

The Role of Context in Stimulus-Response

Binding and Retrieval

Dissertation for the purpose of obtaining the degree of “Dr. phil.”

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By Ruyi Qiu

Primary supervisor: Prof. Dr. Susanne Mayr

Second supervisor: Prof. Dr. Judith Schweppe

PhD candidate: Ruyi Qiu

Ruyi.Qiu@uni-passau.de

Kapuzinerstraße 71a, 94032, Passau

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Preface

This dissertation is comprised of three research articles (two of which have been published in scientific journals and the remaining one is under review), accompanied by a general introduction and a general discussion. The three research articles are:

Chapter 2 (Study One): Qiu, R., Möller, M., Koch, I., & Mayr, S. (2022). 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>

Chapter 3 (Study Two): Qiu, R., Möller, M., Koch, I., & Mayr, S. (2022). Inter-trial variability of context influences the binding structure in a stimulus-response episode. *Journal of Cognition*, 5(1), 25. <http://doi.org/10.5334/joc.215>

Chapter 4 (Study Three): Qiu, R., Möller, M., Koch, I., Frings, C., & Mayr, S. (2022). The influence of event segmentation by context on stimulus-response binding. *Journal of Experimental Psychology: Human Perception and Performance* (revision under review).

The published research articles of Study One and Two are presented in the thesis. As for Study Three, the revised manuscript is presented, which may not be identical to the final published version.

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Abstract

Feature binding has been proven to be a common and general mechanism underlying human information processing and action control. There is strong evidence showing that when humans perform a task, stimuli (e.g., the target, the distractor) and responses are bound together into an episodic representation, called an *event file* or a *stimulus-response (S-R) episode*, which can be retrieved upon feature repetition. As compared with the target and the distractor, the context (i.e., an additional stimulus presented together with the target and the distractor, but not associated with any response keys throughout the whole course of the task), which is considered as task-irrelevant, did not receive that much attention in previous studies. The current thesis was aimed to provide insights into the different roles the context plays in S-R binding and retrieval. Specifically, in Study One and Two, the role of context as an element that can be integrated into an S-R episode was investigated, with a focus on the saliency and the inter-trial variability of the contextual stimulus. Both properties were found to influence how the context is integrated into an S-R episode. More specifically, results show that both saliency and inter-trial variability determine whether the context is directly bound in a binary fashion with the response, or it enters into a configural binding together with another stimulus and the response. In Study Three, intrigued by the role of context as an event segmentation factor in the event perception literature, whether the context can demarcate the integration window of an S-R

episode was tested. Results provide consistent evidence that sharing a common context leads to a stronger binding between a stimulus and the response, as compared with the condition when these elements are separated by different contexts, thereby suggesting a binding principle of common context. Taken together, the current thesis specifies the role of context in S-R binding and retrieval, and sheds some light on how contextual information influences human behavior.

Table of Contents

Preface	2
Acknowledgements	3
Abstract.....	4
Table of Contents	6
Chapter 1: General Introduction.....	7
1.1 Feature Binding in and across Perception and Action	8
1.2 The Role of Context in S-R Binding and Retrieval	15
1.3 Overview of the Studies	21
Chapter 2: Study One	30
Chapter 3: Study Two.....	53
Chapter 4: Study Three.....	67
Chapter 5: General Discussion.....	127
5.1 Summary and Interpretation.....	128
5.2 Remaining Questions and Implications for Future Research	132
5.3 Conclusion.....	136
Reference	138
Declaration of Own Contributions	157

Chapter 1: General Introduction

1.1 Feature Binding in and across Perception and Action

We live in a continuously changing environment. It is assumed that in order to deal with the complex outside world, our brain integrates information of perception and action into a temporary episodic representation, which helps us to control our behavior in an efficient way. The presumed integration of perceptual and action information and its influence on behavior has raised a long and still ongoing research interest (for a recent review, see Frings et al., 2020). To date, studies investigating feature integration (or say, feature binding) in and across perception and action has provided strong evidence that feature binding is a common and general mechanism underlying human information processing and action control. In the following, crucial findings from these studies and theoretical development are summarized and discussed, which motivated the studies in the current thesis.

