affects retrieval, this would be indicated by a significant interaction of the binding effect with probe stimulus distance. If the similarity of stimulus distance during integration and retrieval affects response-response binding effects, we expected stronger binding effects if stimulus distance stays constant between prime and probe than when it changes. Statistically, this would be indicated by a four-way interaction.

EXPERIMENT

Method

Participants. Effect sizes in former studies on RR-binding (computed as t/sqrt(n)) were at least *d* = 0.63 (e.g., Moeller & Frings, 2019b: *d* = 0.63 and *d* = 0.88; Moeller & Frings, 2019c: *d* = 1.07; Moeller & Frings, 2019d: *d* = 0.74 and 1.07; Selimi et al., 2022: *d* = 0.98 and *d* = 0.96). A power analysis with the program G*Power assuming α = .05 and a power of 1–β = .90 suggested that at least 29 participants were necessary (Faul et al., 2007). Thirty-one students (30 women) from Trier University participated in the experiment. The samples' median age was 22 years, with a range from 19 to 30 years. The participants were rewarded with partial course credit. One additional participant had to be excluded from the analysis due to a high number of extremely fast and erroneous responses (faster than 200ms; 380 out of 384 trials had to be discarded).

Design. The design included four within-subjects factors, namely, prime stimulus distance (close vs. far), probe stimulus distance (close vs. far), response R1 relation (response repetition vs. response change from prime to probe), and response R2 relation (response repetition vs. response change from prime to probe).

Materials and procedure. The experiment was programmed in PsychoPy3/PsychoJS (2021.1.2; Peirce et al., 2019) and conducted online on Pavlovia (https://pavlovia.org/). For participation, a computer with a physical keyboard was required. Instructions were presented in white [RGB: 255, 255, 255] on a grey background [RGB: 128, 128, 128]. Stimuli were the letters A, B, C, and D and the digits 1, 2, 3, and 4, each with a height of 35 pixels and presented in white. Stimuli appeared on one of four positions on the same imaginary center screen line, depending on the condition (in pixels, screen center has coordinate [0,0]: [-540, 0], [-

480, 0], [480, 0] and [540,0], see **Figure 1a**). For the close conditions, stimuli appeared in either the two left side or the two right side positions, while stimuli in the far conditions always appeared on opposite screen side positions, while maintaining a fixed distance (either [-540, 0] and [480, 0] or [-480, 0] and [540, 0]). Prime stimuli disappeared after the prime, resulting in a maximum of two response stimuli at a time (see **Figure 1a**).

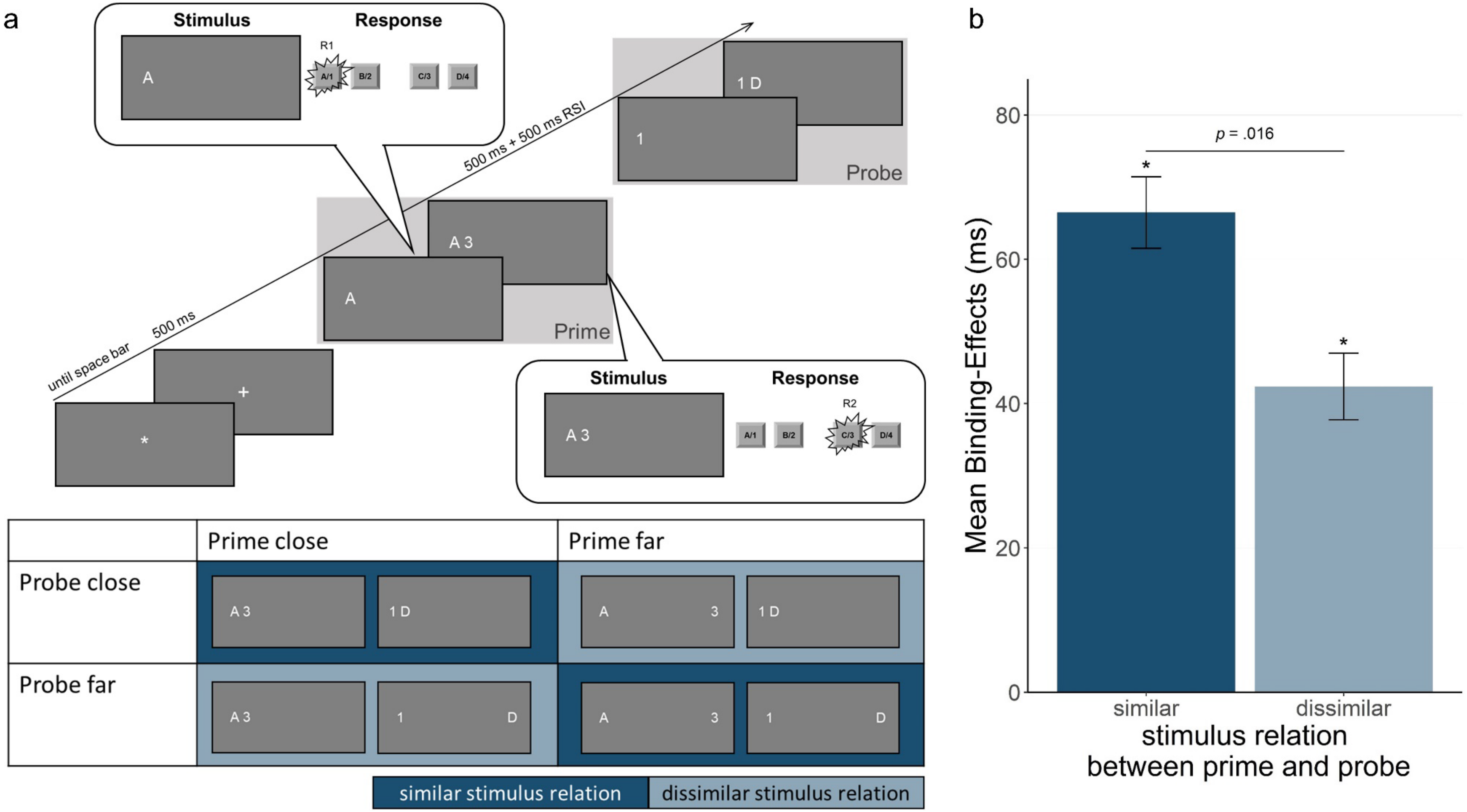

Figure 1. (a) Sequence of events in one example trial. Participants gave two successive responses, R1 and R2, both to the prime and the probe. This is an example of an R1 repetition and R2 change trial in the prime close – probe close stimuli condition. Below are stimulus positions depending on stimulus distance condition and similar vs. dissimilar stimulus relation, respectively. Close stimuli could appear either on the left (as depicted) or on the right side of the screen. The stimuli are not drawn to scale. **(b)** Mean response-response binding effects for response times as a function of stimulus relation (similar vs. dissimilar in prime and probe). Binding effects are calculated as the advantage of probe R1 repetition (vs. probe R1 change) in probe R2 repetition trials minus the advantage of probe R1 repetition (vs. probe R1 change) in probe R2 change trials: [R1cR2r - R1rR2r] - [R1cR2c - R1rR2c]
* $p < .05$ indicates whether binding effects differ significantly from zero.

Procedure. Before the experiment, participants gave informed consent regarding the recording of personal data and responses during the experiment and indicated their age and gender. Instructions were given on the screen. Participants were instructed to place their middle and index fingers on the keys D, F, J, and K. Each key corresponded to a letter and a digit (A/1, B/2, C/3, and D/4)

Their task was to press the key corresponding to the presented letters and digits. Each trial was started by pressing the space bar while an asterisk was presented in the middle of the screen (see **Figure 1a**). Then a plus sign appeared for 500 ms, followed by the first prime stimulus (letter or digit). Then the second prime stimulus appeared indicating prime response R2. The position of stimuli depended on the condition (close vs. far, see **Figure 1a**). Next, a blank screen appeared for 500 ms and was followed by the probe. The procedure in the probe was identical to that in the prime. Every 48 trials participants were allowed to take a short break, after which they resumed the task in their own time.

The relation of R1 between prime and probe (repetition vs. change) was varied orthogonally to the relation of R2 (repetition vs. change). In R1 repetition trials (R1r), the same response was required to the stimulus indicating prime response R1 and the one indicating probe response R1. In R1 change trials (R1c), different responses were required to the stimulus indicating prime response R1 and the one indicating probe response R1. In R2 repetition trials (R2r), the same response was required to the stimulus indicating prime response R2 and the one indicating probe response R2. In R2 change trials (R2c), different responses were required to the stimulus indicating prime response R2 and the one indicating probe response R2. A stimulus distance manipulation was applied to the prime and probe independently, resulting in four distance conditions: prime close – probe close, prime far – probe far, prime close –

probe far, and prime far – probe close, the two first ones represented a similar stimulus relation between prime and probe and the latter ones a dissimilar stimulus relation. These four distance conditions were varied block-wise with one block in each of the four. The order of blocks was balanced across participants via a Latin square. Each experimental block included 96 trials (24 of each of the four conditions R1rR2r, R1rR2c, R1cR2r, R1cR2c), resulting in 384 trials total. At the beginning of the experiment, participants passed a general practice block introducing all distance conditions (8 trials). Before an experimental block started, they practiced their task for 16 trials (a subsample of the experimental trials).

Results

The processing and analysis of data were done in R (R Core Team, 2019; version 4.2.1). We compared the experimental conditions using a repeated-measures analysis of variance (ANOVA) with type-III sums of square. Additionally, we calculated the response-response binding effects as the advantage of probe R1 repetition (vs. probe R1 change) in probe R2 repetition trials minus the advantage of probe R1 repetition (vs. probe R1 change) in probe R2 change trials ([R1cR2r - R1rR2r] - [R1cR2c - R1rR2c]) as another way to represent the two-way interaction between response R1 relation and response R2 relation. Accordingly, the critical four-way interaction can also be expressed as a *t*-test between similar vs. dissimilar prime-probe stimulus relation, with the square root of the *F*-value (i.e., the *t*-value) and the *p*-value of the interaction being equivalent to the *t*-value and *p*-value of the *t*-test.

For the analysis of response times (RTs), we only included trials with correct responses R1 and R2 in both prime and probe. The error rate for prime responses

(R1 or R2) was 8.9%. The probe error rates were 3.9% for R1 and 3.8% for R2 (only including trials with correct previous responses). Furthermore, we excluded RTs of more than 1.5 interquartile ranges above the third quartile of the probe R2 RT distribution of the participant (Tukey, 1977) and RTs shorter than 200 ms from the analysis. Due to these constraints, 18.5% of the trials were excluded from the RT analyses. For the mean RTs and error rates, see **Table 1**.

Table 1. Mean response times (in milliseconds) and mean error rates (in percentages) for probe responses R2, as a function of stimulus distance in prime and probe, R1 relation, and R2 relation between prime and probe

	Prime close		Prime far	
	R2 repetition	*R2 change*	*R2 repetition*	*R2 change*
Probe close				
R1 change	664 (4.7)	635 (1.9)	704 (4.3)	684 (2.2)
R1 repetition	630 (3.0)	672 (4.2)	691 (2.0)	703 (5.0)
Probe far				
R1 change	800 (2.9)	772 (3.6)	732 (4.5)	719 (3.1)
R1 repetition	765 (5.4)	789 (5.0)	685 (3.5)	734 (6.3)

The dependent variable of interest was performance in probe R2. If prime R1 and R2 are integrated, repeating prime R1 in the probe should trigger retrieval of the second prime response and thus influence performance in probe R2. In a 2 (R1 relation: repetition vs. change) × 2 (R2 relation: repetition vs. change) × 2 (prime stimulus distance: close vs. far) × 2 (probe stimulus distance: close vs. far) analysis of variance (ANOVA) on probe R2 RTs, the main effect for probe stimulus distance was significant, $F(1, 30) = 107.81$, $p < .001$, $\eta_p^2 = .78$, with longer RTs if probe stimuli were far apart than when they were close ($M = 750$ vs. 673 ms). The other main effects were not significant: main effect for prime stimulus distance, $F(1, 30) = 2.89$, $p = .099$, $\eta_p^2 = .09$, R1 relation, $F(1, 30) = 3.13$, $p = .087$, $\eta_p^2 = .09$, and R2 relation, F(1,

30) < 1, $p = .374$, $\eta_p^2 = .03$. Importantly, the two-way interaction of R1 and R2 relation was significant, $F(1, 30) = 73.77$, $p < .001$, $\eta_p^2 = .71$, indicating a general response-response binding effect. This binding effect was not modulated by prime stimulus distance, $F(1, 30) = 1.50$, $p = .230$, $\eta_p^2 = .05$, or probe stimulus distance, $F(1, 30) < 1$, $p =.623$, $\eta_p^2 < .01$, individually. However, there was a significant four-way interaction, $F(1, 30) = 6.56$, $p =.016$, $\eta_p^2 = .18$, which can be expressed as a *t*-test between binding effects in conditions with similar stimulus relation in prime and probe (prime close – probe close & prime far – probe far) versus dissimilar stimulus relation (prime close – probe far & probe far – prime close), that revealed a significant difference, $t(30)= 2.56$, $p =.016$, $d_z = 0.55$, $BF_{10} = 3.05$, with stronger binding effects for similar than for dissimilar prime-probe relations (M = 66 vs. 42 ms, see **Figure 1b**). Post-hoc *t*-tests between the binding effects in the four different stimulus distance conditions indicated no significant differences, all $|ts| < 0.58$, $ps_{(holm\text{-}corr.)} >.172$, $|d_{z|} < 0.13$.

For the sake of completeness, the interactions between R1 relation and probe stimulus distance, $F(1, 30) = 5.69$, $p =.024$, $\eta_p^2 = .16$, prime and probe stimulus distance, $F(1, 30) = 32.57$, $p <.001$, $\eta_p^2 = .52$, and prime stimulus distance, probe stimulus distance and R2 relation, $F(1, 30) = 6.74$, $p =.014$, $\eta_p^2 = .18$, were also significant. All other interactions did not reach significance, Fs < 1.6, ps > .225.

In the same analysis on error rates, again the main effect of probe stimulus distance was significant, $F(1, 30) = 5.47$, $p =.026$, $\eta_p^2 = .15$, indicating more errors with far probe stimuli than with close stimuli (M = 4.3 vs 3.4%). Additionally, the main effect for R1 relation was significant, $F(1, 30) = 4.37$, $p =.045$, $\eta_p^2 = .13$, while the other main effects were not, Fs < 1, ps > .796. Again, the interaction of R1 and R2 relation was significant, $F(1, 30) = 20.82$, $p < .001$, $\eta_p^2 = .41$, indicating binding between the responses. This relation was further modulated by prime stimulus distance[1], $F(1, 30) = 7.72$, $p = .009$, $\eta_p^2 = .20$, but not by probe stimulus distance, $F(1, 30) = 3.55$, $p = .069$, $\eta_p^2 = .11$. All other interactions were not significant, *F*s < 2.1, *p*s >.164.

Discussion

In this study, we investigated whether the spatial distance between response stimuli becomes part of the cognitive representation of an action sequence, and thus, whether stimulus distance affects its execution. If the distance between two stimuli that are responded to in sequence is cognitively represented as part of the action sequence, this might modulate response-response binding effects in one of two ways: The stimulus distance might directly impact the represented relation of responses, which might then affect whether responses are integrated and/or retrieved depending on the stimulus distance conditions. Then again, similarity of stimulus distance during integration and retrieval might be crucial for binding effects to occur, which would lead to differences in response-response binding effects, depending on whether the stimulus relation changes or remains constant between prime and probe.

Our results indicate that the stimulus distance is represented in the action sequence in a way that has been described as context effects (see Mayr et al., 2018). We found stronger binding effects in trials with similar than with dissimilar stimulus relation in prime and probe. This is in line with previous findings in the action control literature showing that the context is also part of the representation of

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[1] Albeit we found that prime distance modulated response-response binding effects in the error rates, this interaction was not the one we predicted (i.e. larger binding in the conditions with close prime stimuli), and further, the error data pattern did not fit the RT pattern. In concert, RT and error data do not support the hypothesis that close distance at the prime enhances response-response binding effects.

individual actions (Laub & Frings, 2020; Mayr et al., 2018; Qiu et al., 2022a, 2022b). Thus, we seem to retrieve responses more readily when they occur in the same context and with the same relation of stimuli as the one they were integrated in than if the context changes. While such context effects are well established in the memory literature, where access to learned information is facilitated in similar than dissimilar contexts (e.g., Tulving & Thomson, 1973; Zeelenberg, 2005), this is less clear for short term effects in action control. Here we have shown that context is also relevant in the control of sequential actions, possibly helping us to select action sequences that match the demands of the situation: If the relation of interactable objects remains constant, it is more likely that the same action sequence is appropriate again, thus it makes sense that its retrieval is comparably easy. However, if sudden changes in the object relation occur, it is advantageous to not retrieve an action sequence, as the specific actions might not be appropriate anymore.

Stimulus distance did not directly influence the overall occurrence of response-response binding effects. In fact, responses were integrated and retrieved with close as well as with far stimuli. Thus, multiple responses seem to be represented as one action sequence regardless of stimulus distance. In this, results differ from findings in individual actions. There, the spatial relation between multiple stimuli altered whether they were represented as part of the same event file, with spatially close or connected stimuli being represented together in one event file, while spatially separated stimuli were not (Frings & Rothermund, 2011; Moeller et al., 2012; Schmalbrock et al., 2022). Thus, a specific stimulus setup seems to influence the occurrence of binding and retrieval on the level of individual event files, but not across events.

There was a main effect for probe stimulus distance, which indicated significantly longer RTs and more errors in the second probe response if probe stimuli were far apart than when they were close. This might be explained by the necessity for the participant to shift attention from one side of the screen to the other if the probe stimuli were far, thus consuming more time and potentially allowing for more errors. Longer RTs generally allow more time for retrieval, which is discussed in the binding literature to lead to stronger binding effects (e.g., Frings & Moeller, 2012; Schöpper & Frings, 2022). However, we observe no such influence on binding effects in this experiment, as these do not differ significantly depending on probe stimulus distance.

It makes sense that responses are represented in one action sequence, i.e., that response-response binding effects occur, regardless of whether stimuli are further apart or closer together, as we are usually quite flexible in adapting our movements according to our surroundings (e.g., Gallivan et al., 2018), so that small stimulus distances (as in this study) may not be particularly relevant for the execution of the action sequence. It is possible that a more extreme manipulation with greater stimulus distances would have influenced binding effects. Importantly, stimulus and response location were deliberately independent from each other in this study to vary stimulus distance without potential influences of response distance (see e.g., Lakens et al., 2011; Nett & Frings, 2014; Selimi et al., submitted). While this is representative for some everyday actions like turning on the television by using a remote control, stimulus and response location are confounded in many other everyday actions (e.g., we often have to touch stimuli to interact with them). This independence of stimulus and response location may have made stimulus distance even less relevant, as participants did not even need to adjust their actions to accommodate for the stimulus distance.

We could show that stimulus distance did not affect the perceived relation of responses to an extent that response-response binding effects were affected. Interestingly, there are findings showing that the other way around, the relation of possible responses can have an influence on the perceived relation of stimuli: If responses were separated via response keys, this facilitated the discrimination of corresponding stimulus features (Lakens et al., 2011; Nett & Frings, 2014; but see Schäfer & Frings, 2021). Therefore, it seems that the representation of stimuli is affected by spatial response relations, but the representation of multiple responses is not affected by spatial stimulus relations. This is in line with existing research (Schäfer & Frings, 2021), and seems to be another indication that responses are generally more likely to become part of bindings than stimulus features that can be assumed to receive less attention (see Moeller et al., 2019).

Together with previous findings, the results at hand suggest that varying the relations between stimuli (present at the time of responding), responses, or effects elicited by responses leads to different influences on response-response binding effects. While modulating the relation of responses directly affected how strongly they are integrated and/or retrieved (Fournier & Gallimore, 2013), binding between responses was not influenced by the relation of stimuli (see also Fournier & Gallimore, 2013) or the relation of visual effects elicited by responses (Selimi et al., 2022). Thus, response-response bindings seem to be somewhat robust to influences of stimulus relation at the time point of responding or thereafter, as long as these do not indicate a context change.

In sum, spatial distance between response relevant stimuli can affect the representation of responses given to the respective stimuli. However, stimulus distance does not directly affect the relation of two responses as measured via response-response binding effects, with more binding for close stimuli. Instead, the similarity of stimulus distance at the time points of binding and retrieval is important, with stronger response-response binding effects if the distance remains similar than when it changes. This finding might reflect the ability to quickly adapt the control of action sequences to changing situation demands induced by changes in stimulus setup. Results also indicate that binding between responses is generally possible both if response relevant stimuli appear spatially close together or far apart. In this sense, response-response binding effects are independent of stimulus distance. By contrast, a similar modulation in response setup (close vs. far responses) directly affected stimulus representations (e.g., Lakens et al., 2011). This difference is in line with past findings and underlines the special role responses seem to play in binding and retrieval in action control.

Declarations

Funding

The research reported in this article was supported by grants of the Deutsche Forschungsgemeinschaft to Birte Moeller (MO 2839/2-2), Christian Frings (FOR 2790), Christian Beste and Alexander Münchau (FOR 2698).

Conflicts of interest/Competing interests

The authors declare no competing interests.

Ethics approval

All procedures performed involving human participants were in accordance with the ethical standards at the psychology institute in Trier and with the 1964 Helsinki declaration and its later amendments.

Consent to participate/Consent for publication

Informed consent was obtained from all individual participants included in the study.

Availability of data and materials

All data generated and/or analyzed during the current study is available in the PsychArchives repository under: http://dx.doi.org/10.23668/psycharchives.12199. The experiment was not preregistered.

References

Dilcher, R., Jamous, R., Takacs, A., Tóth-Fáber, E., Münchau, A., Li, S.-C., & Beste, C. (2021). Neurophysiology of embedded response plans: Age effects in action execution but not in feature integration from preadolescence to adulthood. *Journal of Neurophysiology*, *125*(4), 1382–1395. https://doi.org/10.1152/jn.00681.2020

Faul, F., Erdfelder, E., Lang, A.-G., & Buchner, A. (2007). G*power 3: A flexible statistical power analysis program for the social, behavioral, and biomedical sciences. *Behavior Research Methods*, *39*(2), 175–191. https://doi.org/10.3758/BF03193146

Fournier, L. R., & Gallimore, J. M. (2013). What makes an event: Temporal integration of stimuli or actions? *Attention, Perception, & Psychophysics*, *75*(6), 1293–1305. https://doi.org/10.3758/s13414-013-0461-x

Frings, C., Hommel, B., Koch, I., Rothermund, K., Dignath, D., Giesen, C., Kiesel, A., Kunde, W., Mayr, S., Moeller, B., Möller, M., Pfister, R., & Philipp, A. (2020). Binding and Retrieval in Action Control (BRAC). *Trends in Cognitive Sciences*, *24*(5), 375–387. https://doi.org/10.1016/j.tics.2020.02.004

Frings, C., & Moeller, B. (2012). The horserace between distractors and targets: Retrieval-based probe responding depends on distractor–target asynchrony. *Journal of Cognitive Psychology*, *24*(5), 582–590. https://doi.org/10.1080/20445911.2012.666852

Frings, C., & Rothermund, K. (2011). To be or not to be…Included in an event file: Integration and retrieval of distractors in stimulus-response episodes is influenced by perceptual grouping. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, *37*(5), 1209–1227. https://doi.org/10.1037/a0023915

Frings, C., Rothermund, K., & Wentura, D. (2007). Distractor repetitions retrieve previous responses to targets. *Quarterly Journal of Experimental Psychology*, *60*(10), 1367–1377. https://doi.org/10.1080/17470210600955645

Gallivan, J. P., Chapman, C. S., Wolpert, D. M., & Flanagan, J. R. (2018). Decision-making in sensorimotor control. *Nature Reviews. Neuroscience*, *19*(9), 519–534. https://doi.org/10.1038/s41583-018-0045-9

Hommel, B. (1998). Event Files: Evidence for Automatic Integration of Stimulus-Response Episodes. *Visual Cognition*, *5*(1-2), 183–216. https://doi.org/10.1080/713756773

Hommel, B. (2004). Event files: Feature binding in and across perception and action. *Trends in Cognitive Sciences*, *8*(11), 494–500. https://doi.org/10.1016/j.tics.2004.08.007

Lakens, D., Schneider, I. K., Jostmann, N. B., & Schubert, T. W. (2011). Telling things apart: The distance between response keys influences categorization times. *Psychological Science*, *22*(7), 887–890. https://doi.org/10.1177/0956797611412391

Laub, R., & Frings, C. (2020). Distractor-based retrieval in action control: The influence of encoding specificity. *Psychological Research*, *84*(3), 765–773. https://doi.org/10.1007/s00426-018-1082-8

Laub, R., Frings, C., & Moeller, B. (2018). Dissecting stimulus-response binding effects: Grouping by color separately impacts integration and retrieval processes. *Attention, Perception & Psychophysics*, *80*(6), 1474–1488. https://doi.org/10.3758/s13414-018-1526-7

Mayr, S., Möller, M., & Buchner, A. (2018). Contextual modulation of prime response retrieval processes: Evidence from auditory negative priming. *Attention, Perception, & Psychophysics*, *80*(8), 1918–1931. https://doi.org/10.3758/s13414-018-1574-z

Mielke, E., Takacs, A., Kleimaker, M., Schappert, R., Conte, G., Onken, R., Künemund, T., Verrel, J., Bäumer, T., Beste, C., & Münchau, A. (2021). Tourette syndrome as a motor disorder revisited - Evidence from action coding. *NeuroImage. Clinical*, *30*, 102611. https://doi.org/10.1016/j.nicl.2021.102611

Moeller, B., & Frings, C. (2019a). Binding processes in the control of nonroutine action sequences. *Journal of Experimental Psychology: Human Perception and Performance*, *45*(9), 1135–1145. https://doi.org/10.1037/xhp0000665

Moeller, B., & Frings, C. (2019b). From simple to complex actions: Response-response bindings as a new approach to action sequences. *Journal of Experimental Psychology: General*, *148*(1), 174–183. https://doi.org/10.1037/xge0000483

Moeller, B., & Frings, C. (2019c). Lost time: Bindings do not represent temporal order information. *Psychonomic Bulletin & Review*, *26*(1), 325–331. https://doi.org/10.3758/s13423-018-1493-y

Moeller, B., & Frings, C. (2019d). Response-response binding across effector-set switches. *Psychonomic Bulletin & Review*, *26*(6), 1974–1979. https://doi.org/10.3758/s13423-019-01669-8

Moeller, B., & Frings, C. (2021). Response-response bindings do not decay for 6 seconds after integration: A case for bindings' relevance in hierarchical action control. *Journal of Experimental Psychology: Human Perception and Performance*, *47*(4), 508–517. https://doi.org/10.1037/xhp0000897

Moeller, B., & Frings, C. (2022). All together now: Simultaneous feature integration and feature retrieval in action control. *Psychonomic Bulletin & Review*, *29*(2), 512–520. https://doi.org/10.3758/s13423-021-01999-6

Moeller, B., Pfister, R., Kunde, W., & Frings, C. (2019). Selective binding of stimulus, response, and effect features. *Psychonomic Bulletin & Review*, *26*(5), 1627–1632. https://doi.org/10.3758/s13423-019-01646-1

Moeller, B., Rothermund, K., & Frings, C. (2012). Integrating the irrelevant sound. *Experimental Psychology*, *59*(5), 258–264. https://doi.org/10.1027/1618-3169/a000151

Nett, N., & Frings, C. (2014). Things can be told apart: No influence of response categories and labels on the distance effect in Stroop tasks. *Experimental Psychology*, *61*(2), 142–148. https://doi.org/10.1027/1618-3169/a000234

Peirce, J., Gray, J. R., Simpson, S., MacAskill, M., Höchenberger, R., Sogo, H., Kastman, E., & Lindeløv, J. K. (2019). Psychopy2: Experiments in behavior made easy. *Behavior Research Methods*, *51*(1), 195–203. https://doi.org/10.3758/s13428-018-01193-y

Qiu, R., Möller, M., Koch, I., & Mayr, S. (2022a). Inter-Trial Variability of Context Influences the Binding Structure in a Stimulus-Response Episode. *Journal of Cognition*, *5*(1), Article 25. https://doi.org/10.5334/joc.215

Qiu, R., Möller, M., Koch, I., & Mayr, S. (2022b). Saliency determines the integration of contextual information into stimulus-response episodes. *Attention, Perception, & Psychophysics*, *84*(4), 1264–1285. https://doi.org/10.3758/s13414-021-02428-5

R Core Team. (2019). *R: A language and environment for statistical computing* (Version 4.2.1) [Computer software]. Vienna, Austria. https://scholar.google.com/citations?user=yvs1queaaaaj&hl=de&oi=sra

Schäfer, S., & Frings, C. (2021). Different effects of spatial separation in action and perception. *Psychonomic Bulletin & Review*, *28*(3), 845–852. https://doi.org/10.3758/s13423-020-01867-9

Schmalbrock, P., Kiesel, A., & Frings, C. (2022). What Belongs Together Retrieves Together – The Role of Perceptual Grouping in Stimulus-Response Binding and Retrieval. *Journal of Cognition*, *5*(1), Article 28. https://doi.org/10.5334/joc.217

Schöpper, L.-M., & Frings, C. (2022). Same, but different: Binding effects in auditory, but not visual detection performance. *Attention, Perception, & Psychophysics.* Advance online publication. https://doi.org/10.3758/s13414-021-02436-5

Selimi, S., Frings, C., & Moeller, B. (submitted). Separated hands further response-response binding effects.