Object File and Action File

Features of an object, such as color and shape of a visual object or pitch and loudness of an auditory object, are coded in a distributed fashion in the brain (e.g., Seymour et al., 2009; Stecker et al., 2005). However, human beings perceive and remember the entirety of an object, which requires mechanisms to integrate these separately represented features together (leading to the so-called *binding problem*, for reviews, see Feldman, 2013; Treisman, 1996). Kahneman and Treisman (1984) proposed that when processing an object, the perceptual features of the object are

integrated (or say, bound together) into a temporary episodic representation, called *object file*. Their team was also among the first to investigate the influence of feature binding on behavior (Kahneman et al., 1992). Using the so-called *reviewing paradigm*¹, Kahneman et al. (1992) found that previewing a stimulus facilitated responding to its identity when it reappeared as the target, but this facilitation of responding mainly occurred when the relation between the identity feature and the spatial feature of the stimulus was retained (e.g., when the previewed stimulus reappeared as the target at the same location). This finding suggests that the identity feature and the spatial feature of the stimulus are integrated into one object file during the preview process. When processing the target, the previously constructed object files can be retrieved. If the target and the retrieved information matches, the responding is facilitated. Otherwise the responding may be impaired (Kahneman et al., 1992).

Similar to the way that perceptual features of a stimulus are integrated into an object file, evidence shows that action features (e.g., speed and direction) of a response (e.g., pressing a left key) can be bound together into an *action file* as well (e.g., Mocke et al., 2022; Stoet & Hommel, 1999; Wickens et al., 1994). For

¹ The task consists of two consecutive displays, referred to as the *preview field* and the *target field*. In the preview field, two or more letters are presented, followed by the target field in which a single target letter is presented. The target letter is connected to one of the previewed letters, e.g., by sharing the location or by appearing in the same moving frame successively. These two connected letters can be identical or not. Participants are required to name the target letter as fast and as accurately as possible.

example, Stoet and Hommel (1999) asked participants to prepare a response (the response A) and to hold the execution of response A until a second response (the response B) is executed. Results showed that when there was a feature overlap between response A and response B (e.g., the former is a response with the left index finger and the latter is a response with the left foot—in this case, there is an overlap of the spatial feature “left” between these two responses), response latency of the latter was significantly prolonged as compared with the condition devoid of any feature overlap. The authors explained these results in terms of *code occupation*. In a nutshell, when planning response A, relevant action feature codes are integrated into an action file. These feature codes are thus occupied and no longer readily available for other action planning activities until response A is executed. Therefore, response B is impaired if it requires feature codes still occupied by the action file of response A. This finding indicates that feature binding is a common and general mechanism underlying not only human beings’ perceptual processing of the outside world, but also their intended, goal-directed interaction with it.

Stimulus-Response Binding and Retrieval

It is further assumed that the perceptual and action features in a stimulus environment (in other words, stimulus and response) can be bound together into an episodic representation as well, which is referred to as an *event file* or a

*stimulus-response (S-R) episode*². Re-encountering any feature of the S-R episode will retrieve the whole episodic representation, leading to facilitation or impairment of performance, which depends on whether the retrieved information is compatible with the current processing requirement or not (for overviews of the S-R binding and retrieval processes, see Hommel, 2004; also see the *Binding and Retrieval in Action Control* framework, *BRAC*, Frings et al., 2020). Using the so-called *S1R1-S2R2* task, Hommel (1998) was among the first to investigate S-R binding and retrieval. In the experiment, participants prepared a keypress response (R1) and executed it when a target stimulus (S1) was presented (i.e., the onset of S1 acted as a “go” signal for the execution of R1). Then, a second target stimulus (S2) was presented, which either shared a perceptual feature (e.g., identity) with S1 or not. Participants were required to identify S2 via an appropriate keypress response (R2), which either shared the location feature with R1 (e.g., both R1 and R2 were responses of pressing the left key) or not. Hommel (1998) found that R2 responding was significantly impaired when only the perceptual feature or only the action feature was repeated (while the other feature was changed) as compared with the condition when both features were repeated or changed, leading to a significant interaction between the S1-S2 relationship and the R1-R2 relationship.