Selimi, S., Frings, C., & Moeller, B. (2022). Binding between Responses is not Modulated by Grouping of Response Effects. *Journal of Cognition*, *5*(1), 42. https://doi.org/10.5334/joc.233

Takacs, A., Bluschke, A., Kleimaker, M., Münchau, A., & Beste, C. (2021). Neurophysiological mechanisms underlying motor feature binding processes and representations. *Human Brain Mapping*, *42*(5), 1313–1327. https://doi.org/10.1002/hbm.25295

Tukey, J. W. (1977). *Exploratory data analysis* (Vol. 2). Reading, MA.

Tulving, E., & Thomson, D. M. (1973). Encoding specificity and retrieval processes in episodic memory. *Psychological Review*, *80*(5), 352–373. https://doi.org/10.1037/h0020071

Wendiggensen, P., Adelhöfer, N., Jamous, R., Mückschel, M., Takacs, A., Frings, C., Münchau, A., & Beste, C. (2022). Processing of embedded response plans is modulated by an interplay of frontoparietal theta and beta activity. *Journal of Neurophysiology*, *128*(3), 543–555. https://doi.org/10.1152/jn.00537.2021

Zeelenberg, R. (2005). Encoding specificity manipulations do affect retrieval from memory. *Acta Psychologica*, *119*(1), 107–121. https://doi.org/10.1016/j.actpsy.2004.12.001

4.3 Article 3. Binding between Responses is not Modulated by Grouping of Response Effects

This manuscript has been published as:

Selimi, S., Frings, C., & Moeller, B. (2022). Binding between Responses is not Modulated by Grouping of Response Effects. *Journal of Cognition*, *5*(1), 42.

DOI: http://doi.org/10.5334/joc.233

journal of cognition

Binding between Responses is not Modulated by Grouping of Response Effects

COLLECTION: CORE MECHANISMS IN ACTION CONTROL: BINDING AND RETRIEVAL

RESEARCH ARTICLE

ubiquity press

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ABSTRACT

Several action control theories postulate that individual responses to stimuli are represented by event files that include temporal bindings between stimulus, response, and effect features. Which stimulus features are bound into an event file can be influenced by stimulus grouping. Here, we investigate whether effect grouping moderates response feature binding. For this purpose, we used an adapted response-response binding paradigm introducing a visual effect after each response. These effects could either appear spatially grouped, i.e., close to each other, or non-grouped, thus far from each other. If effect grouping influences response representation, response-response binding effects should be larger for responses producing grouped effects than for responses producing non-grouped effects. In two experiments, we found no indication for a modulation of response-response binding by effect grouping. The role of effect grouping for binding and retrieval processes seems to differ from past evidence regarding stimulus grouping.

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KEYWORDS:
Action and perception; Event cognition; Action

TO CITE THIS ARTICLE:
Selimi, S., Frings, C., and Moeller, B. (2022). Binding between Responses is not Modulated by Grouping of Response Effects. *Journal of Cognition*, 5(1): 42, pp. 1–11. DOI: https://doi.org/10.5334/joc.233

INTRODUCTION

Perceptual input is important for action control. Most of the time, we need to perceive objects to interact with them and our interaction in turn results in perceivable effects, be it plucking strings on a guitar that result in different tones, or simply the button presses on your computer keyboard that result in letters appearing on screen. Prinz (e.g., 1992) suggested that perception and action are closely related. The representation of stimulus and response features in partially overlapping neuronal structures allows for interaction of sensory and motor codes without the need of translation from one format to another, an assumption known as the principle of *common coding* (Prinz, 1992, 1997). The common coding principle is a central element in the *theory of event coding* (Hommel et al., 2001; see Shin et al., 2010), which proposes that the representation of a single action integrates codes of response features and perceptual features into one short-term memory trace termed *event file* (Hommel, 2004). Event files have been described as loose networks of binary bindings between individual (stimulus-, response-, and effect-) features of an event (Hommel, 2004), that can, as a central element in the recent *binding and retrieval in action control* framework, account for various classical effects in action control (Frings et al., 2020). While an event file is active, repeating any of the integrated features triggers retrieval of other integrated features, affecting further action. Event files are not limited to one perceptual domain at a time, but were found to include visual, auditory, and tactile information (e.g., Schöpper et al., 2020; Zmigrod et al., 2009). Additionally, these representations are not limited to relevant stimuli, but might also include stimuli that are task irrelevant (Frings et al., 2007), or even the context (Mayr et al., 2018), cognitive control-states (Dignath et al., 2019) and other responses (Moeller & Frings, 2019a, 2019b).

Different factors influence which perceptual information becomes part of an event file and thus is relevant for representation of an action. One factor that was commonly found to influence integration of perceptual information into an event file is grouping. According to the Gestalt principles of grouping, grouped information is perceived as belonging together (Wagemans et al., 2012). Grouping determined whether irrelevant stimuli were integrated into an event-file and thus could retrieve it later on: If an irrelevant stimulus was grouped with a relevant stimulus, the irrelevant stimulus was more likely integrated into the event-file and thus influenced further action (Frings & Moeller, 2012; Frings & Rothermund, 2011; Giesen & Rothermund, 2011; Laub et al., 2018). For example, distractor sounds were only integrated in an event file, if they appeared spatially close to the target stimulus (Moeller et al., 2012).

While these findings indicate an influence of stimulus grouping on event file integration, this was only tested for stimuli present at the time of responding. It is possible that the same also applies to stimuli triggered by responses, i.e. effects. While effects are theorized as part of an event-file, some theories proclaim a special role for them in action representation. For example, the ideomotor principle proposes that actions and effects are so tightly related that the mere anticipation of an effect might suffice to retrieve the action (i.e. the event-file including the motor program) that has been associated with this effect, or, in other words, we represent a response in terms of its perceivable effects (James, 1890; Shin et al., 2010; Stock & Stock, 2004). Here we aimed to analyze whether grouping of effects has a similar impact on integration of information into an event file as has been reported for stimulus grouping. That is, if two effects are grouped, they should be more likely integrated in the same action representation than if they do not appear grouped. In the typical paradigms (e.g., Kunde, 2001; Kunde et al., 2004), different effects are triggered by individual responses. Therefore, we focused on the influence of effect grouping on binding across responses. Through the tight connection between responses and their effects, modulating the relation of two effects might influence how we represent the two actions that triggered these effects. We thus either did or did not group the effects of individual responses and analyzed whether integration of these responses was affected in turn.

To measure binding between individual responses we adapted the response-response (RR-) binding paradigm that was introduced by Moeller and Frings (2019b). In RR-binding, two (or more, Moeller & Frings, 2019a) simple responses are successively planned and executed. Upon execution, these responses are bound to each other in an action representation of higher order, so that a subsequent repetition of one of them retrieves the other and influences execution of this second response. For the present purpose, we introduced a visual effect after each response. These effects could either appear spatially grouped, i.e. close to each other, or non-grouped, thus far from each other.[1] If effect grouping affects binding and retrieval similar to what is known from stimulus grouping, RR-binding effects should be larger for responses producing grouped effects than for responses producing non-grouped effects.

In two experiments we investigated this question by introducing visual response effects in a grouped vs. non-grouped manipulation. In Experiment 1 effect grouping was varied block-wise while in Experiment 2 effect grouping was varied trial-wise. In an additional control experiment, validating our grouping manipulation (see Appendix A), participants rated to what extent they perceived effects in different spatial positions as being grouped. Anticipating results, we observed standard RR-binding effects but none of the experiments provided evidence for an impact of effect grouping on RR-binding.

EXPERIMENT 1

The aim of Experiment 1 was to investigate whether grouping of effects modulates integration of the corresponding responses. If grouping of effects has an influence on event-file integration, responses that elicit grouped effects should be more likely to be integrated than responses eliciting non-grouped effects. Anticipating that to some degree participants might perceive response effects as artificial, we took measures to increase the perceived relatedness between responses and effects. Previous research found that instructions can influence the way an effect is cognitively represented and can even overrule other influences of response-effect correspondence (Hommel, 1993). We designed the instructions to state that the participants actively make effects light up by giving correct answers. This should prompt the participants to represent the effects in terms of their action goals (making the effect appear; Hommel, 1993). To incentivize participants to attend to the effects, they were also instructed to use them as feedback for whether they answered correctly. To further ensure that responses and effects are perceived as cohesive (Kunde, 2001; Kunde et al., 2004), we presented effects on a horizontal line, similar to the response keys, which are aligned horizontally on the keyboard.

METHOD

Participants

Thirty students (22 women) from Trier University participated in the experiment. The samples' mean age was 22 years, with a range from 19 to 35 years. The participants were rewarded with partial course credit. Effect sizes in former studies on RR-binding (computed as t/sqrt(n)) were at least d = 0.63 (e.g., Moeller & Frings, 2019b: d = 0.63 and d = 0.88; Moeller & Frings, 2019c: d = 1.07; Moeller & Frings, 2019d: d = 0.74 and 1.07). A power-analysis with the program G*Power assuming α = .05 and a power of $1-\beta$ = .85 suggests that at least 25 participants were necessary (Faul et al., 2007).

Design

The design comprised three within-subjects factors, namely, effect grouping (grouped vs. non-grouped), response R1 relation (response repetition vs. response change from prime to probe), and response R2 relation (response repetition vs. response change from prime to probe).

Materials

The experiment was programmed in PsychoPy3/PsychoJS (2021.1.2; Peirce et al., 2019) and conducted online on Pavlovia (https://pavlovia.org/). For participation, a computer with a physical keyboard was required. Instructions were presented in white [RGB: 255, 255, 255] on a grey background [RGB: 128, 128, 128]. Stimuli were the letters A, B, C, and D and the digits 1, 2, 3, and 4, each with a height of 35 pixels and presented in white. Each display consisted of one letter or digit stimulus presented randomly on one out of 18 positions along an imaginary horizontal line drawn through the center of the screen.

Response effects were signified by blue [RGB: 0, 0, 255] squares with a white border and appeared on one of four positions on the same imaginary center screen line, depending on

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[1] We used the term 'grouping' not as spatial proximity in relation to other elements (see Wagemans et al., 2012), but in a sense that was implemented in studies on binding and retrieval processes in the past (e.g., Frings & Rothermund, 2011; Moeller et al., 2012).

the condition (coordinates in pixels, center of screen has coordinates [0, 0]: [–530, 0] and [530, 0] for non-grouped condition, and [–30, 0] and [30, 0] for grouped condition). Prime response effects disappeared after the prime, resulting in a maximum of two response effects visible at a time (see Figure 1a & b).

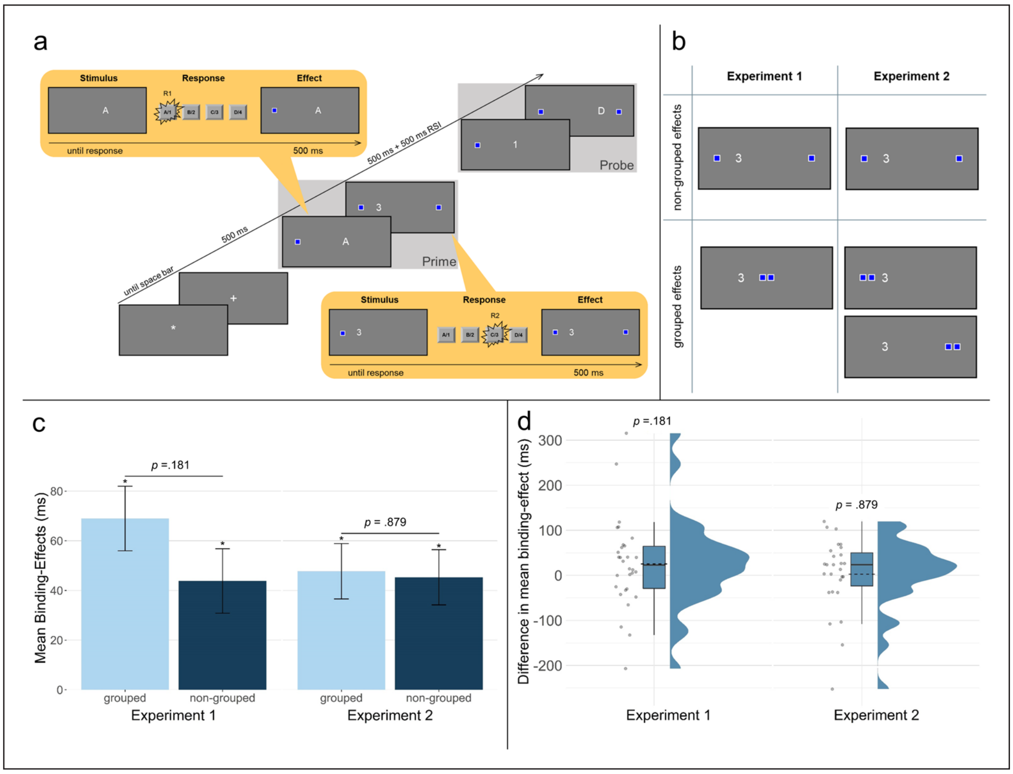

Figure 1 (a) Sequence of events in Experiments 1 and 2 in one example trial. Participants gave two successive responses, R1 and R2, both to the prime and to the probe. This is an example of a R1 repetition and R2 change trial in the non-grouped condition. The stimuli and effects are not drawn to scale. **(b)** Effect positions depending on effect grouping condition and Experiment. **(c)** Response-response binding effects in response times across Experiments 1 and 2 as a function of effect grouping (grouped vs. non-grouped). Binding effects were calculated as R1 repetition minus R1 change RTs for R2 change trials, subtracted from R1 repetition minus R1 change RTs for R2 repetition trials [(R1cR2r – R1rR2r) – (R1cR2c – R1rR2c)] **(d)** Distribution of difference in mean response-response binding effects between effect grouping conditions (calculated as [grouped]–[non-grouped] for each participant) for Experiment 1 and 2. Solid lines indicate medians; dashed lines indicate means.

Procedure

Before the experiment, participants gave informed consent regarding the recording of personal data and responses during the experiment and indicated their age and gender. Instructions were given on the screen. Participants were instructed to place their middle and index fingers on the keys D, F, J, and K. Each key corresponds to a letter and a digit (A/1, B/2, C/3, and D/4).

Their task was to press the key corresponding to the individually presented letters and digits. Each trial was started by pressing the space bar while an asterisk was presented in the middle of the screen (see Figure 1a). Then a plus sign appeared for 500 ms, followed by the first prime stimulus (letter or digit). Upon correct responses, a first response effect square lit up for 500 ms, upon incorrect responses, the trial continued without a response effect square appearing. Then the second prime stimulus appeared indicating prime response R2. Again, execution of a correct response resulted in the presentation of a second effect square for 500 ms while the response stimulus remained on screen. The position of response effect squares depended on condition (grouped vs. non-grouped, see Figure 1b). Afterwards, a blank screen appeared for 500 ms and was followed by the probe. The procedure in the probe was identical to that in the prime. Every 48 trials participants were allowed to take a short break, after which they resumed the task in their own time.

The relation of R1 between prime and probe (repetition vs. change) was varied orthogonally to the relation of R2 (repetition vs. change). In R1 repetition trials (R1r), the same response was required to the stimulus indicating prime response R1 and the one indicating probe response R1. In R1 change trials (R1c), different responses were required to the stimulus indicating prime response R1 and the one indicating probe response R1. In R2 repetition trials (R2r), the same response was required to the stimulus indicating prime response R2 and the one indicating probe response R2. In R2 change trials (R2c), different responses were required to the stimulus indicating prime response R2 and the one indicating probe response R2. The factor effect grouping was varied block-wise with one block in each of the two conditions. The order of blocks was balanced across participants. Each experimental block included 96 trials, with 24 of each of the four conditions R1rR2r, R1rR2c, R1cR2r, R1cR2c. Stimuli indicating the R1 and R2 responses in prime and probe were selected at random, but in accordance to the requirements of the current condition. There were no stimulus repetitions within a trial. At the beginning of the experiment, participants passed a general practice block introducing both grouping conditions to avoid block order effects (4 trials). Before each experimental block started, they practiced their task for 16 trials (subsample of the experimental trials).

RESULTS

For the analysis of response times (RTs) we only included trials with correct responses R1 and R2 in both prime and probe. The rate of prime response errors (R1 or R2) was 12.9%. The probe error rates were 6.3% for R1 and 6.6% for R2 (only including trials with correct previous responses). Furthermore, we excluded RTs of more than 1.5 interquartile ranges above the third quartile of the probe R2 RT distribution of the participant (Tukey, 1977) and RTs shorter than 200 ms from the analysis. Due to these constraints, 26.0% of the trials were excluded from the RT analyses. For the mean RTs and error rates, see Table 1.

Table 1 Mean response times (in milliseconds) and mean error rates (in percentages) for probe responses R2, as a function of effect grouping, R1 relation and R2 relation between prime and probe.

	GROUPED EFFECTS		**NON-GROUPED EFFECTS**	
	R2 REPETITION	***R2 CHANGE***	***R2 REPETITION***	***R2 CHANGE***
R1 change	692 (9.1)	628 (2.4)	708 (9.6)	650 (5.4)
R1 repetition	668 (7.9)	672 (8.2)	690 (8.2)	676 (5.6)

The dependent variable of interest was performance in probe R2. If prime R1 and R2 are integrated, repeating prime R1 in the probe should trigger retrieval of the second prime response and thus influence performance in probe R2. In a 2 (R1 relation: repetition vs. change) × 2 (R2 relation: repetition vs. change) × 2 (effect grouping: grouped vs. non-grouped) analysis of variance (ANOVA) on probe R2 RTs, the main effect for R2 relation was significant, $F(1, 29) = 41.35$, $p < .001$, $\eta_p^2 = .59$, while the main effect for R1 relation was not, $F(1, 29) = 2.59$, $p = .118$, $\eta_p^2 = .08$. Additionally, the main effect for effect grouping was significant, $F(1, 29) = 4.59$, $p = .041$, $\eta_p^2 = .14$, with longer RTs in the non-grouped than in the grouped condition. More importantly, the two-way interaction of R1 and R2 relation was significant, $F(1, 29) = 29.01$, $p < .001$, $\eta_p^2 = .50$, indicating binding between the responses: The repetition of R1 facilitated performance only if R2 was repeated as well, $t(59) = 4.03$, $p < .001$, but impaired performance if R2 changed, $t(59) = -4.98$, $p < .001$. However, this was not further modulated by effect grouping, $F(1, 29) = 1.88$, $p = .181$, $\eta_p^2 = .06$, (see Figure 1c, for distributions of participants binding effects differences between grouping conditions, see Figure 1d). Bayes factors provided anecdotal evidence for an absence of the effect grouping modulation, $BF_{01} = 2.21$.

In the same analysis on error rates, the main effect of R2, $F(1, 29) = 15.36$, $p < .001$, $\eta_p^2 = .35$, was significant, while the main effect of R1, $F(1, 29) = 2.23$, $p = .146$, $\eta_p^2 = .07$, was not. However, the interaction of R1 and R2 was significant, $F(1, 29) = 11.14$, $p = .002$, $\eta_p^2 = .28$, again indicating binding between the responses: The repetition of R1 did not facilitate performance if R2 was repeated as well, $t(59) = 1.36$, $p = .18$, but impaired performance if R2 changed, $t(59) = -3.05$, $p = .003$. The relation was not further modulated by effect grouping, $F(1, 29) = 2.82$, $p = .10$, $\eta_p^2 = .09$, $BF_{01} = 1.47$. Taken together, results from both, RT and error rate data, indicate that RR-binding effects are not modulated by grouping of response effects.

DISCUSSION

Results from Experiment 1 indicate that responses are integrated and thus, they clearly replicate previous findings on RR-binding. However, RR-binding effects were not modulated by effect grouping. Three factors might explain the results: Firstly, it stands to question whether the grouping manipulation itself was actually successful, i.e., whether the participants perceived the two effects as more grouped in the spatially close condition than in the far condition. We used a grouping manipulation for our effects that was similar to the one used before to investigate stimulus grouping on binding and retrieval processes (e.g., Frings & Rothermund, 2011; Moeller et al., 2012). Yet, it is unclear whether such a modulation is perceived the same way when used on response effects. Thus, we conducted a manipulation check experiment (see Appendix A), where participants rated the perceived grouping between response effects. The results were very clear and indicated that participants perceived the effects as significantly more grouped in the spatially close condition than in the far condition. Secondly, one can argue that grouping manipulations might rely on a subjective frame of reference: To perceive two effects as grouped, we need to establish a stable representation of what grouped means in comparison to non-grouped. Since we manipulated grouping block-wise, variance on the factor effect grouping may have lacked to draw sufficient attention to it and to provide a constant comparison of grouped effects for the non-grouped trials and vice versa (for a similar argument regarding the influence of perceptual grouping of stimuli - via figure ground segmentation - on binding, see Frings & Rothermund, 2017). Even though we shortly introduced both conditions at the beginning of the experiment through a general training, this might not have been sufficient to ensure an ongoing representation of the grouped vs. non-grouped manipulation. Thus, introducing a trial-wise manipulation might help establish a proper frame of reference regarding the distance of effects. Thirdly, we cannot be entirely sure that effects were perceived as being related to the responses rather than just being perceived as random. Here a manipulation check would be necessary.

EXPERIMENT 2

In Experiment 2, conditions were varied trial-wise instead of block-wise. To avoid additional complexity of the display with changing effect positions in a trial-wise manipulation, we decided to adjust the effect positions, so that the same four possible positions were used in both conditions. Additionally, we ran a short manipulation check questionnaire at the end of the experiment asking about the participants' impression on the relatedness between responses and effects.

METHOD

Participants

Twenty-seven students (20 women) from Trier University participated in the experiment. The samples' mean age was 23 years, with a range from 19 to 36 years. The participants were rewarded with partial course credit. Three additional participants were excluded due to extremely high error rates (more than 90% of trials had to be excluded).

Design

The design comprised three within-subjects factors, namely, effect grouping (grouped vs. non-grouped), response R1 relation (response repetition vs. response change from prime to probe), and response R2 relation (response repetition vs. response change from prime to probe).

Materials and procedure

Materials and procedure were identical to those in Experiment 1, except for the following differences. Unlike Experiment 1, the factor effect grouping (grouped vs. non-grouped) was variated trial-wise. Thus, the part of the training introducing the two conditions separately was omitted. Additionally, response effects appeared in one of four possible positions (in pixels, screen center has coordinate [0, 0]: [–540, 0], [–480, 0], [480, 0] and [540, 0], see Figure 1b). For the grouped condition, response effects in each trial appeared in either the two left side or the two right side positions, while response effects in the non-grouped condition always appeared on opposite screen side positions, while maintaining a fixed distance (either [–540, 0] and [480, 0], or [–480, 0] and [540, 0]). At the end of the experiment, participants had to fill out a short questionnaire (six items; see Appendix B) judging whether they perceived their responses and the effects as related (forced choice; 4 items) and rating the strength of that relation (7-point rating scale; 2 items).

RESULTS

On a questionnaire regarding the perceived relation of responses and effects, the majority (79.8%) of participants reported perceiving the effects as being related to the responses[2] and rated the strength of this relation with *M* = 5.75 (*SD* = 1.25) on a seven-point scale with 1 being not related and 7 being strongly related. Furthermore, the strength of perceived grouping

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[2] Mean across four forced choice items. Frequency distributions did not differ between items, $\chi^2(3) = 3.04$, $p = .385$.

and the difference in binding effects between both conditions (calculated as [grouped]-[non-grouped] for each participant) did not correlate significantly, $r(23) = -.07$, $p = .736$ (7-point scale), and $r(23) = -.04$, $p = .842$ (forced choice items).

For the analysis of RTs, we considered only trials with correct responses R1 and R2 in both prime and probe. The error rate for prime responses (R1 or R2) was 10.6%. The probe error rates were 5.7% for R1 and 5.1% for R2 (only including trials with correct previous responses). Due to the same constraints as in the previous experiments, 20.0% of the trials were excluded from the RT analyses. For the mean RTs and error rates, see Table 2.

Table 2 Mean response times (in milliseconds) and mean error rates (in percentages) for probe responses R2, as a function of effect grouping, as well as R1 relation and R2 relation between prime and probe.

	GROUPED EFFECTS		NON-GROUPED EFFECTS	
	R2 REPETITION	*R2 CHANGE*	*R2 REPETITION*	*R2 CHANGE*
R1 change	677 (7.4)	619 (2.1)	675 (8.5)	622 (3.9)
R1 repetition	664 (6.0)	653 (4.5)	654 (6.3)	646 (6.5)

In a 2 (R1 relation: repetition vs. change) × 2 (R2 relation: repetition vs. change) × 2 (effect grouping: grouped vs. non-grouped) ANOVA on probe R2 RTs, the main effect for R2 relation was significant, $F(1, 26) = 55.85$, $p < .001$, $\eta_p^2 = .68$, while the main effect for R1 relation was not, $F(1, 26) = 1.58$, $p = .220$, $\eta_p^2 = .06$. Additionally, the main effect of effect grouping was not significant, $F(1, 26) = 1.02$, $p = .321$, $\eta_p^2 = .04$. More importantly, the two-way interaction of R1 and R2 relation was significant, $F(1, 26) = 24.72$, $p < .001$, $\eta_p^2 = .49$, indicating binding between the responses: The repetition of R1 facilitated performance only if R2 was repeated as well, $t(53) = 3.49$, $p < .001$, but impaired performance if R2 changed, $t(53) = -4.29$, $p < .001$. However, this was not further modulated by effect grouping, $F(1, 26) = 0.02$, $p = .879$, $\eta_p^2 < .01$, (see Figure 1c, for distributions of participants binding effects differences between grouping conditions, see Figure 1d). This is supported by a Bayes factor of $BF_{01} = 4.86$, indicating that the data are more than four times more likely under the null hypothesis that assumes no modulation by effect grouping than under the alternative hypothesis.

In the same analysis on error rates, the main effect of R2, $F(1, 26) = 9.67$, $p =.004$, $\eta_p^2 = .27$, was significant, while the main effects of R1, $F(1, 26) = 0.45$, $p = .507$, $\eta_p^2 = .02$ and effect grouping, $F(1, 26) = 3.83$, $p = .061$, $\eta_p^2 = .13$, were not. However, the interaction of R1 and R2 was significant, $F(1, 26) = 12.15$, $p = .002$, $\eta_p^2 = .32$, again indicating binding between the responses: The repetition of R1 facilitated performance if R2 was repeated as well, $t(53) = 2.00$, $p = .050$, but impaired performance if R2 changed: $t(53) = -3.31$, $p = .002$. The relation was not further modulated by effect grouping, $F(1, 26) = 0.16$, $p = .69$, $\eta_p^2 < .01$, $BF_{01} = 4.55$. In sum, results from RT and error rate data do not indicate modulating effects of response effect grouping on RR-binding effects.

DISCUSSION

We again replicated binding between responses but found no modulation by grouping of response effects. Introducing a trial-wise instead of a blocked manipulation to establish a frame of reference regarding grouping did neither impact RR-binding nor the grouping manipulation. This was the case, even though results from a manipulation check questionnaire suggest that participants indeed perceived responses and effects as related in the present experiment. This again indicates that grouping of effects has no influence on whether they are integrated in the same action representation.

GENERAL DISCUSSION

In two experiments, we investigated the role of effect grouping on event-file integration. Using an adapted RR-binding task (Moeller & Frings, 2019b), we manipulated whether responses produced grouped vs. non-grouped effects. If grouping influenced whether effects are integrated in the same representation, we expected grouped effects to lead to stronger RR-binding than non-grouped effects. In sum, we could replicate standard RR-binding effects in both experiments. However, these remained unaffected by the effect grouping manipulation. For an overview of binding effects across both experiments, see Figure 1c.

Regarding the impact of grouping on integration of information into event files, time of appearance seems to make a difference: While stimulus grouping seems to affect what is integrated into an event file, effect grouping does at least not affect integration and retrieval of corresponding responses. When considering potential stimuli to interact with, it makes sense to be somewhat selective, as not every stimulus in our environment is relevant for the action we want to conduct. There may also be some stimuli that are irrelevant for the action itself, but are nevertheless integrated into an event file because they are close to relevant stimuli (Frings et al., 2007; Frings & Rothermund, 2011; van Dam & Hommel, 2010) and need to be attended to be avoided, for example, reaching over a line of mugs on a shelf to fetch the bottle behind them (Moeller & Frings, 2014). In contrast, the number of effects that our actions can elicit in ourselves and in the environment is limited and much more relevant for us (to be able to learn and manipulate our environment). Thus, it might not be necessary to be as selective; on the contrary, being selective would here limit our potential to meaningfully interact with our environment. Hence, we do not need to rely on grouping when it comes to effects.

A limitation of our study is that we only manipulated one type of effect. Response effects can be differentiated into body-related effects, e.g. proprioceptive consequences of responses like the sensation of a keypress, and environment-related effects, like stimuli lighting up on screen (Pfister, 2019). These different types of effects co-occur and thus, either of these can be part of an action representation. In our experiments, we only manipulated grouping of environment-related effects. However, body-related effects always remained the same and likely remained grouped, as fingers giving responses were positioned closely together on the keyboard, making the keypress sensations spatially close to each other. While the integration of environment-related effects alone was not influenced by grouping, it remains to be tested whether the same is true for body-related effects. One could even argue that grouping of body-related effects might have overshadowed the grouping manipulation of environment-related effects. In line with this, we find significant RR-binding effects across both conditions in both experiments. Another argument for some kind of overshadowing of environment-related effect grouping by body-related effects comes from comparing the role of effects in action representation in the context of learning. Environment-related effects might only become important for action representation after their relation to responses has been learned, whereas body-related effects are already past early stages of learning (see James, 1890; Pfister, 2019). It remains to be seen whether findings on grouping can be generalized over both, body-related and environment-related effects, or whether these two are affected differently by grouping and how this might be affected by learning.

In this study, we focused on the spatial grouping of response effects, while keeping temporal factors constant. Due to the trial structure one could argue that responses (and effects) might also be temporally grouped: the stimulus indicating the second prime (probe) response followed immediately upon execution of the first prime (probe) response, while there was a 500 ms blank interval after the second prime response before the probe started. There are findings suggesting that the intent to execute two responses as one (temporally grouped) vs. in sequence influences whether they were integrated as one event (Fournier & Gallimore, 2013). Although responses in our paradigm were executed separately, we cannot rule out that temporal grouping of prime and probe responses might have influenced our results. Interestingly, emphasizing the temporal grouping of responses by elongating the time interval between prime and probe does not lead to stronger binding effects (Moeller & Frings, 2021). In the future, it could be interesting to further investigate the temporal relation between responses (and their effects), especially as it has been shown that temporal features like presentation times of stimuli or response-effect time intervals can also be integrated into event files (Bogon et al., 2017; Dignath et al., 2014). Temporal grouping of responses might potentially interact with, or even overshadow, spatial grouping.

Also regarding temporal grouping, a difference from previous studies on stimulus grouping in binding is that in most instances, stimuli shared a common onset (Frings & Rothermund, 2011; Giesen & Rothermund, 2011; Schmalbrock et al., 2022; but see Laub et al., 2018), while in our study, the effect onsets were asynchronous, as they were dependent on response execution. We attempted to alleviate this asynchrony by making the effect of R1 stay on screen during the performance of R2 and the consequent R2 effect presentation. That is, even though the effects differed in their onset time, they were presented together for 500 ms and shared a common offset. Due to these factors, and regarding the additional experiment checking our grouping manipulation (see Appendix A), we are confident that effect stimuli were perceived as grouped at least to some degree. However, we cannot exclude the possibility that the lack of a common effect onset interfered with a grouping perception.

To conclude, grouping of effects does not seem to influence which information is integrated into one action representation. From the results at hand, we can draw two possible conclusions. It might be that the representation of the two responses was altered through their effects but did simply not affect response-response binding. This could be due to overshadowing by temporal grouping factors. Alternatively, it might be that the spatial distance of this kind of response effect did not alter response representation. Here it is possibly important to differentiate between body- and environment-related effects (see Pfister, 2019). For example, a longer learning history might be necessary before the features of a certain effect can affect the representation of the associated response.

DATA ACCESSIBILITY STATEMENT

Data of this study is available under: https://doi.org/10.23668/psycharchives.5356.

ADDITIONAL FILE

The additional file for this article can be found as follows:

- **Appendices.** Appendix A and B. DOI: https://doi.org/10.5334/joc.233.s1

ETHICS AND CONSENT

All procedures performed involving human participants were in accordance with the ethical standards at the psychology institute in Trier and with the 1964 Helsinki declaration and its later amendments. Informed consent was obtained from all individual participants included in the study.

FUNDING INFORMATION

The research reported in this article was supported by the Deutsche Forschungsgemeinschaft (MO 2839/2-2).

COMPETING INTERESTS

The authors have no competing interests to declare.

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REFERENCES

Bogon, J., Thomaschke, R., & **Dreisbach, G.** (2017). Binding time: Evidence for integration of temporal stimulus features. *Attention, Perception, & Psychophysics*, *79*(5), 1290–1296. DOI: https://doi.org/10.3758/s13414-017-1330-9

Dignath, D., Johannsen, L., Hommel, B., & **Kiesel, A.** (2019). Reconciling cognitive-control and episodic-retrieval accounts of sequential conflict modulation: Binding of control-states into event-files. *Journal of Experimental Psychology: Human Perception and Performance*, *45*(9), 1265–1270. DOI: https://doi.org/10.1037/xhp0000673

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

Faul, F., Erdfelder, E., Lang, A.-G., & **Buchner, A.** (2007). G*power 3: A flexible statistical power analysis program for the social, behavioral, and biomedical sciences. *Behavior Research Methods*, *39*(2), 175–191. DOI: https://doi.org/10.3758/BF03193146

Fournier, L. R., & **Gallimore, J. M.** (2013). What makes an event: Temporal integration of stimuli or actions? *Attention, Perception, & Psychophysics*, *75*(6), 1293–1305. DOI: https://doi.org/10.3758/s13414-013-0461-x

Frings, C., & **Moeller, B.** (2012). The horserace between distractors and targets: Retrieval-based probe responding depends on distractor–target asynchrony. *Journal of Cognitive Psychology*, *24*(5), 582–590. DOI: https://doi.org/10.1080/20445911.2012.666852

Frings, C., & **Rothermund, K.** (2011). To be or not to be…Included in an event file: Integration and retrieval of distractors in stimulus-response episodes is influenced by perceptual grouping. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, *37*(5), 1209–1227. DOI: https://doi.org/10.1037/a0023915

Frings, C., & **Rothermund, K.** (2017). How perception guides action: Figure-ground segmentation modulates integration of context features into S-R episodes. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, *43*(11), 1720–1729. DOI: https://doi.org/10.1037/xlm0000403

Frings, C., Rothermund, K., & **Wentura, D.** (2007). Distractor repetitions retrieve previous responses to targets. *Quarterly Journal of Experimental Psychology*, *60*(10), 1367–1377. DOI: https://doi.org/10.1080/17470210600955645

Frings, C., Hommel, B., Koch, I., Rothermund, K., Dignath, D., Giesen, C., Kiesel, A., Kunde, W., Mayr, S., Moeller, B., Möller, M., Pfister, R., & Philipp, A. (2020). Binding and Retrieval in Action Control (BRAC). *Trends in Cognitive Sciences*, *24*(5), 375–387. DOI: https://doi.org/10.1016/j.tics.2020.02.004

Giesen, C., & **Rothermund, K.** (2011). Affective matching moderates S-R binding. *Cognition & Emotion*, *25*(2), 342–350. DOI: https://doi.org/10.1080/02699931.2010.482765

Hommel, B. (1993). Inverting the Simon effect by intention. *Psychological Research*, *55*(4), 270–279. DOI: https://doi.org/10.1007/BF00419687

Hommel, B. (2004). Event files: Feature binding in and across perception and action. *Trends in Cognitive Sciences*, *8*(11), 494–500. DOI: https://doi.org/10.1016/j.tics.2004.08.007

Hommel, B., Müsseler, J., Aschersleben, G., & **Prinz, W.** (2001). The Theory of Event Coding (TEC): A framework for perception and action planning. *The Behavioral and Brain Sciences*, *24*(5), 849-78; discussion 878–937. DOI: https://doi.org/10.1017/S0140525X01000103

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

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

Kunde, W., Koch, I., & **Hoffmann, J.** (2004). Anticipated action effects affect the selection, initiation, and execution of actions. *The Quarterly Journal of Experimental Psychology. A, Human Experimental Psychology*, *57*(1), 87–106. DOI: https://doi.org/10.1080/02724980343000143

Laub, R., Frings, C., & **Moeller, B.** (2018). Dissecting stimulus-response binding effects: Grouping by color separately impacts integration and retrieval processes. *Attention, Perception & Psychophysics*, *80*(6), 1474–1488. DOI: https://doi.org/10.3758/s13414-018-1526-7

Mayr, S., Möller, M., & **Buchner, A.** (2018). Contextual modulation of prime response retrieval processes: Evidence from auditory negative priming. *Attention, Perception, & Psychophysics*, *80*(8), 1918–1931. DOI: https://doi.org/10.3758/s13414-018-1574-z

Moeller, B., & **Frings, C.** (2014). Attention meets binding: Only attended distractors are used for the retrieval of event files. *Attention, Perception, & Psychophysics*, *76*(4), 959–978. DOI: https://doi.org/10.3758/s13414-014-0648-9

Moeller, B., & **Frings, C.** (2019a). Binding processes in the control of nonroutine action sequences. *Journal of Experimental Psychology: Human Perception and Performance*, *45*(9), 1135–1145. DOI: https://doi.org/10.1037/xhp0000665

Moeller, B., & **Frings, C.** (2019b). From simple to complex actions: Response-response bindings as a new approach to action sequences. *Journal of Experimental Psychology: General*, *148*(1), 174–183. DOI: https://doi.org/10.1037/xge0000483

Moeller, B., & **Frings, C.** (2019c). Lost time: Bindings do not represent temporal order information. *Psychonomic Bulletin & Review*, *26*(1), 325–331. DOI: https://doi.org/10.3758/s13423-018-1493-y

Moeller, B., & **Frings, C.** (2019d). Response-response binding across effector-set switches. *Psychonomic Bulletin & Review*, *26*(6), 1974–1979. DOI: https://doi.org/10.3758/s13423-019-01669-8

Moeller, B., & **Frings, C.** (2021). Response-response bindings do not decay for 6 seconds after integration: A case for bindings' relevance in hierarchical action control. *Journal of Experimental Psychology: Human Perception and Performance*, 47(4), 508–517. DOI: https://doi.org/10.1037/xhp0000897

Moeller, B., Rothermund, K., & **Frings, C.** (2012). Integrating the irrelevant sound. *Experimental Psychology*, *59*(5), 258–264. DOI: https://doi.org/10.1027/1618-3169/a000151

Peirce, J., Gray, J. R., Simpson, S., MacAskill, M., Höchenberger, R., Sogo, H., Kastman, E., & **Lindeløv, J. K.** (2019). Psychopy2: Experiments in behavior made easy. *Behavior Research Methods*, *51*(1), 195–203. DOI: https://doi.org/10.3758/s13428-018-01193-y

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

Prinz, W. (1992). Why don't we perceive our brain states? *European Journal of Cognitive Psychology*, 4(1), 1–20. DOI: https://doi.org/10.1080/09541449208406240

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

Schmalbrock, P., Kiesel, A., & **Frings, C.** (2022). What Belongs Together Retrieves Together – The Role of Perceptual Grouping in Stimulus-Response Binding and Retrieval. *Journal of Cognition*, *5*(1), Article 28. DOI: https://doi.org/10.5334/joc.217

Schöpper, L.-M., Singh, T., & **Frings, C.** (2020). The official soundtrack to "Five shades of grey": Generalization in multimodal distractor-based retrieval. *Attention, Perception, & Psychophysics*, *82*(7), 3479–3489. DOI: https://doi.org/10.3758/s13414-020-02057-4

Shin, Y. K., Proctor, R. W., & **Capaldi, E. J.** (2010). A review of contemporary ideomotor theory. *Psychological Bulletin*, *136*(6), 943–974. DOI: https://doi.org/10.1037/a0020541

Stock, A., & **Stock, C.** (2004). A short history of ideo-motor action. *Psychological Research*, *68*(2–3), 176–188. DOI: https://doi.org/10.1007/s00426-003-0154-5

Tukey, J. W. (1977). *Exploratory data analysis* (Vol. 2). Reading, MA.

van Dam, W. O., & **Hommel, B.** (2010). How object-specific are object files? Evidence for integration by location. *Journal of Experimental Psychology: Human Perception and Performance*, *36*(5), 1184–1192. DOI: https://doi.org/10.1037/a0019955

Wagemans, J., Elder, J. H., Kubovy, M., Palmer, S. E., Peterson, M. A., Singh, M., & **von der Heydt, R.** (2012). A century of Gestalt psychology in visual perception: I. Perceptual grouping and figure-ground organization. *Psychological Bulletin*, *138*(6), 1172–1217. DOI: https://doi.org/10.1037/a0029333

Zmigrod, S., Spapé, M., & **Hommel, B.** (2009). Intermodal event files: integrating features across vision, audition, taction, and action. *Psychological Research*, *73*(5), 674–684. DOI: https://doi.org/10.1007/s00426-008-0163-5

TO CITE THIS ARTICLE:
Selimi, S., Frings, C., and Moeller, B. (2022). Binding between Responses is not Modulated by Grouping of Response Effects. *Journal of Cognition,* 5(1): 42, pp. 1–11. DOI: https://doi.org/10.5334/joc.233

Submitted: 25 January 2022
Accepted: 16 June 2022
Published: 01 August 2022

Journal of Cognition is a peer-reviewed open access journal published by Ubiquity Press.

4.4 Article 4. Instructed speed and accuracy affect binding

This manuscript has been submitted for publication as:

Selimi, S., & Moeller, B. (2022). *Instructed speed and accuracy affect binding.* Manuscript submitted for publication.

RUNNING HEAD: Instructed speed and accuracy affect binding

Instructed speed and accuracy affect binding

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Word count: 4464 (main text)

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Funding Information: The research reported in this article was supported by a grant of the Deutsche Forschungsgemeinschaft to Birte Moeller (MO 2839/2-2).

Abstract

In the past few decades, binding and retrieval mechanisms have gained increased interest in research on human action control. Recent studies show that these mechanisms also play a role in the control of multiple independent actions. Here, two or more successively executed responses seem to be bound to each other so that repeating one of them can retrieve the other, affecting performance in this second response and resulting in so-called response-response binding effects. Binding effects are typically found in the response time data and, somewhat less reliably, also in the error rates. Whether binding effects show in the response times, the error rates, or both, is likely influenced by the current speed-accuracy settings of the participants, with binding effects more likely showing in error rates under a speed setting, while more likely showing in RTs under an accuracy setting. Alternatively, different speed-accuracy settings might also entail changes in executive control, affecting the size of observed binding effects. In this study, we tested these assumptions by comparing binding effects under different speed-accuracy settings that were induced via instructions focusing on speed, accuracy, or both (ambivalent). Binding effects were observed in response times independent of instructions, while in error rates they only showed under speed or ambivalent instructions. These findings indicate that binding effects can be affected by instructions regarding speed and accuracy.

Keywords: Action control, Response-response binding, Task instructions, Speed-accuracy trade-off

Introduction

According to current action control theories, when planning and conducting an action, stimulus, response, and effect features belonging to that action are bound into a short-term memory trace called an *event file* (Hommel, 2004). Repeating any of the bound features can then start retrieval of the other features later on, which affects further performance (Frings et al., 2020; Hommel, 1998; Logan, 1988; Schmidt et al., 2016). For example, repeating a feature that was bound to a response will trigger retrieval of the response. If the response is repeated as well, retrieval of the (compatible) response due to feature repetition facilitates responding. By contrast, if the required response changes, the retrieved and required responses are incompatible and retrieval due to feature repetition leads to significantly less facilitation or even impairment. Statistically, this binding effect is indicated by an interaction of response relation and feature relation.

Results in many action control paradigms (e.g., repetition priming, negative priming, distractor-response binding, or response-response binding) can be explained as a result of such binding effects (Frings et al., 2020; Henson et al., 2014; Hommel et al., 2001; Moeller & Frings, 2019b). Binding and retrieval effects are typically found in the response time data and, somewhat less reliably, also in the error rates (e.g., Frings et al., 2007; Moeller & Frings, 2019b; for an exception see Mayr & Buchner, 2006). One factor proposed to influence binding effects and thus influencing whether an effect appears in the RTs, the error rates, or both is the current speed-accuracy settings of the participants (Frings et al., 2020). Different speed-accuracy settings can be induced by a multitude of factors, e.g. via deadlines, payoffs, or instructions, and can prompt a participant to trade accuracy for speed (or vice versa), a so-called speed-accuracy trade-off (Heitz, 2014; e.g., Wickelgren, 1977). These speed or accuracy settings lead to differences in RTs and error rates, with generally faster RTs but more errors under a speed setting and slower RTs but fewer errors under an accuracy setting (e.g., Fitts, 1966; Hale, 1969; Howell & Kreidler, 1963). This sort of variability in response choice can be accounted for by the diffusion model of Ratcliff (e.g., Ratcliff, 1978; Ratcliff & Rouder, 1998, 2000), proposing that information about stimuli and their identity is accumulated over time and only if a decision criterion is reached a decision is made, e.g. a response is given. Speed or accuracy settings serve to alter the decision criterion. A speed setting leads to a lower criterion, meaning that less evidence about stimuli and an appropriate response is needed for a decision, which leads to more errors, but faster decisions. On the other hand, an accuracy setting leads to a higher decision criterion, meaning that more evidence is accumulated before a decision is made, then resulting in fewer errors but also slower responses (Ratcliff & Rouder, 1998).

Notably, speed and accuracy are oftentimes mentioned in instructions of experiments. One intention here is to ensure responsible participation and thus maximize the probability to find the effect of interest. Regarding speed and accuracy, such instructions seem to aim for a criterion that excludes both very long response times and an abundance of errors: oftentimes both speed and accuracy are stressed, i.e. instructions are ambivalent, prompting participants to answer as quickly and as accurately as possible. Here we aim to analyze whether this kind of instruction can also affect observed binding effects. To this end, we either stressed only accuracy or only speed in the instructions to a binding task and compared these conditions to a baseline condition that stressed both speed and accuracy.

The most obvious prediction is that we may find a simple speed-accuracy trade-off so that the binding effect is observable mostly in the response times under accuracy instructions and mostly in the error rates under the speed instructions, with generally no effect of the instructions on the magnitude of the binding effect (see e.g., Liesefeld &

Janczyk, 2019). Yet, another possibility is that differences in speed and accuracy instructions modulate the magnitude of the measured binding effects. A change specifically in participants' response criterion in the direction of less accuracy might entail a change in executive control, increasing the chance of influence due to additional mechanisms (e.g., distracting information, see Heitz & Engle, 2007). In turn, binding effects that are due to automatically triggered binding and retrieval processes might be more likely observed under speed than under accuracy conditions, leading to increased observed effects in a speed condition.

To investigate the influence of instruction-induced speed and accuracy settings on binding effects, a speed vs. accuracy instruction manipulation is applied to a response-response (RR) binding paradigm (Moeller & Frings, 2019b). RR-binding effects are typically investigated using trials with a prime-probe structure that includes two individually planned and executed responses both in the prime and in the probe (Moeller & Frings, 2019b). Upon execution, the consecutively given prime responses are bound. If one of the bound responses repeats as the first probe response, the other response is retrieved. If the retrieved response matches the required second probe response, retrieval facilitates response execution. If a different response is required as the second probe response, i.e. the retrieved and required responses are incompatible, retrieval leads to significantly less facilitation or even impairment, signified by higher error rates and longer response times. In accordance with the speed-accuracy trade-off literature, a speed vs. accuracy instruction manipulation should result in generally shorter RTs and higher error rates under speed instructions and likewise longer RTs but fewer errors under accuracy instructions. We furthermore expect that speed vs. accuracy instructions induce a shift in whether RR-binding effects are observed in RTs or error rates. In two online Experiments, we looked at a baseline condition of RR-binding with standard, ambivalent instructions (Experiment 1a) and set this in relation to conditions with speed vs. accuracy instructions (Experiment 1b). To anticipate results, instructions affected error rate binding effects, with the strongest binding effects under speed instructions, followed by ambivalent and then accuracy instructions. However, instructions had no impact on RTs and RT binding effects.

EXPERIMENT 1a

Method

Participants. The sample size was matched to those of past studies, investigating and finding response-response binding effects (Moeller & Frings, 2019a, 2019b, 2019c). Twenty-eight students (26 women) from Trier University participated in the experiment. The samples' median age was 21.5 years, with a range from 18 to 38 years. The participants were rewarded with partial course credit. Two additional participants had to be excluded due to high error rates (more than 30% errors, more errors than three times the interquartile range).

Design. The design comprised two within-subjects factors, namely, response A relation (response repetition vs. response change from prime to probe), and response B relation (response repetition vs. response change from prime to probe).

Materials. The experiment was programmed in PsychoPy3/PsychoJS (2020.2.6; Peirce et al., 2019) and conducted online on Pavlovia (https://pavlovia.org/). For participation, a computer with a physical keyboard was required. Instructions were presented in white (RGB_{255}: 255, 255, 255) on a grey background (RGB_{255}: 128, 128, 128). The list of possible stimuli consisted of eight different shapes that were approximately 70x70 pixels in size and made up of four overlapping lines of different lengths. The shapes could be presented in eight different colors: blue (RGB_{255}: 45, 120, 232), green (RGB_{255}: 18, 186, 46), red (RGB_{255}: 255, 0, 0), yellow (RGB_{255}: 255, 252, 0), purple (RGB_{255}: 164, 45, 232), brown (RGB_{255}: 98, 58, 0), and orange (RGB_{255}: 255, 144, 0). In each display, two shapes were presented simultaneously 65 pixels to the left and right of the screen center. Participants responded via four keys on a computer keyboard.

Procedure. Before the experiment, participants gave informed consent regarding the recording of personal data and responses during the experiment and indicated their age and gender. Instructions were given on the screen. Participants were instructed to place their middle and index fingers on the keys G, H, K, and L. They were told that they would always see two line patterns that would be either identical or different in shape and identical or different in color. Their task was always to first categorize the shapes (Response A) and then the colors (Response B) of these patterns as identical or different, by successively pressing two keys with the corresponding fingers. The left index and middle fingers were used for the shape classification. For identical shapes, participants were instructed to press the key with the left index finger (H) and for different shapes, they were supposed to press the key with the left middle finger (G). To classify the colors, the index and middle fingers of the right hand were used, respectively. For identical colors, a key was pressed with the right index finger (K), and for different colors, a key was pressed with the right middle finger (L).

An asterisk that was presented for 500 ms in the middle of the screen indicated the beginning of each trial (see **Fig. 1**). Then a plus sign appeared for 500 ms, followed by the prime line patterns. These were presented in white for the shape comparison and, in the case of a correct response, changed color upon Response A execution (via the left hand). The colored shapes remained on the screen until Response B (via the right hand) was given.

During training trials, a feedback message appeared on screen for 600 ms immediately following the response, indicating whether the given response was correct or not. Afterward, a blank screen appeared for 500 ms and was followed by the probe line patterns. The procedure in the probe was identical to that in the prime. Every 40 trials participants were allowed to take a short break, after which they resumed the task in their own time. In Response A repetition trials (Ar), the same response was required to the shapes of the prime and probe line patterns (e.g., the prime shapes differed, and the probe shapes differed). In Response A change trials (Ac), different responses were required for the categorization of the prime and probe line patterns (e.g., the prime shapes were identical, and the probe shapes differed). In Response B repetition trials (Br), the same response was required to the colors of the prime and probe line patterns (e.g., the prime colors were identical, and the probe colors were also identical). In Response B change trials (Bc), different responses were required to the prime and probe colors (e.g., the prime colors differed, and the probe colors were identical). These relations resulted in the four conditions Response A repetition with Response B repetition (ArBr), Response A repetition with Response B change (ArBc), Response A change with Response B repetition (AcBr), and Response A change with Response B change (AcBc). Each of these conditions was presented 8 times with each of the four possible combinations of identical/different shapes and colors in the probe, resulting in 128 experimental trials. Shapes and colors were randomly assigned to the different positions/displays. Before the experimental block started, participants first completed a training where participants practiced their task for at least 16 trials (subsample of the experimental trials). During the task instructions, the participants were told to respond as quickly as possible without making errors.

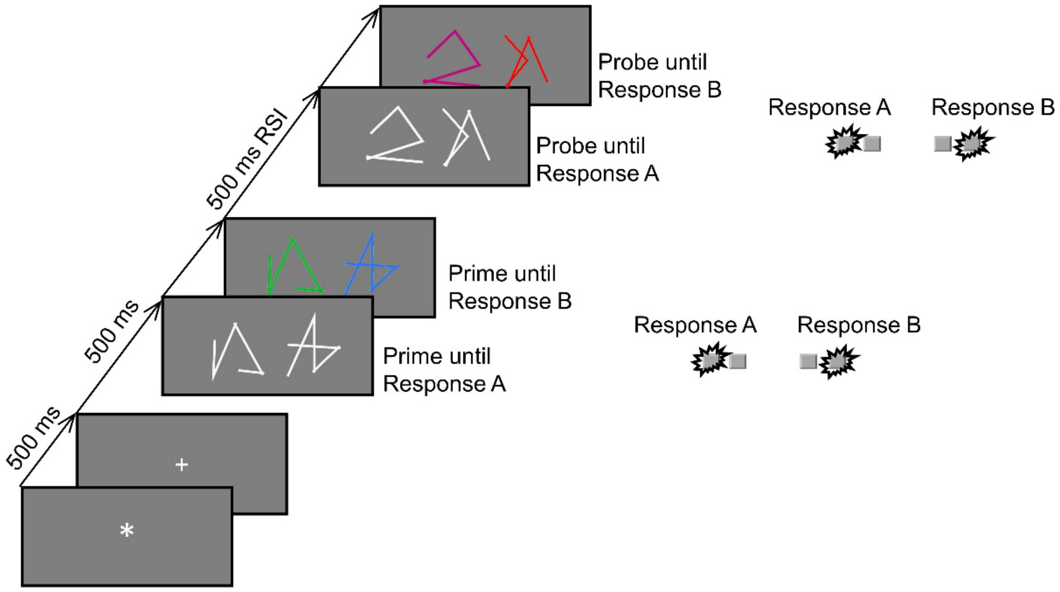

Fig. 1 The sequence of events in one example trial in Experiments 1a and b. Participants decided for each prime and each probe whether the presented stimuli had identical or different shapes (Response A) and identical or different colors (Response B). This is an example of a Response A repetition and Response B repetition trial. The stimuli are not drawn to scale

Results

The dependent variable of interest was the performance in probe Response B. If prime Responses A and B are integrated, repeating prime Response A in the probe should trigger retrieval of the later response and thus influence performance on probe Response B. Only trials with correct responses A and B in both prime and probe were considered. The error rate for prime responses (A or B) was 9.4%. The probe error rates were 3.0% for Response A and 4.4% for Response B (only including trials with correct previous responses). We excluded RTs of more than 1.5 interquartile ranges above the third quartile of the probe Response B RT distribution of the participant (Tukey, 1977) and RTs shorter than 200 ms from the analysis. Due to these constraints, 20.1% of the trials were excluded from the RT analyses. For the mean RTs and error rates, see **Table 1**.

Table 1. Mean response times (in milliseconds) and mean error rates (in percentages) for probe Response B, as a function of Response A relation and Response B relation and instruction (Experiment 1a: ambivalent; Experiment 1b: accuracy, speed)

	Accuracy instruction		Speed instruction		Ambivalent instruction	
	B repetition	*B change*	*B repetition*	*B change*	*B repetition*	*B change*
A change	662 (4.2)	646 (1.7)	578 (8.5)	567 (2.7)	678 (5.7)	643 (2.0)
A repetition	632 (4.2)	651 (2.9)	550 (5.2)	577 (9.0)	629 (3.0)	644 (7.6)

In a 2 (Response A relation: repetition vs. change) × 2 (Response B relation: repetition vs. change) analysis of variance (ANOVA) on probe Response B RTs, the main effect for Response A relation was significant, $F(1, 28) = 37.41$, $p <.001$, $\eta_p^2 = .57$, while the main effect for Response B relation was not, $F(1, 28) = 3.35$, $p = .077$, $\eta_p^2 = .11$. More importantly, the interaction of Response A and Response B relation was significant, $F(1, 28) = 24.26$, $p < .001$, $\eta_p^2 = .46$, indicating binding between the responses: the repetition of Response A facilitated performance only if Response B was repeated as well, $t(28)= 7.23$, $p <.001$, but not if Response B changed, $t(28)= -0.18$, $p =.859$.

In the same analysis on error rates, the main effects of Response A relation, $F(1, 28) = 3.19$, $p = .085$, $\eta_p^2 = .10$, and Response B relation, $F(1, 28) < 1$, $p = .628$, $\eta_p^2 = .01$, were not significant. However, the interaction of Response A and Response B relation was significant, $F(1, 28) = 13.37$, $p < .001$, $\eta_p^2 = .32$, again indicating binding between the responses: The repetition of Response A numerically facilitated performance if Response B was repeated as well, $t(28)= 1.87$, $p =.071$, but impaired performance if Response B changed, $t(28)=4.13$, $p <.001$.

Discussion

In line with existing literature, we find significant RR-binding effects in both, RTs and error rates under ambivalent instructions obtained in an online setting. With this as a baseline, Experiment 1b set out to investigate whether RR-binding is affected by instructed speed vs. accuracy settings. If instructions induce speed and accuracy settings, this should influence mean RTs and error rates, with comparably faster RTs, but more errors under speed instructions than accuracy instructions, in line with findings on speed-accuracy instruction manipulations (e.g., Hale, 1969; Howell & Kreidler, 1963). Furthermore, we expect speed vs. accuracy instructions to induce a shift in whether RR-binding effects are observed in RTs or error rates.

EXPERIMENT 1b

Method

Participants. Again, the sample size was approximated to those of past studies investigating response-response binding. Twenty-eight students (18 women) from Trier University participated in the online experiment. The samples' median age was 23 years, with a range from 19 to 56 years. The participants were rewarded with partial course credit.

Design. The design comprised two within-subjects factors, namely, response A relation (response repetition vs. response change from prime to probe), and response B relation (response repetition vs. response change from prime to probe), and one between-subject factor, instructions (accuracy vs. speed instruction).

Materials and procedure. Materials and procedure were identical to Experiment 1a with the following exceptions. Each of the four possible Response A and B repetition and change conditions (ArBr, ArBc, AcBr, AcBc) was presented 12 times, resulting in 192 experimental trials. Before the experimental block started, participants first completed a short pre-training explaining the task, followed by a training where participants practiced their task for at least 16 trials (subsample of the experimental trials) and had to pass a 75% accuracy threshold to proceed to the main experiment. Depending on the condition, an accuracy vs. speed manipulation was implemented: During the task instructions, the participants were told to answer either as fast as possible (speed) or as correctly as possible (accuracy). Additionally, participants received condition-dependent feedback on mean response speed (in ms) or mean accuracy (in %) every 12 trials.

Results

As in Experiment 1a, only trials with correct responses A and B in both prime and probe were considered. The error rate for prime responses (A or B) was 8.0%. The probe error rates were 2.8% for Response A and 4.5% for Response B (only including trials with correct previous responses). We excluded RTs of more than 1.5 interquartile ranges above the third quartile of the probe Response B RT distribution of the participant (Tukey, 1977) and RTs shorter than 200 ms from the analysis. Due to these constraints, 18.1% of the trials were excluded from the RT analyses. For the mean RTs and error rates, see **Table 1**.

The dependent variable of interest was again performance in probe Response B. In a 2 (Response A relation: repetition vs. change) × 2 (Response B relation: repetition vs. change) × 2 (task instructions: accuracy vs. speed) ANOVA on probe Response B RTs the main effect for instructions was not significant, $F(1, 26) = 2.06$, $p = .163$, $\eta_p^2 = .07$, indicating that the instruction manipulation had no impact on RTs. The main effect for Response A relation was significant, $F(1, 26) = 5.43$, $p =.028$, $\eta_p^2 = .17$, while the main effect for Response B relation was not, $F(1, 26) < 1$, $p = .452$, $\eta_p^2 = .02$. More importantly, the interaction of

Response A and Response B relation was significant, $F(1, 26) = 19.41$, $p < .001$, $\eta_p^2 = .43$, indicating binding between the responses. However, this was not further modulated by task instructions, $F(1, 26) < 1$, $p = .895$, $\eta_p^2 < .01$. RT binding effects were significantly different from zero for both, speed instructions, $t(12)=3.11$, $p =.009$, and accuracy instructions, $t(14)=3.12$, $p =.007$.

In the same analysis on error rates, the main effect of task instructions was significant, $F(1, 26) = 7.20$, $p = .012$, $\eta_p^2 = .22$, signifying an influence of task instructions on error rates. There were higher mean error rates in the speed condition ($M = 6.32\%$) than in the accuracy condition ($M = 3.27\%$). The main effect of Response A relation, $F(1, 26) = 4.85$, $p = .037$, $\eta_p^2 = .16$ was again significant, while the main effect of and Response B relation, $F(1, 26) = 2.94$, $p = .098$, $\eta_p^2 = .10$, was not. The interaction of Response A and Response B relation was significant, $F(1, 26) = 18.63$, $p < .001$, $\eta_p^2 = .42$, again indicating binding between the responses. Importantly, this relation was further modulated by task instructions, $F(1, 26) = 12.54$, $p = .002$, $\eta_p^2 = .33$. Under speed instructions, a significant error rate binding effect emerged, $t(12)=5.10$, $p <.001$, while it was not significant under accuracy instructions, $t(14)=0.81$, $p =.431$. In sum, results suggest a modulating influence of task instructions on RR-binding only for error rates. For a summary of mean binding effects, see **Fig. 2**.

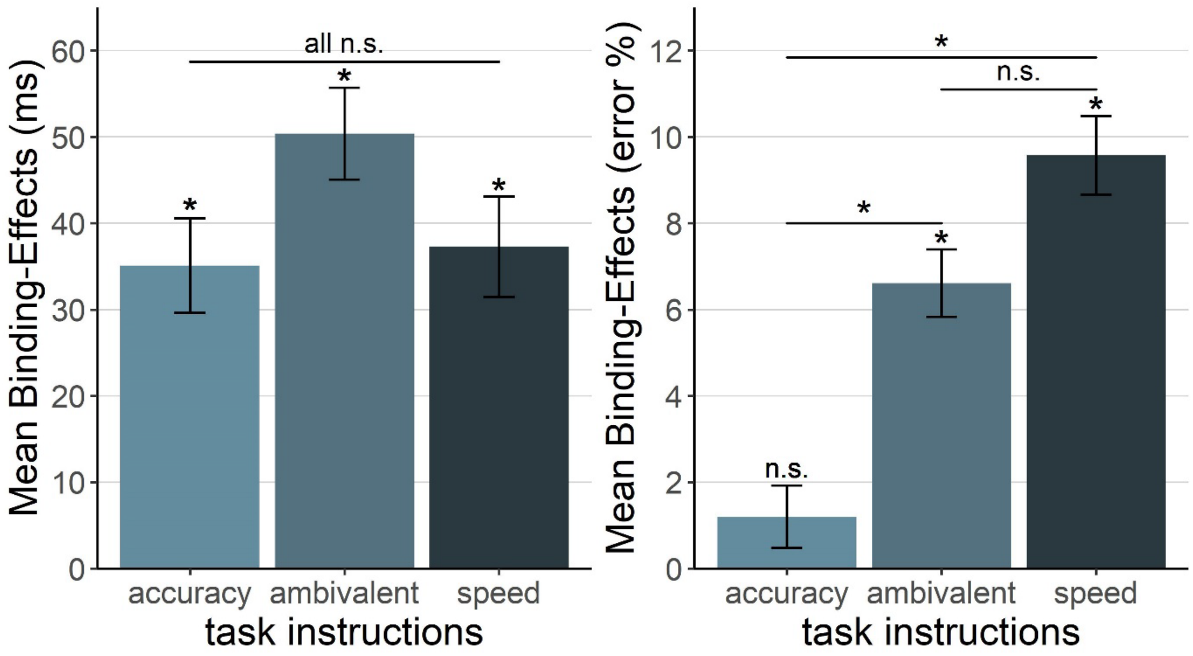

Fig. 2 Mean response-response binding effects for response times and error rates in Experiments 1a and 1b as a function of task instructions (accuracy vs. ambivalent vs. speed). Binding effects are calculated as the advantage of probe Response A repetition (vs. probe Response A change) in probe Response B repetition trials minus the advantage of probe Response A repetition (vs. probe Response A change) in probe Response B change trials: [AcBr - ArBr] - [AcBc - ArBc]

Comparison of Experiments 1a and 1b

Additionally, we compared results from the instruction manipulation of Experiment 1b with the results obtained under ambivalent instructions in Experiment 1a. In a 2 (Response A relation: repetition vs. change) × 2 (Response B relation: repetition vs. change) × 3 (task instructions: accuracy vs. ambivalent vs. speed) ANOVA on probe Response B RTs, again the main effect for task instruction was not significant, $F(1, 53) = 2.34$, $p = .106$., $\eta_p^2 = .08$. The main effect for Response A relation was significant, $F(1, 53) = 32.58$, $p < .001$, $\eta_p^2 = .38$, while the main effect for Response B relation was not, $F(1, 53) < 1$, $p = .521$, $\eta_p^2 = .01$. The interaction of Response A and Response B relation was significant, $F(1, 53) = 40.64$, $p < .001$, $\eta_p^2 = .43$, indicating binding between responses. This was again not further modulated by task instructions, $F(2, 53) < 1$, $p =.574$, $\eta_p^2 = .02$.

The same analysis on error rates revealed a significant main effect for task instructions, $F(2, 53) = 3.84$, $p = .028$, $\eta_p^2 = .13$, again indicating an influence of instructions on error rates. The main effect was significant for Response A relation, $F(1, 53) = 8.10$, $p = .006$, $\eta_p^2 = .13$, but not for Response B relation, $F(1, 53) = .41$, $p = .525$, $\eta_p^2 = .01$. Again, the interaction of Response A and Response B relation was significant, $F(1, 53) = 34.84$, $p < .001$, $\eta_p^2 = .40$. Importantly, this relation was modulated by task instructions, $F(2, 53) = 4.73$, $p =.013$, $\eta_p^2 = .15$. Post-hoc t-tests (holm corrected, Holm, 1979) revealed significant differences between error rate binding effects in the speed and accuracy instruction conditions, $t(23.74)= 3.50$, $p =.006$, and between ambivalent and accuracy instructions, $t(38.34)= 2.49$, $p =.034$, while the difference between speed and ambivalent instructions was not significant, $t(28.76)= 1.20$, $p =.238$. For a summary of binding effects, **see Fig. 2**.

Discussion

Results from Experiment 1b show that the instruction manipulation affected mean error rates, but had no general impact on mean RTs, as signified by the respective main effects. This is in line with previous findings, where instructions seemed to have a stronger impact on response accuracy, while response speed was less affected (Howell & Kreidler, 1963). Consequently, instructions did also not influence binding effects in RTs. However, the speed vs. accuracy instruction manipulation affected error rate binding effects, with significantly stronger RR-binding effects under speed than under accuracy instructions. Additionally, ambivalent instructions of Experiment 1a functioned as a middle category, with both, medium error rates and error rate binding effects compared to the other two instruction conditions.

General Discussion

In this study, we investigated the influence of instruction-induced speed and accuracy settings on binding effects by varying instructions to participants, working through an RR-binding task. Instructions modulated error rates and error rate binding effects but did not influence results in RTs. Participants seem to have adjusted their accuracy criterion according to the instruction, while they did not alter their response speed. Apparently, a simple instruction focusing on speed or accuracy respectively is not sufficient to tip the speed-accuracy trade-off in one or the other direction. In fact, there might be other prevailing influences like the personal motivation of the participant to be quick or accurate in their responses or the expectations evoked by the experimental setting.

Even though we did not find evidence for a classical speed-accuracy trade-off, instructions did affect performance. Error rate analyses indicated both, more errors and larger binding effects in the speed condition. The highest error rate binding effects occurred under speed instructions, followed by ambivalent instructions, while there were no significant binding effects under accuracy instructions. Additionally, error rate binding effects under accuracy instructions differed significantly from the other two instruction conditions. To explain these results, we can only speculate that participants interpreted the speed instructions as not needing to worry about accuracy rather than focusing on speed. In turn, they did not increase speed, which is apparent in our RT results, but only lowered their effort. This might have resulted in reduced executive control and slower focus of attention, in turn leading to more influence of potentially distracting information like the retrieved response (see Heitz & Engle, 2007) and thus in larger error rate binding effects under speed instructions.

The diminished error rate binding effects under accuracy instructions compared to speed or ambivalent instructions indicate that binding effects might only show in the error rates when (at least partially) focusing on speed. For most research questions, it might not be relevant whether binding effects occur in RTs or error rates, but knowing about the influence of different instructions helps to set expectations on where to find effects accordingly. Thus, if one is interested to find error rate binding effects, speed-focused, or at least ambivalent instructions should be considered. On the other hand, regarding RTs, the choice of instructions appears to be less impactful, as binding effects are observed either way. From this, we can derive two things: First, the typical focus in previous studies on RTs as the main dependent variable of interest seems to be sensible. Second, if there are no expectations as to whether a binding effect is supposed to show in RTs or error rates when planning a study, it makes sense to use speed or ambivalent instructions, as under these we seem to have higher chances to observe effects in both dependent variables.

Note that the result pattern in the ambivalent condition was more similar to the speed condition, with binding effects significant in both RTs and error rates and also not significantly different from each other. One possible interpretation would be that the less formal online setting of the study led to a general motivation to pass the experiment fast, rather than accurately. This pattern of results is also in line with previous research on binding effects, indicating that binding effects in general do not differ significantly between online and offline settings, but that there is a tendency for stronger error rate binding effects online (Moeller & Frings, 2021). That is, an online setting might lead to a tendency to prioritize speed over accuracy. Fortunately, it seems that such a shift in operation mode, if anything, facilitates the measurement of these effects.

Our results fit in with the Binding and Retrieval in Action Control framework (Frings et al., 2020), which proposes that binding and retrieval processes can be modulated by different bottom-up and top-down influences and specifically that top-down influences can act on different representational levels, for example, mindsets, speed-accuracy tradeoffs, or instruction-based effects. Our study provided evidence that instructed speed-accuracy settings do indeed modulate whether binding and retrieval processes affect overt behavior. This finding might be explained by an altered amount of executive control under the different instruction conditions. Executive control was previously found to be important for the retrieval process, in that factors associated with less efficient executive control (e.g., lower scores on fluid intelligence measures or autism spectrum disorder) are also associated with more partial repetition costs (Colzato et al., 2006; Zmigrod et al., 2013; for an overview, see Hommel, 2022), thus resulting in stronger binding effects. This is consistent with the present results: when RTs and error rates are considered together, we find stronger overall binding effects for speed instructions, i.e., instructions that we hypothesize exert the least amount of executive control. Even though we cannot distinguish with this type of modulation to what extent binding and retrieval processes were independently affected by the instructions, the broad agreement in the literature seems to be that the retrieval process is generally more easily affected by modulations than the binding process (Hommel et al., 2014; Hommel, 2022; Moeller & Frings, 2014). This, together with the previously found influences of executive control on retrieval, suggests that also in the present data pattern it was most likely the retrieval process that was affected by the instruction modulation.

In sum, the results at hand provide evidence that instructed speed and accuracy can affect observed binding effects. A focus on speed rather than accuracy in the instructions resulted in larger binding effects in error rates, while observed binding effects in RTs remained largely unaffected by instructions. Hence, on a practical note, for effects regarding automatic processes (like binding and retrieval) to show up in a data set, it might be reasonable to focus more on speed than on accuracy in the instructions.

Author notes

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Statements and declarations

Funding

The research reported in this article was supported by the Deutsche Forschungsgemeinschaft to Birte Moeller (MO 2839/2-2).

Authors' contributions

BM provided funding for the research. SE and BM contributed to the study conception and design. Material preparation, data collection, and analysis were performed by SE. The first draft of the manuscript was written by SE and both authors commented on previous versions of the manuscript. Both authors read and approved the final manuscript.

Competing interests

The authors have no relevant financial or non-financial interests to disclose.

Ethical approval

All procedures performed involving human participants were in accordance with the ethical standards at the psychology institute in Trier and with the 1964 Helsinki declaration and its later amendments.

Informed consent

Informed consent was obtained from all individual participants included in the study.

Data and code availability

The data and analysis code of the current study are available in the Psycharchives repository under http://dx.doi.org/10.23668/psycharchives.7967 (data) and http://dx.doi.org/10.23668/psycharchives.7966 (code).

References

Colzato, L. S., van Wouwe, N. C., Lavender, T. J., & Hommel, B. (2006). Intelligence and cognitive flexibility: Fluid intelligence correlates with feature "unbinding" across perception and action. *Psychonomic Bulletin & Review*, *13*(6), 1043–1048. https://doi.org/10.3758/BF03213923

Fitts, P. M. (1966). Cognitive aspects of information processing. Iii. Set for speed versus accuracy. *Journal of Experimental Psychology*, *71*(6), 849–857. https://doi.org/10.1037/h0023232

Frings, C., Hommel, B., Koch, I., Rothermund, K., Dignath, D., Giesen, C., Kiesel, A., Kunde, W., Mayr, S., Moeller, B., Möller, M., Pfister, R., & Philipp, A. (2020). Binding and Retrieval in Action Control (BRAC). *Trends in Cognitive Sciences*, *24*(5), 375–387. https://doi.org/10.1016/j.tics.2020.02.004

Frings, C., Rothermund, K., & Wentura, D. (2007). Distractor repetitions retrieve previous responses to targets. *Quarterly Journal of Experimental Psychology (2006)*, *60*(10), 1367–1377. https://doi.org/10.1080/17470210600955645

Hale, D. J. (1969). Speed-error tradeoff in a three-choice serial reaction task. *Journal of Experimental Psychology*, *81*(3), 428–435. https://doi.org/10.1037/h0027892

Heitz, R. P. (2014). The speed-accuracy tradeoff: History, physiology, methodology, and behavior. *Frontiers in Neuroscience*, *8*, 150. https://doi.org/10.3389/fnins.2014.00150

Heitz, R. P., & Engle, R. W. (2007). Focusing the spotlight: Individual differences in visual attention control. *Journal of Experimental Psychology. General*, *136*(2), 217–240. https://doi.org/10.1037/0096-3445.136.2.217

Henson, R. N., Eckstein, D., Waszak, F., Frings, C., & Horner, A. J. (2014). Stimulus-response bindings in priming. *Trends in Cognitive Sciences*, *18*(7), 376–384. https://doi.org/10.1016/j.tics.2014.03.004

Holm, S. (1979). A Simple Sequentially Rejective Multiple Test Procedure. *Scandinavian Journal of Statistics*, *6*(2), 65–70. http://www.jstor.org/stable/4615733

Hommel, B. (1998). Event Files: Evidence for Automatic Integration of Stimulus-Response Episodes. *Visual Cognition*, *5*(1-2), 183–216. https://doi.org/10.1080/713756773

Hommel, B. (2004). Event files: Feature binding in and across perception and action. *Trends in Cognitive Sciences*, *8*(11), 494–500. https://doi.org/10.1016/j.tics.2004.08.007

Hommel, B. (2022). The Control of Event-File Management. *Journal of Cognition*, *5*(1), Article 1. https://doi.org/10.5334/joc.187

Hommel, B., Memelink, J., Zmigrod, S., & Colzato, L. S. (2014). Attentional control of the creation and retrieval of stimulus-response bindings. *Psychological Research*, *78*(4), 520–538. https://doi.org/10.1007/s00426-013-0503-y

Hommel, B., Müsseler, J., Aschersleben, G., & Prinz, W. (2001). The Theory of Event Coding (TEC): A framework for perception and action planning. *The Behavioral and Brain Sciences*, *24*(5), 849-78; discussion 878-937. https://doi.org/10.1017/S0140525X01000103

Howell, W. C., & Kreidler, D. L. (1963). Information processing under contradictory instructional sets. *Journal of Experimental Psychology*, *65*(1), 39–46. https://doi.org/10.1037/h0038982

Liesefeld, H. R., & Janczyk, M. (2019). Combining speed and accuracy to control for speed-accuracy trade-offs(?). *Behavior Research Methods*, *51*(1), 40–60. https://doi.org/10.3758/s13428-018-1076-x

Logan, G. D. (1988). Toward an instance theory of automatization. *Psychological Review*, *95*(4), 492–527. https://doi.org/10.1037/0033-295X.95.4.492

Mayr, S., & Buchner, A. (2006). Evidence for episodic retrieval of inadequate prime responses in auditory negative priming. *Journal of Experimental Psychology: Human Perception and Performance*, *32*(4), 932–943. https://doi.org/10.1037/0096-1523.32.4.932

Moeller, B., & Frings, C. (2014). Attention meets binding: Only attended distractors are used for the retrieval of event files. *Attention, Perception & Psychophysics*, *76*(4), 959–978. https://doi.org/10.3758/s13414-014-0648-9

Moeller, B., & Frings, C. (2019a). Binding processes in the control of nonroutine action sequences. *Journal of Experimental Psychology: Human Perception and Performance*, *45*(9), 1135–1145. https://doi.org/10.1037/xhp0000665

Moeller, B., & Frings, C. (2019b). From simple to complex actions: Response-response bindings as a new approach to action sequences. *Journal of Experimental Psychology: General*, *148*(1), 174–183. https://doi.org/10.1037/xge0000483

Moeller, B., & Frings, C. (2019c). Response-response binding across effector-set switches. *Psychonomic Bulletin & Review*, *26*(6), 1974–1979. https://doi.org/10.3758/s13423-019-01669-8

Moeller, B., & Frings, C. (2021). Remote binding counts: Measuring distractor-response binding effects online. *Psychological Research*, *85*(6), 2249–2255. https://doi.org/10.1007/s00426-020-01413-1

Peirce, J., Gray, J. R., Simpson, S., MacAskill, M., Höchenberger, R., Sogo, H., Kastman, E., & Lindeløv, J. K. (2019). Psychopy2: Experiments in behavior made easy. *Behavior Research Methods*, *51*(1), 195–203. https://doi.org/10.3758/s13428-018-01193-y

Ratcliff, R. (1978). A theory of memory retrieval. *Psychological Review*, *85*(2), 59–108. https://doi.org/10.1037/0033-295X.85.2.59

Ratcliff, R., & Rouder, J. N. (1998). Modeling Response Times for Two-Choice Decisions. *Psychological Science*, *9*(5), 347–356. https://doi.org/10.1111/1467-9280.00067

Ratcliff, R., & Rouder, J. N. (2000). A diffusion model account of masking in two-choice letter identification. *Journal of Experimental Psychology: Human Perception and Performance*, *26*(1), 127–140. https://doi.org/10.1037/0096-1523.26.1.127

Schmidt, J. R., Houwer, J. de, & Rothermund, K. (2016). The Parallel Episodic Processing (PEP) model 2.0: A single computational model of stimulus-response binding, contingency learning, power curves, and mixing costs. *Cognitive Psychology*, *91*, 82–108. https://doi.org/10.1016/j.cogpsych.2016.10.004

Tukey, J. W. (1977). *Exploratory data analysis* (Vol. 2). Reading, MA.

Wickelgren, W. A. (1977). Speed-accuracy tradeoff and information processing dynamics. *Acta Psychologica*, *41*(1), 67–85. https://doi.org/10.1016/0001-6918(77)90012-9

Zmigrod, S., Sonneville, L. M. J. de, Colzato, L. S., Swaab, H., & Hommel, B. (2013). Cognitive control of feature bindings: Evidence from children with autistic spectrum disorder. *Psychological Research*, *77*(2), 147–154. https://doi.org/10.1007/s00426-011-0399-3

4.5 Article 5. Does the modality matter? Binding between responses generalizes to auditory tasks

This manuscript is in preparation for publication as:

Selimi, S., Frings, C., & Moeller, B. (2023). *Does the modality matter? Binding between responses generalizes to auditory tasks.* Manuscript in preparation.

RUNNING HEAD: Binding between responses in auditory tasks

Does the modality matter? Binding between responses generalizes to auditory tasks

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Word count: 5093 (main text)

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Abstract

In everyday life, interacting with our environment involves responding to stimuli from different sensory modalities. Current theories of action control propose that simple actions such as responding to a stimulus lead to the integration of stimulus and response features in a common representation. Repetition of one of these features retrieves the other integrated features and thus influences further actions. The processes of integration and retrieval also scale up to more complex actions that consist of a sequence of simpler actions. Here, multiple responses become part of the same action representation and can retrieve each other, if one of them is repeated, leading to so-called response-response binding effects (Moeller & Frings, 2019b). Although stimuli of different sensory modalities can differ in the way they are processed, it has been shown that this does usually not affect binding effects. However, to date, this has only been researched for simple actions, while research on response-response binding effects has exclusively used visual stimuli. In light of previous findings, this study designed and tested a response-response binding task with auditory stimuli and compared results to a parallel version with visual stimuli. Indeed, the results show that binding between responses occurs when responding to auditory stimuli, underlining that binding is not restricted to the visual domain even in more complex actions. The results serve as a basis for further investigation of complex actions separated from visual influences.

Keywords: Action control, Response-response binding, Modality differences

Introduction

When we compare looking at a painting and listening to music, it is apparent that the visual and the auditory modality work differently in some regards. If we look at a painting, a lot of information is visible at once and we get a gist of what we are looking at before we scan the painting for specific information (e.g., Hollingworth, 2009; Võ & Henderson, 2010). In that, it is quite different from listening to music: We must first attend to the sequence of tones played to make sense of the music we are listening to. And every tone not only has an onset, offset, and duration, as could also be the case with visual stimuli, but its identity is also defined by temporal factors like the rise times of tones and tone frequencies (e.g., Bizley & Cohen, 2013; Shamma, 2001).

The processing of auditory information such as music works sequentially, and in that, it is similar to the processing of actions (Fitch & Martins, 2014; Lashley, 1951), as we also manipulate our surroundings in a sequential way. Like individual notes begin to make sense only when we attend the whole sequence, individual movements, such as the typing of individual letters, unfold additional meaning if we process the whole sequence resulting in a word. Most actions in our everyday life consist of sequences to some degree, be it sequences of simple actions like keypresses or individual muscle contractions, or more complex actions like baking a cake (e.g., De Jong, 1995; Moeller & Frings, 2019b; Schneider & Logan, 2006). A common idea seems to be that sequences of simpler actions can be assembled into more complex actions (Moeller & Frings, 2019a, 2019b) and more complex actions can be segmented into simpler ones (Lashley, 1951; Zacks et al., 2001; Zacks & Swallow, 2007), respectively.

Aside from potential similarities in the way we process them, the perception of our surroundings and the actions we produce are closely related, so much that they are cognitively represented in a common code format and that the anticipation of a perceptual effect can elicit a corresponding action (Prinz, 1992, 1997), e.g., the anticipation of a tone can elicit the press of the corresponding piano key. Through this common code, simple actions are represented on a small-scale unit via bindings between stimulus and response features (Frings et al., 2020; Henson et al., 2014; Hommel, 1998; Schmidt et al., 2016), indicating that upon execution of an action (like a keypress), stimulus and response features are temporarily integrated into one common representation. A subsequent repetition of one feature may then retrieve the other features, influencing the execution of further actions. If a response is retrieved that matches the next required response, its execution is facilitated. If it does not match the required response, responding is less facilitated or can even be impaired. The processes of integration and retrieval also scale up to more complex actions that consist of a sequence of simpler actions (Moeller & Frings, 2019a, 2019b, 2022; Selimi et al., 2022): In such action sequences, consecutively given responses are integrated with each other and can retrieve each other if one of them is repeated, resulting in so called response-response binding effects. Like this, the principle of integration and retrieval processes can be used to explain a wide range of action control phenomena (for an overview, see Frings et al., 2020) and actions of different levels of complexity.

In the research on actions, it is often assumed that their cognitive representations are multimodal (e.g., Friston, 2012; Hommel et al., 2001; Hommel, 2009; Zacks et al., 2007). For binding between stimuli and responses, it has been shown that they are indeed not limited to the visual modality but also occur with auditory (Mayr et al., 2018; Mayr & Buchner, 2006; Moeller et al., 2012; Schöpper &

Frings, 2022), tactile (Wesslein et al., 2019), and multisensory stimuli (Zmigrod et al., 2009). We can furthermore integrate stimuli of different modalities on a conceptual level, so that pictures and sounds of the same concept (e.g., corresponding animal noises and pictures) can retrieve each other (Frings et al., 2013). Findings from the visual and auditory modality indicate that bindings with different stimulus modalities are affected similarly by the same modulations (Moeller et al., 2012; Schöpper, Singh, & Frings, 2020). However, there is also some evidence that binding effects can differ between stimulus modalities: Schöpper and Frings (2022) found that in detection tasks, the binding effect was dependent on stimulus modality. No binding effects were observed in the detection of visual stimuli, as is in line with previous findings (Schöpper et al., 2022; Schöpper, Hilchey, et al., 2020), however, they observed bindings effects when detecting auditory stimuli. They argue that this might be due to differences in how stimuli are processed. In line with this, findings from the negative priming literature indicate that inhibition can explain spatial negative priming with visual, but not with auditory stimuli, again indicating that auditory and visual stimuli might be processed differently (Mayr et al., 2009; Möller et al., 2016). For complex actions, binding effects have yet only been analyzed in fully visual tasks (e.g., Moeller & Frings, 2019b). Thus, we cannot say for sure whether response-response binding effects are independent of stimulus modality. While most evidence suggests that binding effects should occur independent of stimulus modality, differences in how visual and auditory are processed might play a role in response-response binding. Given that both actions and auditory processing are theorized to work sequentially (Fitch & Martins, 2014; Lashley, 1951), using auditory instead of visual stimuli might even be beneficial for response-response bindings, if it is different at all.

For response-response binding, other stimulus modalities than the visual have not been investigated yet. Thus, this study aims at clarifying whether response-response binding effects are specific to visual tasks or whether they also occur when responding to auditory stimuli. Thus, we designed an auditory version of the response-response binding task (Moeller & Frings, 2019b), where participants had to judge the similarity of sequentially presented pairs of tones (Experiment 1a), and as a control, a visual version introducing sequentially presented shapes (Experiment 1b). Each trial consisted of two prime responses A and B (associated with integration) and two probe responses A and B (associated with retrieval). For each of these responses, participants had to decide whether a pair of successively presented stimuli had the same frequency (auditory stimuli; Experiment 1a) or shape (visual stimuli; Experiment 1b). To avoid repetitions within a prime or probe, response A was given with the left hand and stimuli were either sine tones or yellow shapes, while the response B was always given to square tones or green shapes with the right hand. We expect response-response binding effects to occur regardless of stimulus modality. If, however, the modality has an influence on binding effects, we expect the effects to be larger with auditory stimuli than with visual stimuli.

EXPERIMENT 1a

Method

Participants. Effect sizes in former studies on response-response-binding (computed as t/sqrt(n)) were at least *d* = 0.63 (e.g., Moeller & Frings, 2019b: *d* = 0.63 and *d* = 0.88; Moeller & Frings, 2019c: *d* = 1.07; Moeller & Frings, 2019d: *d* = 0.74 and *d* = 1.07; Selimi et al., 2022: *d* = 0.98 and *d* = 0.96). A power-analysis with the program G*Power assuming α = .05 and a power of 1–β = .90 suggests that at least 29 participants were necessary (Faul et al., 2007).

Twenty-nine students (19 women) from Trier University participated in the experiment. The samples' median age was 23 years, with a range from 19 to 36 years. The participants were rewarded with partial course credit. One additional participant had to be excluded due to high error rates (more than 30% errors, more errors than three times the interquartile range).

Design. The design comprised two within-participant factors, namely, response A relation (response repetition vs. response change from prime to probe), and response B relation (response repetition vs. response change from prime to probe).

Materials. The experiment was programmed in PsychoPy3/PsychoJS (2021.1.4; Peirce et al., 2019) and conducted online on Pavlovia (https://pavlovia.org/). Data processing and statistical analyses were conducted in R (R Core Team, 2022). For participation, a computer with a physical keyboard was required. Instructions were presented in white (RGB_{255}: 255, 255, 255) on a grey background (RGB_{255}: 128, 128, 128). The list of possible stimuli consisted of seven different sine tones and seven different square tones (with frequencies 220, 300, 380, 460, 540, 620 and 700 Hz). In each display, two tones of the same type were presented consecutively for 200 ms with 200 ms in between. Participants responded via four keys (G, H, K, and L) on a computer keyboard.

Procedure. Before the experiment, participants gave informed consent regarding the recording of personal data and responses during the experiment and indicated their age and gender. Instructions were given on the screen. Participants were instructed to place their middle and index fingers on the keys G, H, K, and L. They were told that they would always hear two consecutively presented tones that would be either of identical or different frequency. Their task was always to first categorize the frequency of the sine tones (Response A) and then the frequency of the square tones (Response B) as identical or different, by successively pressing two keys with the corresponding fingers. The left index and middle fingers were used for the sine tone classification. For tones of identical frequency, participants were instructed to press the key with the left index finger (H) and for tones of different frequency, they were supposed to press the key with the left middle finger (G). To classify the square tones, the index and middle fingers of the right hand were used, respectively. For tones of identical frequency, a key was pressed with the right index finger (K), and for tones of different frequency, a key was pressed with the right middle finger (L).

The beginning of each trial was indicated by an asterisk that was presented for 500 ms in the middle of the screen (see **Figure 1**). Then a plus sign appeared for 500 ms, followed by an empty screen and a pair of sine tones. These were presented for 200 ms each with a 200 ms interval in between. Response A execution was possible as soon as the second tone appeared. Upon Response A execution (via the left hand), a pair of square tones appeared, again for 200 ms each with a 200 ms interval in between and was responded to with Response B (via the right hand). During training trials, a feedback message appeared on screen for 600 ms immediately following the response, indicating whether the given response was correct or not. Afterward, a blank screen appeared for 500 ms and was followed by the probe tones. The procedure in the probe was identical to that in the prime. Every 32 trials participants were allowed to take a short break, after which they resumed the task in their own time. In Response A repetition trials (Ar), the same response was required to the frequency of the prime and probe sine tones (e.g., the prime frequencies differed, and the probe frequencies differed). In Response A change trials (Ac), different responses were required for the categorization of the prime and probe sine tones (e.g., the prime frequencies were identical, and the probe frequencies differed). In Response B repetition trials (Br), the same response was required to the frequency of the prime and probe square tones (e.g., the prime frequencies were identical, and the probe frequencies were also identical). In Response B change trials (Bc), different responses were required to the prime and probe square tones (e.g., the prime frequencies differed, and the probe frequencies were identical). These relations resulted in the four conditions Response A repetition with Response B repetition (ArBr), Response A repetition with Response B change (ArBc), Response A change with Response B repetition (AcBr), and Response A change with Response B change (AcBc). Each of these conditions was presented 8 times with each of the four possible combinations of identical/different sine and square tone frequencies in the probe, resulting in 128 experimental trials. Tone frequencies were randomly assigned to the different displays. Before the experimental block started, participants first adjusted the volume to a comfortable level and completed a soundcheck where they were prompted to discriminate sine and square tones by pressing one of two keys (F for sine and J for square tones). The soundcheck served to introduce them to sine and square tones, as well as to ensure that they had the computer volume turned on. An average accuracy of > 80% was necessary to complete the soundcheck. Subsequently, participants were introduced to the experimental task and completed a training where they practiced their task for at least 16 trials (subsample of the experimental trials) and until they passed a 75% accuracy threshold.

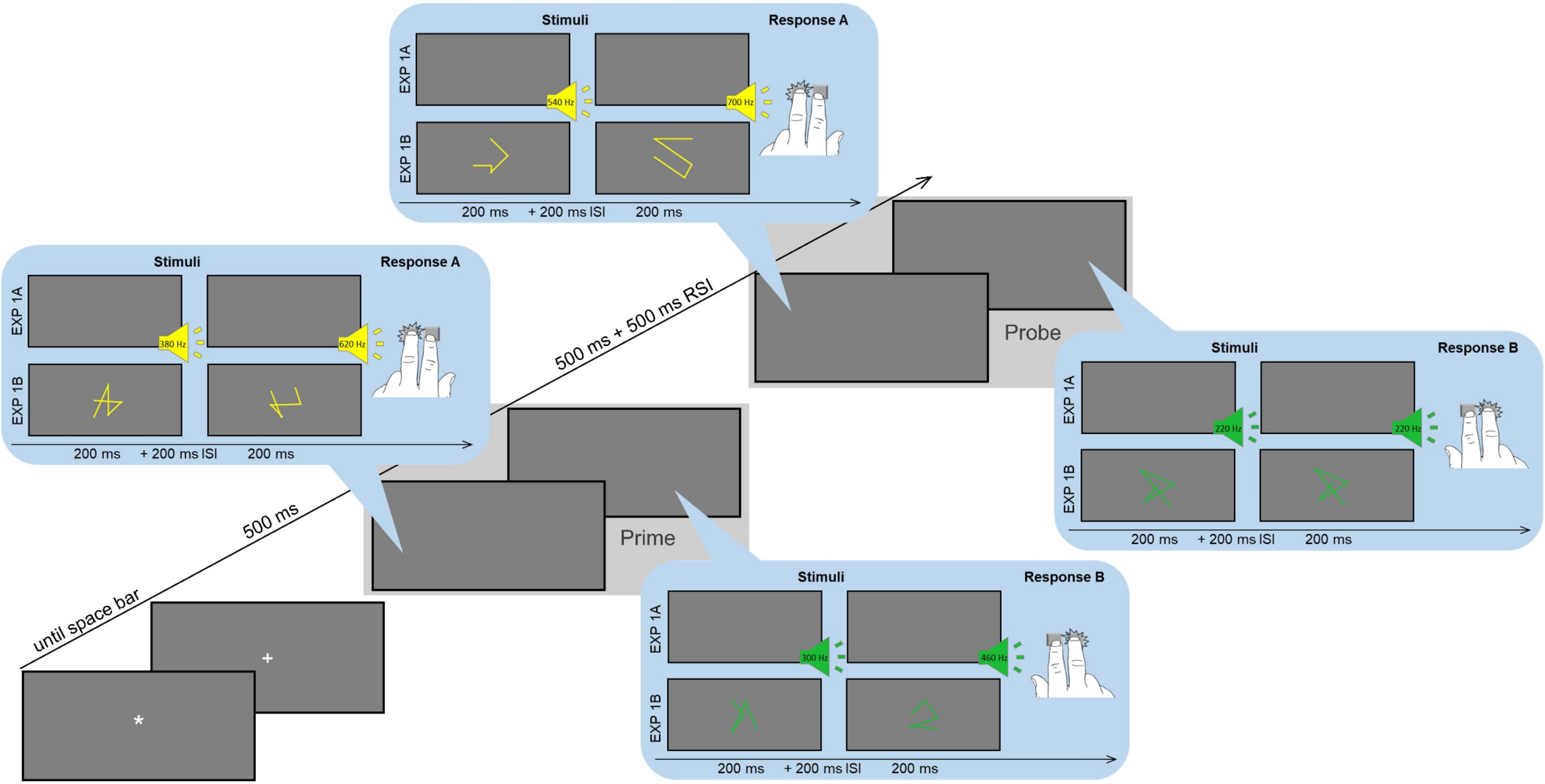

Figure 1. The sequence of events in one example trial in Experiments 1a and b. Participants decided twice in each prime and each probe whether the presented auditory stimuli had an identical or different frequency (Experiment 1a) or whether visual stimuli had identical or different shapes (Experiment 1b). The first response was a classification of sine wave tones or yellow stimuli with the left hand, the second response was a classification of square wave tones or green stimuli with the right hand. This is an example of a Response A repetition and Response B change trial. The stimuli are not drawn to scale.

Results

The data processing and analysis were conducted in R (R Core Team, 2022). Processing and aggregation of data were done with the 'dplyr'-package (Wickham et al., 2022). We compared the experimental conditions using a repeated-measures analysis of variance (ANOVA) with type-III sums of square, calculated via the 'ezANOVA'-function from the 'ez'-package (Lawrence, 2016). In addition, we calculated the response-response binding effects as the advantage of probe Response A repetition (vs. probe Response A change) in probe Response B repetition trials minus the advantage of probe Response A repetition (vs. probe Response A change) in probe Response B change trials ([AcBr - ArBr] - [AcBc - ArBc]), which is another way to represent the two-way interaction between Response A relation and Response B relation.

The dependent variable of interest was the performance in probe Response B. If prime Responses A and B are integrated, repeating prime Response A in the probe should trigger retrieval of the later response and thus influence performance on probe Response B. Only trials with correct responses A and B in both prime and probe were considered for the RT analyses. The error rate for prime responses (A or B) was 8.2%. The probe error rates were 6.0% for Response A and 2.9% for Response B (only including trials with correct previous responses). We excluded RTs of more than 1.5 interquartile ranges above the third quartile of the probe Response B RT distribution of the participant (Tukey, 1977) and RTs shorter than 200 ms from the analysis. Due to these constraints, 20.9% of the trials were excluded from the RT analyses. For the mean RTs and error rates, see **Table 1**.

Table 1. Mean response times (in milliseconds) and mean error rates (in percentages) for probe Response B, as a function of Response A relation and

Response B relation and stimulus type (Experiment 1a: auditory; Experiment 1b: visual)

	Auditory		Visual	
	B repetition	*B change*	*B repetition*	*B change*
A change	663 (4.3)	625 (2.8)	551 (5.9)	520 (3.8)
A repetition	617 (3.0)	640 (2.3)	536 (4.9)	534 (5.4)

In a 2 (Response A relation: repetition vs. change) × 2 (Response B relation: repetition vs. change) analysis of variance (ANOVA) on probe Response B RTs, the main effect for Response A relation was significant, $F(1, 28) = 4.25$, $p = .049$, $\eta_p^2 = .13$, while the main effect for Response B relation was not, $F(1, 28) = 0.89$, $p = .354$, $\eta_p^2 = .031$. More importantly, the interaction of Response A and Response B relation was significant, $F(1, 28) = 23.85$, $p < .001$, $\eta_p^2 = .46$, indicating binding between the responses: The repetition of Response A facilitated performance if Response B was repeated as well, $t(28)= 3.83$, $p <.001$, but impaired performance if Response B changed, $t(28)= -2.22$, $p =.035$.

In the same analysis on error rates, the main effects of Response A relation, $F(1, 28) = 1.40$, $p = .247$, $\eta_p^2 = .048$, and Response B relation, $F(1, 28) = 2.85$, $p = .102$, $\eta_p^2 = .09$, were not significant. Additionally, the interaction of Response A and Response B relation was not significant, $F(1, 28) = 0.33$, $p = .573$, $\eta_p^2 = .01$.

EXPERIMENT 1b

Method

Participants. Thirty students (19 women) from Trier University participated in the online experiment. The samples' median age was 23 years, with a range from 19 to 33 years. The participants were rewarded with partial course credit.

Design. The design comprised two within-participant factors, namely, response A relation (response repetition vs. response change from prime to probe), and response B relation (response repetition vs. response change from prime to probe).

Materials and procedure. Materials and procedure were identical to Experiment 1a with the following exceptions. Experiment 1b was programmed in Psychopy version 2021.2.3 (Peirce et al., 2019). Instead of tones, the list of possible stimuli consisted of eight different line patterns that were approximately 70x70 pixels in size and made up of four overlapping lines of different lengths. The line patterns were presented in yellow (RGB_{255}: 255, 252, 0) for Response A, or green (RGB_{255}: 18, 186, 46) for Response B. In each display, two line patterns were consecutively presented in the screen center, again for a duration of 200 ms with a 200 ms interval in between.

Participants were told that they would always see two consecutively presented line patterns that would be either of identical or different shape. Their task was always to first categorize the shape of the yellow line patterns (Response A) and then the shape of the green line patterns (Response B) as identical or different, by successively pressing two keys with the corresponding fingers. The left index and middle fingers were used for the yellow line pattern classification. For identical shapes, participants were instructed to press the key with the left index finger (H) and for different shapes, they were supposed to press the key with the left middle finger (G). To classify the green line patterns, the index and middle fingers of the right hand were used, respectively. For identical green shapes, a key was pressed with the right index finger (K), and for different shapes, a key was pressed with the right middle finger (L).

Again, both response A and B could either repeat or change between prime and probe, resulting in the four conditions ArBr, AcBr, ArBc and AcBc, of which each was presented 8 times with each of the four possible combinations of identical/different shapes in the probe, resulting in at least 16 training trials (or until a 75% accuracy threshold was reached) and 128 experimental trials. Shapes were randomly assigned to the different displays with the exception that no shape was repeated between prime and probe of one trial. As no auditory stimuli were presented, there was no soundcheck at the beginning of this experiment.

Results

As in Experiment 1a, only trials with correct responses A and B in both prime and probe were considered. The error rate for prime responses (A or B) was 9.1%. The probe error rates were 6.8% for Response A and 4.7% for Response B (only including trials with correct previous responses). We excluded RTs of more than 1.5 interquartile ranges above the third quartile of the probe Response B RT distribution of the participant (Tukey, 1977) and RTs shorter than 200 ms from the analysis. Due to these constraints, 22.7% of the trials were excluded from the RT analyses. For the mean RTs and error rates, see **Table 1**.

The dependent variable of interest was again performance in probe Response B. In a 2 (Response A relation: repetition vs. change) × 2 (Response B relation: repetition vs. change) ANOVA on probe Response B RTs the main effect for Response B relation was significant, $F(1, 29) = 14.40$, $p < .001$, $\eta_p^2 = .33$, while the main effect for Response A relation was not, $F(1, 29) < 1$, $p = .868$, $\eta_p^2 < .01$. More importantly, the interaction of Response A and Response B relation was significant, $F(1, 29) = 12.50$, $p = .001$, $\eta_p^2 = .30$, indicating binding between the responses: The repetition of Response A facilitated performance if Response B was repeated as well, *t*(29)= 3.16, *p* =.004, but impaired performance if Response B changed, *t*(29)= -2.51, *p* =.018. For a summary of mean binding effects, see **Figure 2**.

In the same analysis on error rates, the main effects of Response A relation, *F*(1, 29) < 1, *p* = .765, $\eta_p^2 < .01$, and Response B relation, *F*(1, 29) = 1.62, *p* = .213, $\eta_p^2 = .05$, were not significant. The interaction of Response A and Response B relation was also not significant, *F*(1, 29) = 3.83, *p* = .060, $\eta_p^2 = .12$.

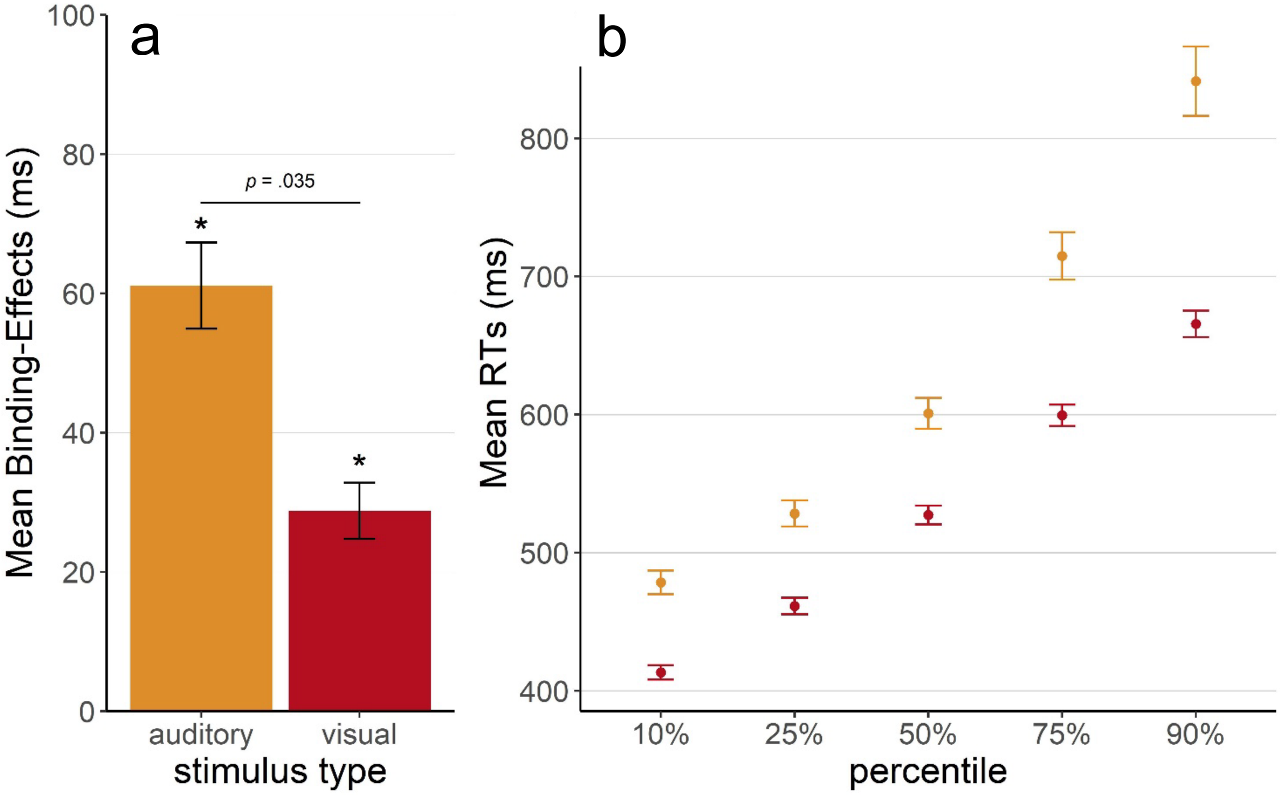

Figure 2. (a) Mean response-response binding effects for response times in Experiments 1a and 1b as a function of stimulus type (auditory vs. visual). Binding effects are calculated as the advantage of probe Response A repetition (vs. probe Response A change) in probe Response B repetition trials minus the advantage of probe Response A repetition (vs. probe Response A change) in probe Response B change trials: [AcBr - ArBr] - [AcBc - ArBc]. **(b)** Mean response times for the 10th, 25th, 50th, 75th and 90th percentile, depending on stimulus type (auditory in orange vs. visual in red). The errorbars signify the standard error of the response times for the mean of each percentile.

Comparison of Experiments 1a and 1b

We compared results of Experiments 1a and 1b to test for differences in response-response binding effects between auditory and visual stimuli. In a 2 (Response A relation: repetition vs. change) × 2 (Response B relation: repetition vs. change) × 2 (stimulus type: auditory vs. visual) ANOVA on probe Response B RTs, the main effect for stimulus type was significant, $F(1, 57) = 12.02$, $p = .001$., $\eta_p^2 = .17$, with faster RTs with visual stimuli ($M = 535$ ms) than with auditory stimuli ($M = 636$ ms). The main effect for Response B relation was significant, $F(1, 57) = 8.03$, $p = .006$, $\eta_p^2 = .12$, while the main effect for Response A relation was not, $F(1, 57) = 3.84$, $p = .055$, $\eta_p^2 = .06$. The interaction of Response A and Response B relation was significant, $F(1, 57) = 36.32$, $p < .001$, $\eta_p^2 = .38$, indicating binding between responses. This was further modulated by stimulus type, $F(1, 57) = 4.76$, $p =.034$, $\eta_p^2 = .08$, with stronger binding effects with auditory than with visual stimuli ($M = 61$ vs. 29). For a summary of binding effects, **see Figure 2a**.

The same analysis on error rates revealed a significant main effect for stimulus type, $F(1, 57) = 5.11$, $p = .028$, $\eta_p^2 = .08$, indicating an influence of stimulus type on error rates, with more errors with visual stimuli ($M = 4.98\%$) than with auditory stimuli ($M = 3.11\%$). The main effect for Response B relation was significant, $F(1, 57) = 4.39$, $p = .041$, $\eta_p^2 = .07$, but not for Response A relation, $F(1, 57) < .1$, $p = .551$, $\eta_p^2 < .01$. The interaction of Response A and Response B relation was not significant, $F(1, 57) = 3.31$, $p = .074$, $\eta_p^2 = .05$ and this relation was not modulated by stimulus type, $F(1, 57) = 1.02$, $p =.318$, $\eta_p^2 = .02$.

Analysis of percentiles with similar RTs

In the binding literature, it is discussed that longer RTs can lead to systematically stronger binding effects, as they leave more time between responses for retrieval (Frings & Moeller, 2012; for a similar argument, see Schöpper & Frings, 2022). To investigate whether the difference in RT binding effects for stimulus types might be due to differences in RTs, we calculated the 10th, 25th, 50th, 75th and 90th percentile of the cumulative RT distribution of each participant (**see Figure 2b**). To get an idea of whether RT differences caused the observed differences in binding effects between stimulus types, we exploratorily conducted an additional ANOVA on probe Response B RTs including only those percentiles with similar mean RTs between stimulus type conditions, i.e., the 10th, 25th and 50th percentile of the auditory RT distribution and the 25th, 50th and 75th percentile of the visual RT distribution. In a 2 (Response A relation: repetition vs. change) × 2 (Response B relation: repetition vs. change) × 2 (stimulus type: auditory vs. visual) ANOVA on probe Response B RTs, there was no significant main effect for stimulus type, $F(1, 57) < 1$, $p = .773$, $\eta_p^2 < .01$, and for Response A relation, $F(1, 57) = 1.85$, $p = .180$, $\eta_p^2 = .03$, but for Response B relation, $F(1, 57) = 10.30$, $p = .002$, $\eta_p^2 = .15$. The interaction of Response A and Response B relation was significant, $F(1, 57) = 37.83$, $p < .001$, $\eta_p^2 = .40$, again indicating binding between responses. However, this was not further modulated by stimulus type, $F(1, 57) = 2.17$, $p =.146$, $\eta_p^2 = .04$, indicating no significant differences in bindings effects depending on modality. All other interactions did not reach significance, *F*s < 4, *p*s > .051. For a summary of mean RTs, binding effects, and effect sizes per percentile, see also **Table A1** and **A2** in the **appendix**.

General Discussion

Previous findings focusing on individual actions show that binding effects can be independent of stimulus modality (Schöpper, Singh, & Frings, 2020; Wesslein et al., 2019; Zmigrod et al., 2009), but that binding effects can in some instances also depend on modality, probably due to differences in processing of visual and auditory features (Möller et al., 2016; Schöpper & Frings, 2022). It is generally assumed that representations of simple, as well as of more complex actions, can contain stimuli of other modalities than the visual (Friston, 2012; Hommel et al., 2001; Zacks et al., 2007), but, at least in the binding research, the influence of stimulus modality on the control of complex actions has not been investigated before. To do so, we created an auditory version of the response-response binding task (Moeller & Frings, 2019b) and compared resulting effects to a parallel version with visual stimuli. We observe significant binding effects in both versions of the task, indicating that response-response binding effects are not dependent on a particular stimulus modality. Binding effects were slightly higher with auditory than with visual stimuli, a pattern that might in part be accounted for by systematic differences in RTs depending on stimulus modality: Longer RTs (as was the case in the auditory modality) leave more time between responses for retrieval, which is discussed to lead to stronger binding effects (Frings & Moeller, 2012). In line with this, the observed modality difference is no longer significant if we compare binding effects only for response times of similar length.

The auditory and the visual task were designed to be as similar as possible, requiring the judgement of sequentially presented shapes or tones as same or different. When comparing both tasks, we observed main effects of RTs and error rates, with slightly more errors but faster RTs for the visual than the auditory task, suggesting that the tasks led to slightly different answer patterns. This might be due to a variety of reasons, for example, it might be a product of interindividual differences between the samples of both experiments. It might also be due to differences in the tasks and their difficulty leading to shifts in cognitive focus on speed and/or accuracy (e.g., Heitz & Engle, 2007). Differences in RTs and error rates could also indicate general differences in the processing of auditory and visual stimuli (Bizley & Cohen, 2013; for a discussion, see also Schöpper & Frings, 2022). Especially the modality difference in response times seems to be in line with previous findings in the action control literature, showing generally slower responses to auditory than to visual stimuli (Buchner et al., 2003; Mayr & Buchner, 2006; Schöpper & Frings, 2022). Regardless of the source of the RT and error rate differences, we observe binding effects in both modalities. Thus, it is possible that a variety of factors play a role in influencing the magnitude of binding effects, but in general, response-response binding effects occur independent of stimulus modality.

Finding response-response binding effects in both the visual and the auditory modality is in line with findings indicating that action representations can contain information from other modalities than the visual modality (Buchner et al., 2003; Mayr et al., 2018; Moeller et al., 2012; Schöpper, Singh, & Frings, 2020). More specifically, this applies not only to representations of simple actions like keypresses (Hommel, 1998, 2004), but our findings indicate that it also applies to the representation of more complex and sequential actions. Thus, they support the idea of bindings between features as a rather ubiquitous phenomenon underlying most actions (e.g., Frings et al., 2020; Hommel et al., 2001; Hommel, 2009).

The visual task in Experiment 1b was a conceptual replication of previous response-response binding experiments (Moeller & Frings, 2019b, 2019d) with one major difference: The two stimuli in each pair were not presented simultaneously and remained on screen until a response was given, but were presented sequentially and only for 200 ms each. In simple actions, sequential presentation of stimuli had no influence on binding effects (Laub et al., 2018). If the sequentialness of stimulus presentation had an influence on the magnitude of response-response binding effects, this should show when we compare results to data from previous experiments. At first glance, the size of the binding effect in experiment 1b (*d* = 0.65; *d* computed as (t/sqrt(n)) was comparable with findings of previous experiments (Moeller & Frings, 2019b: *d* = 0.63 and *d* = 0.88; Moeller & Frings, 2019d: *d* = 0.74 and *d* = 1.07). This indicates no general influence of sequential stimulus presentation on response-response binding effects, which is in line with previous findings showing no influence of the temporo-spatial organization of stimuli on the execution of sequential actions (Fournier & Gallimore, 2013; Selimi et al., 2022).

Although we looked at action sequences instead of individual actions, results might still be somewhat different in more complex settings, i.e., with natural actions, more complex tasks, or more complex stimuli. There are findings showing that the task load and the complexity of the settings (e.g., single vs. dual-tasking, laboratory vs. simulated driving) can have an influence on whether we attend to, and thus benefit from uni- and multimodal warning signals: In some instances of high task load, multimodal warning signals can be more effective in capturing our attention than unimodal warning signals, while they often showed no additional benefit in conditions of low task load (for a review, see Spence, 2010). This indicates that differences in how we process information from different modalities might become more relevant for action control in more complex scenarios. Thus our findings indicate that response-response binding effects occur modality independent in controlled settings, but further research is needed to show whether findings can be generalised to more complex situations. At the same time, showing that response-response binding can occur with auditory stimuli opens up opportunities to investigate the processing of multimodal information in binding of more complex actions.

It is often assumed that effects transfer from the visual to other modalities, and that representations of our actions are multimodal. Our results extend previous findings from individual actions to actions sequences, showing that also response-response binding occurs when responding to other stimulus modalities than the visual modality. This was the first time that response-response binding was done with a purely auditory task, thus establishing a new variant of this paradigm to be used in future studies. Findings underline the relevance of feature binding as a general mechanism in action control, showing once more that bindings are not dependent on one stimulus modality.

APPENDIX

Table A1. Mean Probe Response B response times as a function of condition (Response A and B relation between prime and probe), stimulus type (auditory vs. visual) and percentile (10th, 25th, 50th, 75th and 90th).

Condition	Stimulus Type	Percentile				
		10th	*25th*	*50th*	*75th*	*90th*
ArBr	Auditory	468	512	591	688	794
	Visual	405	464	527	606	674
ArBc	Auditory	486	535	601	719	851
	Visual	419	465	528	592	655
AcBr	Auditory	491	548	626	750	885
	Visual	437	482	545	608	668
AcBc	Auditory	469	519	586	702	836
	Visual	392	435	510	592	665

Table A2. *t*-tests against zero and corresponding effect sizes d_z for binding effects as a function of stimulus type (auditory vs. visual) and percentile (10th, 25th, 50th, 75th and 90th).

Percentile	Stimulus Type	*t*	df	*p*	d_z
10th	Auditory	4.03	28	< .001	0.75
	Visual	5.13	29	< .001	0.94
25th	Auditory	4.75	28	< .001	0.88
	Visual	4.25	29	< .001	0.78
50th	Auditory	3.81	28	.001	0.71
	Visual	3.77	29	.001	0.69
75th	Auditory	3.39	28	.002	0.63
	Visual	0.26	29	.797	0.05
90th	Auditory	3.01	28	.005	0.56
	Visual	-0.95	29	.349	-0.17

References

Bizley, J. K., & Cohen, Y. E. (2013). The what, where and how of auditory-object perception. *Nature Reviews Neuroscience*, *14*(10), 693–707. https://doi.org/10.1038/nrn3565

Buchner, A., Zabal, A., & Mayr, S. (2003). Auditory, visual, and cross-modal negative priming. *Psychonomic Bulletin & Review*, *10*(4), 917–923. https://doi.org/10.3758/BF03196552

De Jong, R. (1995). The role of preparation in overlapping-task performance. *The Quarterly Journal of Experimental Psychology. A, Human Experimental Psychology*, *48*(1), 2–25. https://doi.org/10.1080/14640749508401372

Faul, F., Erdfelder, E., Lang, A.-G., & Buchner, A. (2007). G*power 3: A flexible statistical power analysis program for the social, behavioral, and biomedical sciences. *Behavior Research Methods*, *39*(2), 175–191. https://doi.org/10.3758/BF03193146

Fitch, W. T., & Martins, M. D. (2014). Hierarchical processing in music, language, and action: Lashley revisited. *Annals of the New York Academy of Sciences*, *1316*, 87–104. https://doi.org/10.1111/nyas.12406

Fournier, L. R., & Gallimore, J. M. (2013). What makes an event: Temporal integration of stimuli or actions? *Attention, Perception & Psychophysics*, *75*(6), 1293–1305. https://doi.org/10.3758/s13414-013-0461-x

Frings, C., Hommel, B., Koch, I., Rothermund, K., Dignath, D., Giesen, C., Kiesel, A., Kunde, W., Mayr, S., Moeller, B., Möller, M., Pfister, R., & Philipp, A. (2020). Binding and Retrieval in Action Control (BRAC). *Trends in Cognitive Sciences*, *24*(5), 375–387. https://doi.org/10.1016/j.tics.2020.02.004

Frings, C., & Moeller, B. (2012). The horserace between distractors and targets: Retrieval-based probe responding depends on distractor–target asynchrony. *Journal of Cognitive Psychology*, *24*(5), 582–590. https://doi.org/10.1080/20445911.2012.666852

Frings, C., Moeller, B., & Rothermund, K. (2013). Retrieval of event files can be conceptually mediated. *Attention, Perception, & Psychophysics*, *75*(4), 700–709. https://doi.org/10.3758/s13414-013-0431-3

Friston, K. (2012). Prediction, perception and agency. *International Journal of Psychophysiology : Official Journal of the International Organization of Psychophysiology*, *83*(2), 248–252. https://doi.org/10.1016/j.ijpsycho.2011.11.014

Heitz, R. P., & Engle, R. W. (2007). Focusing the spotlight: Individual differences in visual attention control. *Journal of Experimental Psychology. General*, *136*(2), 217–240. https://doi.org/10.1037/0096-3445.136.2.217

Henson, R. N., Eckstein, D., Waszak, F., Frings, C., & Horner, A. J. (2014). Stimulus-response bindings in priming. *Trends in Cognitive Sciences*, *18*(7), 376–384. https://doi.org/10.1016/j.tics.2014.03.004

Hollingworth, A. (2009). Two forms of scene memory guide visual search: Memory for scene context and memory for the binding of target object to scene location. *Visual Cognition*, *17*(1-2), 273–291. https://doi.org/10.1080/13506280802193367

Hommel, B. (1998). Event Files: Evidence for Automatic Integration of Stimulus-Response Episodes. *Visual Cognition*, *5*(1-2), 183–216. https://doi.org/10.1080/713756773

Hommel, B. (2004). Event files: Feature binding in and across perception and action. *Trends in Cognitive Sciences*, *8*(11), 494–500. https://doi.org/10.1016/j.tics.2004.08.007

Hommel, B. (2009). Action control according to TEC (theory of event coding). *Psychological Research*, *73*(4), 512–526. https://doi.org/10.1007/s00426-009-0234-2

Hommel, B., Müsseler, J., Aschersleben, G., & Prinz, W. (2001). The Theory of Event Coding (TEC): A framework for perception and action planning. *The Behavioral and Brain Sciences*, *24*(5), 849-78; discussion 878-937. https://doi.org/10.1017/S0140525X01000103

Lashley, K. S. (1951). The problem of serial order in behavior. In L. A. Jeffress (Ed.), *Cerebral mechanisms in behavior* (pp. 112–147).

Laub, R., Frings, C., & Moeller, B. (2018). Dissecting stimulus-response binding effects: Grouping by color separately impacts integration and retrieval processes. *Attention, Perception & Psychophysics*, *80*(6), 1474–1488. https://doi.org/10.3758/s13414-018-1526-7

Lawrence, M. A. (2016). *ez: Easy Analysis and Visualization of Factorial Experiments*. https://CRAN.R-project.org/package=ez

Mayr, S., & Buchner, A. (2006). Evidence for episodic retrieval of inadequate prime responses in auditory negative priming. *Journal of Experimental Psychology: Human Perception and Performance*, *32*(4), 932–943. https://doi.org/10.1037/0096-1523.32.4.932

Mayr, S., Hauke, R., & Buchner, A. (2009). Auditory location negative priming: A case of feature mismatch. *Psychonomic Bulletin & Review*, *16*(5), 845–849. https://doi.org/10.3758/PBR.16.5.845

Mayr, S., Möller, M., & Buchner, A. (2018). Contextual modulation of prime response retrieval processes: Evidence from auditory negative priming. *Attention, Perception, & Psychophysics*, *80*(8), 1918–1931. https://doi.org/10.3758/s13414-018-1574-z

Moeller, B., & Frings, C. (2019a). Binding processes in the control of nonroutine action sequences. *Journal of Experimental Psychology: Human Perception and Performance*, *45*(9), 1135–1145. https://doi.org/10.1037/xhp0000665

Moeller, B., & Frings, C. (2019b). From simple to complex actions: Response-response bindings as a new approach to action sequences. *Journal of Experimental Psychology: General*, *148*(1), 174–183. https://doi.org/10.1037/xge0000483

Moeller, B., & Frings, C. (2019c). Lost time: Bindings do not represent temporal order information. *Psychonomic Bulletin & Review*, *26*(1), 325–331. https://doi.org/10.3758/s13423-018-1493-y

Moeller, B., & Frings, C. (2019d). Response-response binding across effector-set switches. *Psychonomic Bulletin & Review*, *26*(6), 1974–1979. https://doi.org/10.3758/s13423-019-01669-8

Moeller, B., & Frings, C. (2022). All together now: Simultaneous feature integration and feature retrieval in action control. *Psychonomic Bulletin & Review*, *29*(2), 512–520. https://doi.org/10.3758/s13423-021-01999-6

Moeller, B., Rothermund, K., & Frings, C. (2012). Integrating the irrelevant sound. *Experimental Psychology*, *59*(5), 258–264. https://doi.org/10.1027/1618-3169/a000151

Möller, M., Mayr, S., & Buchner, A. (2016). The time-course of distractor processing in auditory spatial negative priming. *Psychological Research*, *80*(5), 744–756. https://doi.org/10.1007/s00426-015-0685-6

Peirce, J., Gray, J. R., Simpson, S., MacAskill, M., Höchenberger, R., Sogo, H., Kastman, E., & Lindeløv, J. K. (2019). Psychopy2: Experiments in behavior made easy. *Behavior Research Methods*, *51*(1), 195–203. https://doi.org/10.3758/s13428-018-01193-y

Prinz, W. (1992). Why don't we perceive our brain states? *European Journal of Cognitive Psychology*, *4*(1), 1–20. https://doi.org/10.1080/09541449208406240

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

R Core Team. (2022). *R: A language and environment for statistical computing.* (Version 4.2.1) [Computer software]. R Foundation for Statistical Computing. Vienna, Austria. https://www.R-project.org/

Schmidt, J. R., Houwer, J. de, & Rothermund, K. (2016). The Parallel Episodic Processing (PEP) model 2.0: A single computational model of stimulus-response binding, contingency learning, power curves, and mixing costs. *Cognitive Psychology*, *91*, 82–108. https://doi.org/10.1016/j.cogpsych.2016.10.004

Schneider, D. W., & Logan, G. D. (2006). Hierarchical control of cognitive processes: Switching tasks in sequences. *Journal of Experimental Psychology. General*, *135*(4), 623–640. https://doi.org/10.1037/0096-3445.135.4.623

Schöpper, L.-M., & Frings, C. (2022). Same, but different: Binding effects in auditory, but not visual detection performance. *Attention, Perception, & Psychophysics*, 1–14. https://doi.org/10.3758/s13414-021-02436-5

Schöpper, L.-M., Hilchey, M. D., Lappe, M., & Frings, C. (2020). Detection versus discrimination: The limits of binding accounts in action control. *Attention, Perception, & Psychophysics*, *82*(4), 2085–2097. https://doi.org/10.3758/s13414-019-01911-4

Schöpper, L.-M., Lappe, M., & Frings, C. (2022). Found in translation: The role of response mappings for observing binding effects in localization tasks. *Visual Cognition*, *30*(8), 527–545. https://doi.org/10.1080/13506285.2022.2139033

Schöpper, L.-M., Singh, T., & Frings, C. (2020). The official soundtrack to “Five shades of grey”: Generalization in multimodal distractor-based retrieval. *Attention, Perception, & Psychophysics*, *82*(7), 3479–3489. https://doi.org/10.3758/s13414-020-02057-4

Selimi, S., Frings, C., & Moeller, B. (2022). Binding between Responses is not Modulated by Grouping of Response Effects. *Journal of Cognition*, *5*(1), 42. https://doi.org/10.5334/joc.233

Shamma, S. (2001). On the role of space and time in auditory processing. *Trends in Cognitive Sciences*, *5*(8), 340–348. https://doi.org/10.1016/S1364-6613(00)01704-6

Spence, C. (2010). Crossmodal spatial attention. *Annals of the New York Academy of Sciences*, *1191*(1), 182–200. https://doi.org/10.1111/j.1749-6632.2010.05440.x

Tukey, J. W. (1977). *Exploratory data analysis* (Vol. 2). Reading, MA.

Võ, M. L.-H., & Henderson, J. M. (2010). The time course of initial scene processing for eye movement guidance in natural scene search. *Journal of Vision*, *10*(3), 14.1-13. https://doi.org/10.1167/10.3.14

Wesslein, A.-K., Moeller, B., Frings, C., & Giesen, C. (2019). Separating after-effects of target and distractor processing in the tactile sensory modality. *Attention, Perception, & Psychophysics*, *81*(3), 809–822. https://doi.org/10.3758/s13414-018-01655-7

Wickham, H., François, R., Henry, L., & Müller, K. (2022). *dplyr: A Grammar of Data Manipulation*. https://CRAN.R-project.org/package=dplyr

Zacks, J. M., Braver, T. S., Sheridan, M. A., Donaldson, D. I., Snyder, A. Z., Ollinger, J. M., Buckner, R. L., & Raichle, M. E. (2001). Human brain activity time-locked to perceptual event boundaries. *Nature Neuroscience*, *4*(6), 651–655. https://doi.org/10.1038/88486

Zacks, J. M., Speer, N. K., Swallow, K. M., Braver, T. S., & Reynolds, J. R. (2007). Event perception: A mind-brain perspective. *Psychological Bulletin*, *133*(2), 273–293. https://doi.org/10.1037/0033-2909.133.2.273

Zacks, J. M., & Swallow, K. M. (2007). Event Segmentation. *Current Directions in Psychological Science*, *16*(2), 80–84. https://doi.org/10.1111/j.1467-8721.2007.00480.x

Zmigrod, S., Spapé, M., & Hommel, B. (2009). Intermodal event files: integrating features across vision, audition, taction, and action. *Psychological Research*, *73*(5), 674–684. https://doi.org/10.1007/s00426-008-0163-5

5. General Discussion

Hierarchical action control means that actions can be represented on different levels of complexity. Representations of complex actions may consist of multiple more fine-grained actions (e.g., Moeller & Frings, 2019b; Zacks, Tversky, & Iyer, 2001), which in turn consist of clusters of stimulus, response, and effect features (Hommel, 1998; Hommel et al., 2001). The articles in this dissertation aimed to explore the factors that influence whether individual actions (or event files) are represented as part of a more complex, hierarchical action (i.e., whether they form response-response bindings). We specifically looked at the influence of space and context. Up to now, we did not know what influence individual components (stimuli, responses, and effects) of an individual action have on whether it is perceived as part of a larger action. We investigated this by varying the spatial relations between components of multiple individual actions. In addition, it was of interest to explore whether different types of changing and constant contexts have an influence on the representation of actions.

In Articles 1, 2, and 3 (chapters 4.1, 4.2, and 4.3), we systematically manipulated the spatial relation of different components that make up an action and compared whether they influence the way a hierarchical action is represented, as measured via response-response binding. Results indicate that spatial separation between two consecutively executed responses by the placement of a barrier between responding hands impacted bindings between them (Article 1), with stronger binding effects for spatially separated responses than for non-separated responses. This is in line with findings showing that the separation of responding hands can make responses more distinct (Lakens et al., 2011; Nett & Frings, 2014), which might have in turn, similar to findings on stimulus separation (Laub et al., 2018; Schmalbrock, Kiesel, & Frings, 2022), affected the strength of retrieval. If instead of the responses, the corresponding stimuli or action effects were separated by varying their spatial distance on screen, this had no impact on response-response binding effects (Articles 2 & 3). As these manipulations were quite comparable to previous manipulations at the level of individual actions (Frings & Rothermund, 2011; Laub et al., 2018; Schmalbrock, Kiesel, & Frings, 2022), the absence of an influence on response-response binding effects allows us to draw conclusions about the structure of hierarchical actions. Furthermore, this finding indicates that the spatial relation of stimuli or effects, isolated from the position of responses, does not affect whether individual actions are represented as part of a more complex action, whereas the spatial relation of responses may be relevant for representing individual actions as part of a more complex action.

From findings on individual actions, we know that also the context in which an action is executed can become part of an event representation in different ways. Based on this, Articles 2, 4, and 5 (chapters 4.2, 4.4, and 4.5) addressed the role of internal and external context for hierarchical action representations. Consistent with findings on the level of individual event files (Laub & Frings, 2020; Mayr et al., 2018; Qiu et al., 2022a, 2022b), changes in external context from the time points of integration and retrieval, as realized through the spatial distance between stimuli, lead to significantly weaker response-response binding effects (Article 2), indicating that the context became part of the event representation and acted as an additional retrieval cue. Also, these results might tie in with assumptions on the role of feature changes in the event segmentation literature (as will be discussed further in chapter 5.2.1). Results from Article 4 demonstrate that also a constant internal context, modulated through instructed speed-accuracy sets, affected the strength of response-response binding effects. We observed overall stronger binding effects under instructions that focused at least partially on speed compared to accuracy-focused instructions. Speed instructions might have reduced the amount of cognitive control, which is associated with more partial repetition costs and thus higher binding effects (Colzato et al., 2006; Zmigrod et al., 2013). Article 5 investigated the stimulus modality as a constant external context and demonstrates that response-response binding effects occur with auditory as well as with visual stimuli. The finding confirms the assumption that, similarly to representations of individual actions (e.g., Moeller et al., 2012; Schöpper et al., 2020; Zmigrod et al., 2009; Zmigrod & Hommel, 2013), also representations of hierarchical actions do not depend on a particular stimulus modality (Zacks et al., 2007).

5.1 The structure of response-response bindings

As discussed before, spatial relations were previously found to affect whether features become part of one event representation, but the representations previously spanned no response (object files, e.g., van Dam & Hommel, 2010) or only one response (event files, e.g., Frings & Rothermund, 2011). Three articles of this dissertation (Articles 1, 2, & 3) imply that spatial feature relations may also play a role in representations spanning multiple responses, but that this is the case for some features and not for others. Only the separation of responses affected response-response binding effects. The finding that the spatial relation of stimuli or effects did not affect response-response bindings allows for some structural considerations regarding response-response bindings and the feature relations that are relevant for hierarchical action representations.

5.1.1 The importance of binary bindings

The TEC postulates that actions are represented in the form of event files that are internally structured via binary bindings (Hommel, 2004). While binary bindings are assumed, bindings between three or more features are not ruled out (Hommel, 1998).

Later findings even show that bindings can take other more abstract forms, for example, bindings between whole objects and responses (cf. *configural bindings*, Moeller et al., 2016; see also chapter 5.1.3). In TEC and later research, it is further assumed that the repetition of one feature retrieves the whole event file (e.g., Foerster, Moeller, et al., 2022; Frings et al., 2020; Hommel, 2004; Moeller & Frings, 2019d; Schmalbrock, Kiesel, & Frings, 2022), which suggests that an event file is to some degree a holistic representation of an action, similar to how object files represent objects (Treisman, 1992). If we assumed that an event file is a holistic representation of an action with all its features, it would make sense that manipulating the spatial relation of any two features between event files would affect the relation of these event files. Making the features spatially closer should make the event files more related and less distinct from one another. This could, in consequence, affect whether these files are integrated into and/or retrieved from one overarching event representation, similar to how one vs. two separate object files are formed (van Dam & Hommel, 2010). The findings of this dissertation do not support such a strong claim: Measuring the relation of individual action representations (event files) via response-response binding effects indicated that only the relation of responses affected binding between them (Article 1), while the relation of effects or stimuli did not affect response-response binding effects (Articles 2 & 3). However, findings can be interpreted in the sense of binary bindings between stimulus features: While a direct manipulation of the relation between responses affects response-response binding, the relation of two stimuli (S1 and S2; or the relation of effects, respectively) might influence whether they form binary bindings with only their corresponding response (S1-R1 and S2-R2) or also with the other response (additional bindings between S1-R2 and S2-R1). This interpretation would be analogous to findings from distractor-response bindings, where the target of

R1 (S1) acts as a distractor at R2, which would lead to S1-R2 bindings. Such stimulus-response bindings across individual event files could affect action control, by, for example, leading to competition between retrieved stimulus and/or response alternatives (Frings & Moeller, 2012) but do not affect the relation of responses themselves.[5]

There are other findings arguing against the use of the event file metaphor, and instead focusing on action representations as clusters of binary bindings: Recent findings show that the repetition of one feature does indeed not retrieve the whole event file, but rather only those features that are bound to this feature (Schöpper et al., 2023). Also, a central assumption of event files is that information that is coded in an event file is occupied, so that to bind it to a new event file, the previous event file needs to be disassembled (code occupation hypothesis, Hommel et al., 2001; Stoet & Hommel, 1999). However, Geissler et al. (2023) show that the same response can be part of multiple response-response bindings at the same time, which questions the assumption of code occupation as a basic principle of event files. And as will be discussed further in a later chapter (chapter 5.2.1), it is still debated where such an event file ends (e.g., Frings, Selimi, et al., 2022). In sum, findings indicate that connections between features are more complex than the event file metaphor can account for. While the term event file helps to describe an action representation existing at a given time, an event file is probably not as holistic as often assumed –

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[5] While this interpretation is likely, this cannot be confirmed with the results of the present articles, as any stimulus repetitions were excluded to avoid confounds of stimulus retrieval on response-response binding effects. Note that stimuli were presented sequentially in the present studies so that not all stimulus-response combinations were possible, e.g., in Article 2, probably no binding could occur between R1 and S2, as S2 was only presented after R1 execution.

and in some cases, it might even be misleading to refer to event files instead of referring to specific feature bindings that are of interest.

5.1.2 Hierarchy and response-response binding

We assume that bindings follow a hierarchical structure of action representation (Hommel et al., 2001), with stimulus-response and response-effect bindings at a lower level and bindings between responses at a higher level of representation (Moeller & Frings, 2019b, 2022). And we do so in line with a greater part of the literature on action perception and control (e.g., Botvinick, 2008; Herwig et al., 2013; Koechlin & Jubault, 2006; Lashley, 1951; Logan & Crump, 2011; Miller et al., 1960; Rosenbaum et al., 1983; Uithol et al., 2012; Vallacher & Wegner, 1987; Zacks, Tversky, & Iyer, 2001). However, it is possible that the response-response binding effects we observed here do not indicate hierarchy but that bindings are coded as a *flat* structure (cf. Lien & Ruthruff, 2004), where all types of bindings are on the same hierarchy level. In a recent paper, Moeller and Frings (2019b) argued that each response might – together with its corresponding stimuli and effects – be represented in its own *instance* (cf. Logan, 1988), and that binding effects could also reflect integration and retrieval of these separate instances.

It is difficult to settle the question definitively, but there are some findings on response-response bindings that speak in favor of a hierarchical representation: While different forms of binding exist at the same time (Moeller & Frings, 2022), response-response bindings usually have a considerably longer duration than stimulus-response bindings (Moeller & Frings, 2021; but see Moutsopoulou & Waszak, 2013; Pfeuffer et al., 2017). This longer duration does not prove hierarchy, but is at least a prerequisite for hierarchical representations, as response-response bindings need to exist long enough to account for binding between events that get increasingly more distant in time (Moeller & Frings, 2021). Additionally, other literature on hierarchical actions proposes that actions on different levels of hierarchy can differ in the feedback they use (Crump & Logan, 2010; Snyder et al., 2015), in the way goals are represented (Uithol et al., 2012; Vallacher & Wegner, 1987; Zacks & Tversky, 2001), or even in the way they are modulated (Logan, 2003), and thus, such differences might be used to detect different levels of representation (Logan & Crump, 2011). When comparing results from Article 2 to the existing literature, findings indicate that different forms of bindings might be modulated differently by stimulus distance manipulations: We found no impact of stimulus distance on response-response binding effects (Article 2), whereas it influenced stimulus-response binding (Frings & Rothermund, 2011), as well as binding between stimuli (van Dam & Hommel, 2010). Taken together, the findings of Article 2 and the existing literature might indicate that bindings are represented hierarchically.

5.1.3 Internal and external context in action representations

Results from Articles 1, 2, and 3 underline the relevance of binary bindings. When talking about the structure of event representations, it is important to look at information that is probably also part of these representations, but that does not (necessarily) fit the idea of binary bindings. Findings of Articles 2 and 4 show that internal and external contexts affect response-response binding effects. Changes in external (stimulus) context influenced the retrieval of previously integrated responses (Article 2). A constant internal context (instructed speed and/or accuracy focus) affected the strength of binding effects (Article 4), while a constant external context (auditory or visual stimulus modality) did not affect the occurrence of binding effects (Article 5).

Findings on external context changes (Article 2) fit in with previous findings in the binding literature, indicating that the context can become part of an event representation (e.g., Frings & Rothermund, 2017; Laub & Frings, 2020; Mayr et al., 2018). The external context might be represented in binary bindings as an additional stimulus, giving it the ability to retrieve other integrated features if repeated, or it can be represented in configural bindings, where it can act as an additional retrieval cue (Qiu et al., 2022b). Factors that determine whether it is bound binary, configural, or not at all, are for example saliency and inter-trial variability of context, with binary bindings under high saliency and variability (Qiu et al., 2022a, 2022b). And the way contexts are bound might be more generally dependent on the amount of attention it receives (Frings & Rothermund, 2017; Schmalbrock & Frings, 2022).

If the external context is constant, as is the stimulus modality in Article 5, this does not seem to influence the occurrence of response-response binding effects, which is in line with previous studies finding binding effects independent of, and across stimulus modalities (e.g., Moeller et al., 2012; Schöpper et al., 2020; Wesslein et al., 2019; Zmigrod et al., 2009; but see Möller et al., 2016; Schöpper & Frings, 2022). We cannot ascertain whether that means that the constant external context did not become part of the event representation, for example, because it did not receive sufficient attention (e.g., Chao, 2009; Frings & Rothermund, 2017; Qiu et al., 2022a) or whether it was represented, but did not affect binding effects.

How an internal context, such as an instructed speed-accuracy focus, is represented is not entirely clear. Findings from Article 4 are in line with the existing literature, showing that instructions can influence binding effects (Dreisbach & Haider, 2008; Eder & Dignath, 2017; Memelink & Hommel, 2005). The speed-accuracy instructions in particular probably induced a shift in cognitive control parameters (Heitz

& Engle, 2007; Memelink & Hommel, 2013), thus affecting the amount of partial repetition costs. The instructed control parameters in Article 4 were held constant over the course of the experiment and would thus probably be represented somewhat globally (Memelink & Hommel, 2013). However, cognitive control parameters might also fluctuate during an experiment (e.g., Foerster, Schiltenwolf, et al., 2022; Logan & Gordon, 2001). Previous findings show that non-instructed cognitive control parameters can become part of an event representation and affect the occurrence of binding effects by binding to an external stimulus context, leading to their retrieval if the context repeats (binding of *control states*, Dignath et al., 2019; Dignath & Kiesel, 2021; Egner, 2014; see also Spapé & Hommel, 2008). For all we know, this might have also happened in Article 2: Besides possibly being integrated into the event representation, the external stimulus context might have also been associated with a certain set of cognitive control parameters that might have changed or repeated alongside the context. However, further research is necessary to see if that was the case. Lastly, more recent studies also indicate that specific stimuli and cognitive control parameters can form binary bindings, leading to *stimulus-control bindings* (Whitehead et al., 2020, 2022).

These findings are part of a broader line of research indicating that the structure of bindings in event representations is not limited to binary bindings of specific stimulus features, but that contexts, cognitive control parameters, as well as, for example, complex objects (Moeller et al., 2016), abstract concepts (Frings et al., 2013; Horner & Henson, 2011; Singh et al., 2019), or even abstract parts of responses, such as stimulus classifications (Horner & Henson, 2009; Moutsopoulou & Waszak, 2012; Pfeuffer et al., 2017) can become part of event representations and affect action control. Besides instructions (Article 4) and stimulus modality (Article 5), a globally represented context might also be influenced by interindividual differences, for example in age (Dilcher et al., 2021; Giesen et al., 2015; Hommel et al., 2011; Strobach & Huestegge, 2021), intelligence (Colzato et al., 2006), or neurodevelopmental disposition (Kleimaker et al., 2020; Mielke et al., 2021; Zmigrod et al., 2013). While there is a growing number of studies on the role of context changes (i.e., contexts that change within or between trials) on binding, especially the role of globally, trial unspecific represented contexts might require more research.

5.2 *Cutting* vs. *Gluing*: The ending and structure of event representations

At first glance, it seems like the segmentation of complex behavior into smaller units and the idea of binding smaller units into more complex actions are two sides of the same coin. While these approaches share similarities, I argue that modulating binding between features is not necessarily equivalent to (event) segmentation, but that it is important to differentiate between modulators that cause the ending of a representation from modulators affecting the structure and strength of representations. Event segmentation, that is, where to *cut* behavior into episodes, might be related to the ending of action representations. And thus, some modulators theorized to cause event segmentation, such as predictability, might also influence the ending of binding episodes. In contrast, there might be a different set of modulators that affect the strength and structure of event representations by influencing which features are *glued* into the same episode, such as, for example, spatial relations of features. Thus, the following section aims to disentangle the ideas of segmentation or *cutting* behavior into episodes, as a mechanism indicating the end of representations, from factors that influence which features are *glued* into the same episode, affecting the structure and strength of event representations.

5.2.1 Where to cut: Predictability and ending of events

In the binding literature, the question of where an action or event ends is a debated one. It is often assumed that effects end actions, meaning that they close action representations; this is however not the case for action effects that occur in the environment (e.g., tones or stimuli that appear upon response execution) but might be the case for action effects that are body-related[6] (e.g., the sensation of keypresses; Frings, Selimi, et al., 2022). Body-related effects might end action representations that contain only an individual response (event files), but they cannot explain where response-response binding episodes end: When executing a response-response binding sequence, body-related action effects are experienced throughout the whole sequence after every response and still, this does not hinder binding between responses. Results of Article 3 are in line with this argumentation, indicating that neither body-related effects (that are always present and difficult to manipulate; but see Mocke et al., 2020) nor the introduction of environment-related effects prevented binding between responses.

However, it could be that rather than the occurrence of effects, it is their anticipation that plays a role in closing event files. Event files might be closed through a lack of predictability of what happens next, which can arise if a certain amount of features change (which can be an effect of our actions or not). The ideomotor principle already proposed the relevance of anticipating outcomes of our actions (Prinz, 1992, 1997), and we code actions in the prediction of what is to happen next, which has implications for how we perceive, think about, and produce actions (Schütz-Bosbach

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[6] For a review on the difference of body-related and environment-related action effects, see Pfister (2019).

& Prinz, 2007). Moreover, findings from Kunde et al. (2017) indicate that we code actions in terms of intended perceptual *changes*, that is, as the difference between what we perceive currently and what we will perceive in the future. This fits in with Event Segmentation Theory, which proposes that ending an event, and thus event segmentation occurs when feature changes lead to an increased prediction error, which causes event model updating (Kurby & Zacks, 2008; Zacks et al., 2007; Zacks et al., 2011).[7] Taken together, this suggests that event segmentation may correspond to the closing of action episodes as defined by binding, that is, to the closing of event files or response-response episodes. If so, predictability should play a role in ending an event. For binding effects that would mean that integration stops (or is at least affected) if the next event is unpredictable so that features are no longer integrated when an event has ended. To the best of my knowledge, findings to date cannot completely ascertain whether this assumption is accurate, because we would need to test what happens after a change that impairs predictability. Thus, we would need to introduce such a change within a prime or probe and look at whether the information presented after the change is still integrated. Some studies tackled the role of predictability on binding effects by manipulating the predictability of context changes (Qiu et al., 2022a) or distractors (Schmalbrock, Frings, & Moeller, 2022; Schmalbrock, Hommel, et al., 2022), showing that predictability has an influence, especially on retrieval of stimulus information, with unpredictability leading to more retrieval. While they establish predictability as a modulator of binding effects, these experiments focus on the integration and retrieval of individual responses with simultaneously presented

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[7] Note that also other theories propose the coding of actions in regard to prediction and errors thereof, for example, the predictive coding framework (e.g., Friston, 2012).

stimulus information and thus cannot reveal whether predictability influences the ending of events.

A previous study by Spapé and Hommel (2008) discussed the role of context changes in event segmentation. In their study, conflict in the prime affected performance in the probe only if the context (an irrelevant stimulus feature) was repeated, and not if it was changed. They discuss two possible explanations for these findings: (1) Context features might have been integrated into the event during the prime and could thus act as an additional retrieval cue in the probe (Spapé & Hommel, 2008; see also Frings et al., 2020). It is also possible that (2) context changes after the prime induced the closing of the current event representation, leading to event segmentation (Spapé & Hommel, 2008). Segmentation then potentially leads to the inhibition of the event representation built in the prime, affecting performance in the probe (Spapé & Hommel, 2008). While the first explanation is in line with recent findings from the binding literature (see chapters 4.2 and 5.1.3), there are aspects of the second explanation that need further specification. As we do not know where a representation ends (e.g., Frings, Selimi, et al., 2022), and integration and retrieval can occur simultaneously (Moeller & Frings, 2022), we cannot say whether the context change in the study of Spapé and Hommel (2008) closed the event representation (and led to event segmentation) after the prime or not, because it was not investigated whether further features can be integrated. In that, the findings of Spapé and Hommel (2008) are similar to findings from Article 2 (chapter 4.2), where we again cannot ascertain whether it was the context change after the prime that closed the event representation because we did not measure whether further responses can be integrated after the second prime response. Context changes can induce changes in cognitive control (e.g., Dignath et al., 2019; Egner, 2014; see also chapter 5.1.3) and thus, they are likely relevant for event segmentation. But a look at the binding literature suggests that context changes alone might not be sufficient to induce event segmentation. In binding paradigms, context changes are quite common: There often are feature changes even between every response of a trial, for example, changes in stimulus identity (e.g., Frings et al., 2007; Moeller & Frings, 2019c; Articles 2 & 3) or even tasks (e.g., Moeller & Frings, 2019b; Articles 1 & 4). In fact, in most binding experiments, there are multiple feature changes between each display. And despite all these changes, bindings of different complexity and different timescales, such as stimulus-response and response-response bindings, occur and even co-exist (Moeller & Frings, 2022), indicating that context, or more generally, feature changes alone might not end events.

Additionally, Spapé and Hommel (2008) did not differentiate between predictable and unpredictable context changes. It is open to debate whether context changes in their experiment (realized through a task-irrelevant stimulus feature that changed randomly, but balanced between two possible characteristics) as well as in many other binding experiments (e.g., Laub & Frings, 2020; Mayr et al., 2018; Qiu et al., 2022a), are perceived as unpredictable or not. I propose that the predictability of context changes, or feature changes more generally, might be relevant for our cognitive system to determine whether to segment an action. Context changes might be sufficient to terminate events, but only if they sufficiently impair the predictability of what happens next. If they do not impair predictability, then they might not end an event (stopping integration), but they could still be integrated as an additional retrieval cue and thus affect binding effects (which is in line with the first explanation given by Spapé & Hommel, 2008). The role of context change predictability is somewhat speculative but might be combined with the experimental suggestions from before. One could introduce predictable, as well as unpredictable context changes (or more generally feature changes) between two prime and/or two probe responses in a response-response binding paradigm and test whether these context changes affect response-response binding. If predictable and/or unpredictable context changes lead to event segmentation, and thus prevent integration of prime responses, we should observe no response-response binding effects. If they do not lead to event segmentation, and thus they do not disrupt the integration of responses, response-response binding effects should not differ compared to conditions without context changes. Alternatively, context changes might also influence the perceived relation of responses, affecting the strength of response-response bindings similarly to modulations of spatial separation (Articles 1, 2, & 3).

However, further research is necessary regarding how much feature change is needed (for example, see Schöpper et al., 2020; Singh et al., 2016), and especially how much unpredictable feature change is needed for event segmentation to occur. In Event Segmentation Theory, the end of an event depends on the interplay of changes in sensory information contributing to prediction error, *and* the threshold of how much prediction error is necessary to cause event model updating (Flores et al., 2017; Kurby & Zacks, 2008). This implies that two different approaches can be taken to further investigate how much predictability is necessary: (1) It is possible to manipulate the amount and predictability of feature changes that are contributing to prediction error and (2) it can be further investigated what influences the threshold that prediction error needs to surpass to end an event. While amount and predictability of feature changes can be easily modulated, for example by using a bigger pool of stimuli and/or responses, or by varying the proportions of feature changes (e.g., Pfeuffer et al., 2020; Qiu et al., 2022a; Schmalbrock, Frings, & Moeller, 2022), modulating the threshold might be more complex. The threshold is probably related to the grain size of segmentation: If we focus on finely-grained events, we should have a lower threshold in how much change we tolerate before prediction error becomes too large and causes event segmentation than when we focus on more coarse-grained events. In the context of binding experiments, grain size could be manipulated by instructing different action goals that focus on actions of different complexity (i.e., instructions that focus on individual responses or on a sequence of responses). In addition, both approaches together could probably be modeled via drift-diffusion (e.g., Ratcliff, 1978; Ratcliff et al., 2016; Ratcliff & Rouder, 2000), where the amount of feature changes corresponds to prediction error accumulation (modeled as the drift rate v), while the grain size (which might be modulated by instructions) determines the threshold (a) when to update the event model, leading to segmentation. Note that recently, drift-diffusion modeling has been applied to investigate the role of event boundaries (Michelmann et al., 2023), and of prediction errors (Yazin et al., 2021) for memory scanning, but has, to the best of my knowledge, not yet been used to model processes during segmentation of observed or produced behavior. Overall, findings from Event Segmentation Theory and the literature related to binding suggest that the predictability of what happens next might be an important factor influencing where events end and thus should be researched further, especially in combination with response-response binding.

5.2.2 Gluing together: Space and the structure of event representations

The idea of unpredictability as what ends events might apply to binding effects, but this needs further investigation. However, it might be that somewhat independent from what makes us segment or *cut* behavior into episodes, there are factors that determine what and how strongly we *glue* features into an event representation –

factors that affect the integration and retrieval of features without being related to the ending of events. The spatial organization of features might be such a factor: In Article 1, the spatial response relation affected the strength of binding between responses, with stronger binding effects for separated than for non-separated responses. This also indicates that spatial separation is not related to segmentation, that is, the ending of events: If spatial separation had caused the ending of an event, this would have stopped the integration of prime responses. In this case, we should have observed no more response-response binding effects. Further support for the idea that the spatial organization of features might be a *gluing* factor comes from studies on distractor-response binding. In these studies, the spatial organization of co-occurring target and distractor stimuli directly affected whether distractors became part of the event (e.g., Frings & Rothermund, 2011; Laub et al., 2018; Moeller et al., 2012), whereas binding between targets and responses occurred irrespective of distractors (Frings & Moeller, 2012; e.g., Frings, Moeller, et al., 2022; Giesen & Rothermund, 2014). This indicates that an event representation was built containing target and response, while spatial relation only influenced whether additional features (the co-occurring distractor) also became part of the same representation or not. Space probably affects feature integration and retrieval in multiple ways. In line with Gestalt principles (see Wagemans et al., 2012), space can affect the perceived relatedness of features (influencing binding effects; Frings & Rothermund, 2011; Moeller et al., 2012; Schmalbrock, Kiesel, & Frings, 2022) and thus how discriminable they are (Lakens et al., 2011; Nett & Frings, 2014; Wesslein et al., 2015). Also, space might impact the amount of attention features receive (Moeller & Frings, 2015; Schmalbrock & Frings, 2022), which seems to be a prerequisite for binding effects (Hommel et al., 2014; Moeller & Frings, 2014; Singh et al., 2018; but see Hommel, 2005). Interestingly, these findings show that space not only affects action control when manipulating stimulus features (e.g., Frings & Rothermund, 2011), but also response features (e.g., Lakens et al., 2011; see also Article 1), and that spatial influences are not limited to visual features, but also relevant to tactile (Wesslein et al., 2015) or auditory features (Moeller et al., 2012).

It makes sense that spatial organization alone affects, but not ends event representations, as the spatial organization of features influences how we interact with our environment. That is, it helps determine important movement parameters like where a movement is started and directed to, but it does usually not change whether we execute an action. Space may, for example, determine whether we represent the bottle that is standing next to the coffee mug we want to grab as part of the action or not. If the bottle is in the way, it affects the ‘reaching for the coffee mug’-action and is thus probably integrated into the event representation. If the bottle is spatially separate from the mug, it likely does not interfere with action execution and does not need to be represented. Likewise, if we have several responses, then their spatial relation may influence whether we can execute them sequentially more easily or not (like in the example of preparing a burger, chapter 4.1), thus affecting binding effects. However, this can be independent of whether an event ends because even spatially distant responses can belong to the same event. Further research is needed to determine whether it is feasible to distinguish between predictability, which could terminate or *cut* events, and *gluing* factors, which could modulate the structure and strength of event representations.

6. Conclusion

Research on the cognitive representation of actions often focuses on either very broad everyday actions (Zacks & Swallow, 2007) or very fine-grained individual responses (Hommel et al., 2001), and both approaches have their strengths and weaknesses. What both approaches cannot answer on their own, is how cognitive representations of hierarchical actions are structured. This dissertation aimed to broaden the understanding of this structuring by investigating more complex bindings between individual responses (Moeller & Frings, 2019b) and by identifying the contribution of individual action components on what the structure of a hierarchical action looks like and where such an action ends. In line with general assumptions on action representation, bindings are probably organized in a hierarchy of binary bindings, with response-response binding on a higher level of representation and bindings with stimulus and effect features on a lower level. Contexts can affect and can even become part of response-response binding representations, although the way they can be represented from a structural standpoint needs more investigation. Moreover, especially for increasingly complex actions, it may be important to distinguish factors that influence the strength and structure of action representations from factors that determine where an action representation ends.

References

Bailey, H. R., Kurby, C. A., Giovannetti, T., & Zacks, J. M. (2013). Action perception predicts action performance. *Neuropsychologia*, *51*(11), 2294–2304. https://doi.org/10.1016/j.neuropsychologia.2013.06.022

Botvinick, M. M. (2008). Hierarchical models of behavior and prefrontal function. *Trends in Cognitive Sciences*, *12*(5), 201–208. https://doi.org/10.1016/j.tics.2008.02.009

Chao, H.-F. (2009). Revisiting the prime–probe contextual similarity effect on negative priming: The impact of cue variability. *European Journal of Cognitive Psychology*, *21*(4), 484–500. https://doi.org/10.1080/09541440802049051

Colzato, L. S., van Wouwe, N. C., Lavender, T. J., & Hommel, B. (2006). Intelligence and cognitive flexibility: Fluid intelligence correlates with feature "unbinding" across perception and action. *Psychonomic Bulletin & Review*, *13*(6), 1043–1048. https://doi.org/10.3758/BF03213923

Crump, M. J. C., & Logan, G. D. (2010). Warning: This keyboard will deconstruct--the role of the keyboard in skilled typewriting. *Psychonomic Bulletin & Review*, *17*(3), 394–399. https://doi.org/10.3758/PBR.17.3.394

Dignath, D., Johannsen, L., Hommel, B., & Kiesel, A. (2019). Reconciling cognitive-control and episodic-retrieval accounts of sequential conflict modulation: Binding of control-states into event-files. *Journal of Experimental Psychology: Human Perception and Performance*, *45*(9), 1265–1270. https://doi.org/10.1037/xhp0000673

Dignath, D., & Kiesel, A. (2021). Further Evidence for the Binding and Retrieval of Control-States From the Flanker Task. *Experimental Psychology*, *68*(5), 264–273. https://doi.org/10.1027/1618-3169/a000529

Dilcher, R., Jamous, R., Takacs, A., Tóth-Fáber, E., Münchau, A., Li, S.-C., & Beste, C. (2021). Neurophysiology of embedded response plans: Age effects in action execution but not in feature integration from preadolescence to adulthood. *Journal of Neurophysiology*, *125*(4), 1382–1395. https://doi.org/10.1152/jn.00681.2020

Dinstein, I., Hasson, U., Rubin, N., & Heeger, D. J. (2007). Brain areas selective for both observed and executed movements. *Journal of Neurophysiology*, *98*(3), 1415–1427. https://doi.org/10.1152/jn.00238.2007

Dreisbach, G., & Haider, H. (2008). That's what task sets are for: Shielding against irrelevant information. *Psychological Research*, *72*(4), 355–361. https://doi.org/10.1007/s00426-007-0131-5

Eder, A. B., & Dignath, D. (2017). Influence of verbal instructions on effect-based action control. *Psychological Research*, *81*(2), 355–365. https://doi.org/10.1007/s00426-016-0745-6

Egner, T. (2014). Creatures of habit (and control): A multi-level learning perspective on the modulation of congruency effects. *Frontiers in Psychology*, *5*, 1247. https://doi.org/10.3389/fpsyg.2014.01247

Flores, S., Bailey, H. R., Eisenberg, M. L., & Zacks, J. M. (2017). Event segmentation improves event memory up to one month later. *Journal of Experimental Psychology. Learning, Memory, and Cognition*, *43*(8), 1183–1202. https://doi.org/10.1037/xlm0000367

Foerster, A., Moeller, B., Huffman, G., Kunde, W., Frings, C., & Pfister, R. (2022). The human cognitive system corrects traces of error commission on the fly. *Journal of Experimental Psychology. General*, *151*(6), 1419–1432. https://doi.org/10.1037/xge0001139

Foerster, A., Schiltenwolf, M., Dignath, D., & Pfister, R. (2022). Binding Error-Induced Control States. *Journal of Cognition*, *5*(1), 24. https://doi.org/10.5334/joc.213

Frings, C. (2011). On the decay of distractor-response episodes. *Experimental Psychology*, *58*(2), 125–131. https://doi.org/10.1027/1618-3169/a000077

Frings, C., Hommel, B., Koch, I., Rothermund, K., Dignath, D., Giesen, C., Kiesel, A., Kunde, W., Mayr, S., Moeller, B., Möller, M., Pfister, R., & Philipp, A. (2020). Binding and Retrieval in Action Control (BRAC). *Trends in Cognitive Sciences*, *24*(5), 375–387. https://doi.org/10.1016/j.tics.2020.02.004

Frings, C., & Moeller, B. (2012). The horserace between distractors and targets: Retrieval-based probe responding depends on distractor–target asynchrony. *Journal of Cognitive Psychology*, *24*(5), 582–590. https://doi.org/10.1080/20445911.2012.666852

Frings, C., Moeller, B., Beste, C., Münchau, A., & Pastötter, B. (2022). Stimulus decay functions in action control. *Scientific Reports*, *12*(1), 20139. https://doi.org/10.1038/s41598-022-24499-6

Frings, C., Moeller, B., & Rothermund, K. (2013). Retrieval of event files can be conceptually mediated. *Attention, Perception, & Psychophysics*, *75*(4), 700–709. https://doi.org/10.3758/s13414-013-0431-3

Frings, C., & Rothermund, K. (2011). To be or not to be…Included in an event file: Integration and retrieval of distractors in stimulus-response episodes is influenced by perceptual grouping. *Journal of Experimental Psychology. Learning, Memory, and Cognition*, *37*(5), 1209–1227. https://doi.org/10.1037/a0023915

Frings, C., & Rothermund, K. (2017). How perception guides action: Figure-ground segmentation modulates integration of context features into S-R episodes.

Journal of Experimental Psychology: Learning, Memory, and Cognition, *43*(11), 1720–1729. https://doi.org/10.1037/xlm0000403

Frings, C., Rothermund, K., & Wentura, D. (2007). Distractor repetitions retrieve previous responses to targets. *Quarterly Journal of Experimental Psychology*, *60*(10), 1367–1377. https://doi.org/10.1080/17470210600955645

Frings, C., Selimi, S., Soballa, P., & Weissman, D. (2022). *Effect-less? Event-files are not terminated by action effects* [Manuscript submitted for publication]. Department of Psychology, Trier University, Department of Psychology, University of Michigan.

Friston, K. (2012). Prediction, perception and agency. *International Journal of Psychophysiology : Official Journal of the International Organization of Psychophysiology*, *83*(2), 248–252. https://doi.org/10.1016/j.ijpsycho.2011.11.014

Geissler, C. F., Frings, C., & Moeller, B. (2021). Illuminating the prefrontal neural correlates of action sequence disassembling in response-response binding. *Scientific Reports*, *11*(1), 22856. https://doi.org/10.1038/s41598-021-02247-6

Geissler, C. F., Selimi, S., Schmalbrock, P., Frings, C., & Moeller, B. (2023). *Bindings in Working Memory: Evidence for Content Independent Superposition* [Manuscript in preparation]. Department of Psychology, Trier University.

Giesen, C., Eberhard, M., & Rothermund, K. (2015). Loss of attentional inhibition in older adults--Does it really exist? An experimental dissociation of inhibitory and memory retrieval processes. *Psychology and Aging*, *30*(2), 220–231. https://doi.org/10.1037/pag0000022

Giesen, C., & Rothermund, K. (2014). Distractor repetitions retrieve previous responses and previous targets: Experimental dissociations of distractor-response and distractor-target bindings. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, *40*(3), 645–659. https://doi.org/10.1037/a0035278

Gold, D. A., Zacks, J. M., & Flores, S. (2017). Effects of cues to event segmentation on subsequent memory. *Cognitive Research: Principles and Implications*, *2*(1), 1. https://doi.org/10.1186/s41235-016-0043-2

Grant, L. D., Cookson, S. L., & Weissman, D. H. (2020). Task sets serve as boundaries for the congruency sequence effect. *Journal of Experimental Psychology: Human Perception and Performance*, *46*(8), 798–812. https://doi.org/10.1037/xhp0000750

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

Heitz, R. P., & Engle, R. W. (2007). Focusing the spotlight: Individual differences in visual attention control. *Journal of Experimental Psychology. General*, *136*(2), 217–240. https://doi.org/10.1037/0096-3445.136.2.217

Herwig, A. (2015). Linking perception and action by structure or process? Toward an integrative perspective. *Neuroscience and Biobehavioral Reviews*, *52*, 105–116. https://doi.org/10.1016/j.neubiorev.2015.02.013

Herwig, A., Beisert, M., & Prinz, W. (2013). Action Science Emerging: Introduction and Leitmotifs. In W. Prinz, M. Beisert, & A. Herwig (Eds.), *Action science: Foundations of an emerging discipline* (xii-33). MIT Press. https://doi.org/10.7551/mitpress/9780262018555.003.0001

Hommel, B. (1998). Event Files: Evidence for Automatic Integration of Stimulus-Response Episodes. *Visual Cognition*, *5*(1-2), 183–216. https://doi.org/10.1080/713756773

Hommel, B. (2004). Event files: Feature binding in and across perception and action. *Trends in Cognitive Sciences*, *8*(11), 494–500. https://doi.org/10.1016/j.tics.2004.08.007

Hommel, B. (2005). How much attention does an event file need? *Journal of Experimental Psychology: Human Perception and Performance*, *31*(5), 1067–1082. https://doi.org/10.1037/0096-1523.31.5.1067

Hommel, B., & Frings, C. (2020). The disintegration of event files over time: Decay or interference? *Psychonomic Bulletin & Review*, *27*(4), 751–757. https://doi.org/10.3758/s13423-020-01738-3

Hommel, B., Kray, J., & Lindenberger, U. (2011). Feature integration across the lifespan: Stickier stimulus-response bindings in children and older adults. *Frontiers in Psychology*, *2*, 268. https://doi.org/10.3389/fpsyg.2011.00268

Hommel, B., Memelink, J., Zmigrod, S., & Colzato, L. S. (2014). Attentional control of the creation and retrieval of stimulus-response bindings. *Psychological Research*, *78*(4), 520–538. https://doi.org/10.1007/s00426-013-0503-y

Hommel, B., Müsseler, J., Aschersleben, G., & Prinz, W. (2001). The Theory of Event Coding (TEC): A framework for perception and action planning. *The Behavioral and Brain Sciences*, *24*(5), 849-78; discussion 878-937. https://doi.org/10.1017/S0140525X01000103

Horner, A. J., Bisby, J. A., Wang, A., Bogus, K., & Burgess, N. (2016). The role of spatial boundaries in shaping long-term event representations. *Cognition*, *154*, 151–164. https://doi.org/10.1016/j.cognition.2016.05.013

Horner, A. J., & Henson, R. N. (2009). Bindings between stimuli and multiple response codes dominate long-lag repetition priming in speeded classification tasks. *Journal of Experimental Psychology. Learning, Memory, and Cognition*, *35*(3), 757–779. https://doi.org/10.1037/a0015262

Horner, A. J., & Henson, R. N. (2011). Stimulus-response bindings code both abstract and specific representations of stimuli: Evidence from a classification priming design that reverses multiple levels of response representation. *Memory & Cognition*, *39*(8), 1457–1471. https://doi.org/10.3758/s13421-011-0118-8

James, W. (1890). *The principles of psychology*. NY: Holt.

Kleimaker, M., Takacs, A., Conte, G., Onken, R., Verrel, J., Bäumer, T., Münchau, A., & Beste, C. (2020). Increased perception-action binding in Tourette syndrome. *Brain*, *143*(6), 1934–1945. https://doi.org/10.1093/brain/awaa111

Koechlin, E., & Jubault, T. (2006). Broca's area and the hierarchical organization of human behavior. *Neuron*, *50*(6), 963–974. https://doi.org/10.1016/j.neuron.2006.05.017

Kunde, W., Schmidts, C., Wirth, R., & Herbort, O. (2017). Action effects are coded as transitions from current to future stimulation: Evidence from compatibility effects in tracking. *Journal of Experimental Psychology: Human Perception and Performance*, *43*(3), 477–486. https://doi.org/10.1037/xhp0000311

Kurby, C. A., & Zacks, J. M. (2008). Segmentation in the perception and memory of events. *Trends in Cognitive Sciences*, *12*(2), 72–79. https://doi.org/10.1016/j.tics.2007.11.004

Kurby, C. A., & Zacks, J. M. (2022). Priming of movie content is modulated by event boundaries. *Journal of Experimental Psychology. Learning, Memory, and Cognition*, *48*(11), 1559–1570. https://doi.org/10.1037/xlm0001085

Lakens, D., Schneider, I. K., Jostmann, N. B., & Schubert, T. W. (2011). Telling things apart: The distance between response keys influences categorization times. *Psychological Science*, *22*(7), 887–890. https://doi.org/10.1177/0956797611412391

Lashley, K. S. (1951). The problem of serial order in behavior. In L. A. Jeffress (Ed.), *Cerebral mechanisms in behavior* (pp. 112–147).

Lassiter, G. D., Stone, J. I., & Rogers, S. L. (1988). Memorial consequences of variation in behavior perception. *Journal of Experimental Social Psychology*, *24*(3), 222–239. https://doi.org/10.1016/0022-1031(88)90037-6

Laub, R., & Frings, C. (2020). Distractor-based retrieval in action control: The influence of encoding specificity. *Psychological Research*, *84*(3), 765–773. https://doi.org/10.1007/s00426-018-1082-8

Laub, R., Frings, C., & Moeller, B. (2018). Dissecting stimulus-response binding effects: Grouping by color separately impacts integration and retrieval processes. *Attention, Perception & Psychophysics*, *80*(6), 1474–1488. https://doi.org/10.3758/s13414-018-1526-7

Lien, M.-C., & Ruthruff, E. (2004). Task switching in a hierarchical task structure: Evidence for the fragility of the task repetition benefit. *Journal of Experimental Psychology. Learning, Memory, and Cognition*, *30*(3), 697–713. https://doi.org/10.1037/0278-7393.30.3.697

Logan, G. D. (1988). Toward an instance theory of automatization. *Psychological Review*, *95*(4), 492–527. https://doi.org/10.1037/0033-295X.95.4.492

Logan, G. D. (2003). Simon-type effects: Chronometric evidence for keypress schemata in typewriting. *Journal of Experimental Psychology: Human Perception and Performance*, *29*(4), 741–757. https://doi.org/10.1037/0096-1523.29.4.741

Logan, G. D., & Crump, M. J. (2011). Hierarchical Control of Cognitive Processes. In B. H. Ross (Ed.), *Issn Ser: v.Volume 54. The Psychology of Learning and Motivation: Advances in Research and Theory* (1st ed., Vol. 54, pp. 1–27). Elsevier textbooks. https://doi.org/10.1016/B978-0-12-385527-5.00001-2

Logan, G. D., & Gordon, R. D. (2001). Executive control of visual attention in dual-task situations. *Psychological Review*, *108*(2), 393–434. https://doi.org/10.1037/0033-295x.108.2.393

Magliano, J. P., Miller, J., & Zwaan, R. A. (2001). Indexing space and time in film understanding. *Applied Cognitive Psychology*, *15*(5), 533–545. https://doi.org/10.1002/acp.724

Mattson, P. S., & Fournier, L. R. (2008). An action sequence held in memory can interfere with response selection of a target stimulus, but does not interfere with response activation of noise stimuli. *Memory & Cognition*, *36*(7), 1236–1247. https://doi.org/10.3758/MC.36.7.1236

Mayr, S., Möller, M., & Buchner, A. (2018). Contextual modulation of prime response retrieval processes: Evidence from auditory negative priming. *Attention, Perception, & Psychophysics*, *80*(8), 1918–1931. https://doi.org/10.3758/s13414-018-1574-z

Memelink, J., & Hommel, B. (2005). Attention, instruction, and response representation. *European Journal of Cognitive Psychology*, *17*(5), 674–685. https://doi.org/10.1080/09541440540000059

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

Michelmann, S., Hasson, U., & Norman, K. A. (2023). Evidence That Event Boundaries Are Access Points for Memory Retrieval. *Psychological Science*, 9567976221128206. https://doi.org/10.1177/09567976221128206

Mielke, E., Takacs, A., Kleimaker, M., Schappert, R., Conte, G., Onken, R., Künemund, T., Verrel, J., Bäumer, T., Beste, C., & Münchau, A. (2021). Tourette syndrome as a motor disorder revisited - Evidence from action coding. *NeuroImage. Clinical*, *30*, 102611. https://doi.org/10.1016/j.nicl.2021.102611

Miller, G. A., Galanter, E., & Pribram, K. H. (1960). *Plans and the structure of behavior*. Henry Holt and Co. https://doi.org/10.1037/10039-000

Mocke, V., Weller, L., Frings, C., Rothermund, K., & Kunde, W. (2020). Task relevance determines binding of effect features in action planning. *Attention, Perception, & Psychophysics*, *82*(8), 3811–3831. https://doi.org/10.3758/s13414-020-02123-x

Moeller, B., & Frings, C. (2014). Attention meets binding: Only attended distractors are used for the retrieval of event files. *Attention, Perception & Psychophysics*, *76*(4), 959–978. https://doi.org/10.3758/s13414-014-0648-9

Moeller, B., & Frings, C. (2015). Distractor-response bindings in dual task scenarios. *Visual Cognition*, *23*(4), 516–531. https://doi.org/10.1080/13506285.2015.1041437

Moeller, B., & Frings, C. (2019a). Binding processes in the control of nonroutine action sequences. *Journal of Experimental Psychology: Human Perception and Performance*, *45*(9), 1135–1145. https://doi.org/10.1037/xhp0000665

Moeller, B., & Frings, C. (2019b). From simple to complex actions: Response-response bindings as a new approach to action sequences. *Journal of Experimental Psychology: General*, *148*(1), 174–183. https://doi.org/10.1037/xge0000483

Moeller, B., & Frings, C. (2019c). Lost time: Bindings do not represent temporal order information. *Psychonomic Bulletin & Review*, *26*(1), 325–331. https://doi.org/10.3758/s13423-018-1493-y

Moeller, B., & Frings, C. (2019d). Response-response binding across effector-set switches. *Psychonomic Bulletin & Review*, *26*(6), 1974–1979. https://doi.org/10.3758/s13423-019-01669-8

Moeller, B., & Frings, C. (2021). Response-response bindings do not decay for 6 seconds after integration: A case for bindings' relevance in hierarchical action control. *Journal of Experimental Psychology: Human Perception and Performance*, *47*(4), 508–517. https://doi.org/10.1037/xhp0000897

Moeller, B., & Frings, C. (2022). All together now: Simultaneous feature integration and feature retrieval in action control. *Psychonomic Bulletin & Review*, *29*(2), 512–520. https://doi.org/10.3758/s13423-021-01999-6

Moeller, B., Frings, C., & Pfister, R. (2016). The structure of distractor-response bindings: Conditions for configural and elemental integration. *Journal of Experimental Psychology: Human Perception and Performance*, *42*(4), 464–479. https://doi.org/10.1037/xhp0000158

Moeller, B., Pfister, R., Kunde, W., & Frings, C. (2019). Selective binding of stimulus, response, and effect features. *Psychonomic Bulletin & Review*, *26*(5), 1627–1632. https://doi.org/10.3758/s13423-019-01646-1

Moeller, B., Rothermund, K., & Frings, C. (2012). Integrating the irrelevant sound. *Experimental Psychology*, *59*(5), 258–264. https://doi.org/10.1027/1618-3169/a000151

Möller, M., Mayr, S., & Buchner, A. (2016). The time-course of distractor processing in auditory spatial negative priming. *Psychological Research*, *80*(5), 744–756. https://doi.org/10.1007/s00426-015-0685-6

Moutsopoulou, K., & Waszak, F. (2012). Across-task priming revisited: Response and task conflicts disentangled using ex-Gaussian distribution analysis. *Journal of Experimental Psychology: Human Perception and Performance*, *38*(2), 367–374. https://doi.org/10.1037/a0025858

Moutsopoulou, K., & Waszak, F. (2013). Durability of classification and action learning: Differences revealed using ex-Gaussian distribution analysis. *Experimental Brain Research*, *226*(3), 373–382. https://doi.org/10.1007/s00221-013-3445-0

Nett, N., & Frings, C. (2014). Things can be told apart: No influence of response categories and labels on the distance effect in Stroop tasks. *Experimental Psychology*, *61*(2), 142–148. https://doi.org/10.1027/1618-3169/a000234

Newtson, D. (1973). Attribution and the unit of perception of ongoing behavior. *Journal of Personality and Social Psychology*, *28*(1), 28–38. https://doi.org/10.1037/h0035584

Newtson, D., Engquist, G. A., & Bois, J. (1977). The objective basis of behavior units. *Journal of Personality and Social Psychology*, *35*(12), 847–862. https://doi.org/10.1037/0022-3514.35.12.847

Pfeuffer, C. U., Moutsopoulou, K., Pfister, R., Waszak, F., & Kiesel, A. (2017). The power of words: On item-specific stimulus-response associations formed in the absence of action. *Journal of Experimental Psychology: Human Perception and Performance*, *43*(2), 328–347. https://doi.org/10.1037/xhp0000317

Pfeuffer, C. U., Moutsopoulou, K., Waszak, F., & Kiesel, A. (2020). Execution-based and verbal code-based stimulus-response associations: Proportion manipulations reveal conflict adaptation processes in item-specific priming. *Psychological Research*, *84*(8), 2172–2195. https://doi.org/10.1007/s00426-019-01220-3

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

Prinz, W. (1992). Why don't we perceive our brain states? *European Journal of Cognitive Psychology*, *4*(1), 1–20. https://doi.org/10.1080/09541449208406240

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

Qiu, R., Möller, M., Koch, I., & Mayr, S. (2022a). Inter-Trial Variability of Context Influences the Binding Structure in a Stimulus-Response Episode. *Journal of Cognition*, *5*(1), Article 25. https://doi.org/10.5334/joc.215

Qiu, R., Möller, M., Koch, I., & Mayr, S. (2022b). Saliency determines the integration of contextual information into stimulus-response episodes. *Attention,* *Perception, & Psychophysics*, *84*(4), 1264–1285. https://doi.org/10.3758/s13414-021-02428-5

Radvansky, G. A., & Copeland, D. E. (2006). Walking through doorways causes forgetting: Situation models and experienced space. *Memory & Cognition*, *34*(5), 1150–1156. https://doi.org/10.3758/BF03193261

Radvansky, G. A., & Zacks, J. M. (2014). *Event cognition*. Oxford University Press.

Ratcliff, R. (1978). A theory of memory retrieval. *Psychological Review*, *85*(2), 59–108. https://doi.org/10.1037/0033-295X.85.2.59

Ratcliff, R., & Rouder, J. N. (2000). A diffusion model account of masking in two-choice letter identification. *Journal of Experimental Psychology: Human Perception and Performance*, *26*(1), 127–140. https://doi.org/10.1037/0096-1523.26.1.127

Ratcliff, R., Smith, P. L., Brown, S. D., & McKoon, G. (2016). Diffusion Decision Model: Current Issues and History. *Trends in Cognitive Sciences*, *20*(4), 260–281. https://doi.org/10.1016/j.tics.2016.01.007

Richmond, L. L., & Zacks, J. M. (2017). Constructing Experience: Event Models from Perception to Action. *Trends in Cognitive Sciences*, *21*(12), 962–980. https://doi.org/10.1016/j.tics.2017.08.005

Rizzolatti, G., Fadiga, L., Gallese, V., & Fogassi, L. (1996). Premotor cortex and the recognition of motor actions. *Cognitive Brain Research*, *3*(2), 131–141. https://doi.org/10.1016/0926-6410(95)00038-0

Rosenbaum, D. A., Kenny, S. B., & Derr, M. A. (1983). Hierarchical control of rapid movement sequences. *Journal of Experimental Psychology: Human Perception and Performance*, *9*(1), 86–102. https://doi.org/10.1037/0096-1523.9.1.86

Rumelhart, D. E. (1980). Schemata: The building blocks of cognition. In R. J. Spiro, B. C. Bruce, & W. F. Brewer (Eds.), *Theoretical issues in reading comprehension:: Perspectives from cognitive psychology, linguistics, artificial intelligence, and education* (pp. 33–58). Erlbaum.

Rumelhart, D. E., & Ortony, A. (1977). The Representation of Knowledge in Memory. In R. C. Anderson, R. J. Spiro, & W. E. Montague (Eds.), *Schooling and the acquisition of knowledge* (pp. 97–135). Erlbaum.

Schmalbrock, P., & Frings, C. (2022). A mighty tool not only in perception: Figure-ground mechanisms control binding and retrieval alike. *Attention, Perception, & Psychophysics*, *84*(7), 2255–2270. https://doi.org/10.3758/s13414-022-02511-5

Schmalbrock, P., Frings, C., & Moeller, B. (2022). Pooling it all together – the role of distractor pool size on stimulus-response binding. *Journal of Cognitive Psychology*, *34*(2), 249–260. https://doi.org/10.1080/20445911.2022.2026363

Schmalbrock, P., Hommel, B., Münchau, A., Beste, C., & Frings, C. (2022). Predictability reduces event file retrieval. *Attention, Perception, & Psychophysics*, 1–15. https://doi.org/10.3758/s13414-022-02637-6

Schmalbrock, P., Kiesel, A., & Frings, C. (2022). What Belongs Together Retrieves Together – The Role of Perceptual Grouping in Stimulus-Response Binding and Retrieval. *Journal of Cognition*, *5*(1), Article 28. https://doi.org/10.5334/joc.217

Schneider, D. W., & Logan, G. D. (2006). Hierarchical control of cognitive processes: Switching tasks in sequences. *Journal of Experimental Psychology. General*, *135*(4), 623–640. https://doi.org/10.1037/0096-3445.135.4.623

Schöpper, L.-M., & Frings, C. (2022). Same, but different: Binding effects in auditory, but not visual detection performance. *Attention, Perception & Psychophysics.* Advance online publication. https://doi.org/10.3758/s13414-021-02436-5

Schöpper, L.-M., Köhler, R., Moeller, B., Baldes, M., & Frings, C. (2023). *Less than the sum of its parts: Repeating a component of an event file does not retrieve the whole previous event* [Manuscript in preparation]. Department of Psychology, Trier University.

Schöpper, L.-M., Singh, T., & Frings, C. (2020). The official soundtrack to “Five shades of grey”: Generalization in multimodal distractor-based retrieval. *Attention, Perception, & Psychophysics*, *82*(7), 3479–3489. https://doi.org/10.3758/s13414-020-02057-4

Schütz-Bosbach, S., & Prinz, W. (2007). Prospective coding in event representation. *Cognitive Processing*, *8*(2), 93–102. https://doi.org/10.1007/s10339-007-0167-x

Sebastian, K., Ghose, T., Zacks, J. M., & Huff, M. (2017). Understanding the Individual Cognitive Potential of Persons with Intellectual Disability in Workshops for Adapted Work. *Applied Cognitive Psychology*, *31*(2), 175–186. https://doi.org/10.1002/acp.3315

Singh, T., Frings, C., & Moeller, B. (2019). Binding abstract concepts. *Psychological Research*, *83*(5), 878–884. https://doi.org/10.1007/s00426-017-0897-z

Singh, T., Moeller, B., & Frings, C. (2016). Five shades of grey: Generalization in distractor-based retrieval of S-R episodes. *Attention, Perception, & Psychophysics*, *78*(8), 2307–2312. https://doi.org/10.3758/s13414-016-1210-8

Singh, T., Moeller, B., Koch, I., & Frings, C. (2018). May I have your attention please: Binding of attended but response-irrelevant features. *Attention, Perception & Psychophysics*, *80*(5), 1143–1156. https://doi.org/10.3758/s13414-018-1498-7

Snyder, K. M., Logan, G. D., & Yamaguchi, M. (2015). Watch what you type: The role of visual feedback from the screen and hands in skilled typewriting. *Attention, Perception, & Psychophysics*, *77*(1), 282–292. https://doi.org/10.3758/s13414-014-0756-6

Spapé, M. M., & Hommel, B. (2008). He said, she said: Episodic retrieval induces conflict adaptation in an auditory Stroop task. *Psychonomic Bulletin & Review*, *15*(6), 1117–1121. https://doi.org/10.3758/PBR.15.6.1117

Stoet, G., & Hommel, B. (1999). Action planning and the temporal binding of response codes. *Journal of Experimental Psychology: Human Perception and Performance*, *25*(6), 1625–1640. https://doi.org/10.1037/0096-1523.25.6.1625

Strobach, T., & Huestegge, L. (2021). Structuralist Mental Representation of Dual-action Demands: Mechanisms of Improved Dual-task Performance after Practice in Older Adults. *Experimental Aging Research*, *47*(2), 109–130. https://doi.org/10.1080/0361073X.2021.1873053

Treisman, A. M. (1992). Perceiving and re-perceiving objects. *American Psychologist*, *47*(7), 862–875. https://doi.org/10.1037/0003-066x.47.7.862

Treisman, A. M., & Gelade, G. (1980). A feature-integration theory of attention. *Cognitive Psychology*, *12*(1), 97–136. https://doi.org/10.1016/0010-0285(80)90005-5

Uithol, S., van Rooij, I., Bekkering, H., & Haselager, P. (2012). Hierarchies in action and motor control. *Journal of Cognitive Neuroscience*, *24*(5), 1077–1086. https://doi.org/10.1162/jocn_a_00204

Vallacher, R. R., & Wegner, D. M. (1987). What do people think they're doing? Action identification and human behavior. *Psychological Review*, *94*(1), 3–15. https://doi.org/10.1037/0033-295X.94.1.3

van Dam, W. O., & Hommel, B. (2010). How object-specific are object files? Evidence for integration by location. *Journal of Experimental Psychology: Human Perception and Performance*, *36*(5), 1184–1192. https://doi.org/10.1037/a0019955

Wagemans, J., Elder, J. H., Kubovy, M., Palmer, S. E., Peterson, M. A., Singh, M., & Heydt, R. von der (2012). A century of Gestalt psychology in visual perception: I. Perceptual grouping and figure-ground organization. *Psychological Bulletin*, *138*(6), 1172–1217. https://doi.org/10.1037/a0029333

Wesslein, A.-K., Moeller, B., Frings, C., & Giesen, C. (2019). Separating after-effects of target and distractor processing in the tactile sensory modality. *Attention, Perception, & Psychophysics*, *81*(3), 809–822. https://doi.org/10.3758/s13414-018-01655-7

Wesslein, A.-K., Spence, C., & Frings, C. (2015). You can't ignore what you can't separate: The effect of visually induced target-distractor separation on tactile selection. *Psychonomic Bulletin & Review*, *22*(3), 728–736. https://doi.org/10.3758/s13423-014-0738-7

Whitehead, P. S., Pfeuffer, C. U., & Egner, T. (2020). Memories of control: One-shot episodic learning of item-specific stimulus-control associations. *Cognition*, *199*, 104220. https://doi.org/10.1016/j.cognition.2020.104220

Whitehead, P. S., Pfeuffer, C. U., & Egner, T. (2022). Assessing the Durability of One-Shot Stimulus-Control Bindings. *Journal of Cognition*, *5*(1), 26. https://doi.org/10.5334/joc.218

Yang, G., Nan, W., Zheng, Y., Wu, H., Li, Q., & Liu, X. (2017). Distinct cognitive control mechanisms as revealed by modality-specific conflict adaptation effects. *Journal of Experimental Psychology: Human Perception and Performance*, *43*(4), 807–818. https://doi.org/10.1037/xhp0000351

Yazin, F., Das, M., Banerjee, A., & Roy, D. (2021). *Contextual Prediction Errors Reorganize Naturalistic Episodic Memories in Time*. Research Square Platform LLC. https://doi.org/10.21203/rs.3.rs-146158/v1

Zacks, J. M. (2004). Using movement and intentions to understand simple events. *Cognitive Science*, *28*(6), 979–1008. https://doi.org/10.1207/s15516709cog2806_5

Zacks, J. M., Braver, T. S., Sheridan, M. A., Donaldson, D. I., Snyder, A. Z., Ollinger, J. M., Buckner, R. L., & Raichle, M. E. (2001). Human brain activity time-locked to perceptual event boundaries. *Nature Neuroscience*, *4*(6), 651–655. https://doi.org/10.1038/88486

Zacks, J. M., Kurby, C. A., Eisenberg, M. L., & Haroutunian, N. (2011). Prediction error associated with the perceptual segmentation of naturalistic events. *Journal of Cognitive Neuroscience*, *23*(12), 4057–4066. https://doi.org/10.1162/jocn_a_00078

Zacks, J. M., Speer, N. K., Swallow, K. M., Braver, T. S., & Reynolds, J. R. (2007). Event perception: A mind-brain perspective. *Psychological Bulletin*, *133*(2), 273–293. https://doi.org/10.1037/0033-2909.133.2.273

Zacks, J. M., Speer, N. K., Vettel, J. M., & Jacoby, L. L. (2006). Event understanding and memory in healthy aging and dementia of the Alzheimer type. *Psychology and Aging*, *21*(3), 466–482. https://doi.org/10.1037/0882-7974.21.3.466

Zacks, J. M., & Swallow, K. M. (2007). Event Segmentation. *Current Directions in Psychological Science*, *16*(2), 80–84. https://doi.org/10.1111/j.1467-8721.2007.00480.x

Zacks, J. M., Swallow, K. M., Vettel, J. M., & McAvoy, M. P. (2006). Visual motion and the neural correlates of event perception. *Brain Research*, *1076*(1), 150–162. https://doi.org/10.1016/j.brainres.2005.12.122

Zacks, J. M., & Tversky, B. (2001). Event structure in perception and conception. *Psychological Bulletin*, *127*(1), 3–21. https://doi.org/10.1037/0033-2909.127.1.3

Zacks, J. M., Tversky, B., & Iyer, G. (2001). Perceiving, remembering, and communicating structure in events. *Journal of Experimental Psychology: General*, *130*(1), 29–58. https://doi.org/10.1037//0096-3445.130.1.29

Zmigrod, S., & Hommel, B. (2013). Feature integration across multimodal perception and action: A review. *Multisensory Research*, *26*(1-2), 143–157. https://doi.org/10.1163/22134808-00002390

Zmigrod, S., Sonneville, L. M. J. de, Colzato, L. S., Swaab, H., & Hommel, B. (2013). Cognitive control of feature bindings: Evidence from children with autistic spectrum disorder. *Psychological Research*, *77*(2), 147–154. https://doi.org/10.1007/s00426-011-0399-3

Zmigrod, S., Spapé, M., & Hommel, B. (2009). Intermodal event files: integrating features across vision, audition, taction, and action. *Psychological Research*, *73*(5), 674–684. https://doi.org/10.1007/s00426-008-0163-5

Publication Record

Journal articles (peer-reviewed) and submitted manuscripts

Frings, C., Selimi, S., Soballa, P., & Weissman, D. (2022). *Effect-less? Event-files are not terminated by action effects.* Manuscript submitted for publication.

Selimi, S., Frings, C., & Moeller, B. (2022). *Separated hands further response-response binding effects.* Manuscript submitted for publication.

Selimi, S., Frings, C., & Moeller, B. (2022). Binding between Responses Is Not Modulated by Grouping of Response Effects. *Journal of Cognition*, *5*(1), Article 42. https://doi.org/10.5334/joc.233

Selimi, S., Frings, C., Münchau, A., Beste, C., & Moeller, B. (2022). *It's not distance but similarity of distance: Changing stimulus relations affect the control of action sequences.* Manuscript submitted for publication.

Selimi, S., & Moeller, B. (2022). *Instructed speed and accuracy affect binding.* Manuscript submitted for publication.

Manuscripts in preparation

Selimi, S., Frings, C., & Moeller, B. (2023). *Does the modality matter? Binding between responses generalizes to auditory tasks.* Manuscript in preparation.

Geißler, C. F., Selimi, S., Schmalbrock, P., Frings, C., & Moeller, B. (2023*). Bindings in Working Memory: Evidence for Content Independent Superposition.* Manuscript in preparation.

Note: Manuscripts printed in bold are part of this dissertation

Declaration of Authorship / Eigenständigkeitserklärung

I hereby certify that this thesis has been composed by me and is based on my own work unless stated otherwise. No other person’s work has been used without due acknowledgment in this thesis. All references have been quoted and all sources have been mentioned.

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