² Please note that the terms “event file” and “S-R episode” are both used in the thesis. Specifically, the term “S-R episode” is mainly used in the General Introduction (Chapter 1) and in the General Discussion (Chapter 5), as well as in the published manuscripts of Study One (Chapter 2) and Two (Chapter 3), whereas the term “event file” was adopted in the submitted manuscript of Study Three (Chapter 4).

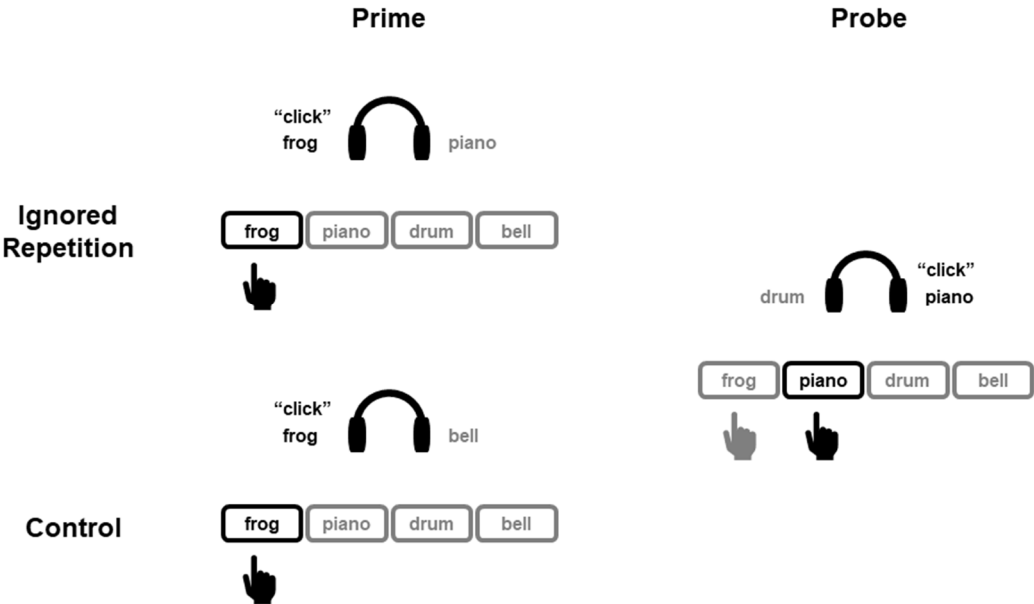
Following the above-mentioned assumption of S-R binding and retrieval, the interaction effect emerges because S1 and R1 were bound together into an S-R episode, which can be retrieved when re-encountering any feature of the S-R episode during the processing of S2 and R2. In the case of partial repetition, the retrieved S-R episode is incompatible with the processing requirement of S2 or R2, which causes conflicts that have to be resolved, thereby impairing responding as compared with the full repetition/change condition. Such an S-R episode was found to survive for four to five seconds before becoming functionally disintegrated (e.g., Hommel & Colzato, 2004; Hommel & Frings, 2020).

The findings of S-R binding and retrieval were also conceptually replicated in several other studies using different paradigms, including the *four-alternative negative priming paradigm* (Mayr & Buchner, 2006) as well as the *distractor-response binding paradigm* (Frings et al., 2007) that are most relevant to the current thesis. Taken together, these studies provide supportive evidence that S-R binding and retrieval is a common mechanism of human information processing and action control, which underlies several empirical phenomena (see Frings et al., 2020 for a summary). These studies focused not only on the binding between target stimuli and responses, but also on the integration of distractor stimuli into S-R episodes. For example, Mayr and Buchner (2006) found evidence for a binding between the distractor stimulus and the response using the four-alternative negative priming paradigm. In the experiment (Experiment 2B, Mayr & Buchner, 2006), four different environmental sounds were selected as the target

and the distractor stimuli, and each sound was associated with a unique response key. Each trial was comprised of a prime presentation and a probe presentation, and each presentation contained a target stimulus and a distractor stimulus. Participants were required to identify the target via an appropriate keypress and to ignore the simultaneously presented distractor. The so-called *ignored repetition* trials and their *control* counterparts were of most interest in the experiment. In the former, the distractor stimulus in the prime reappeared as the target in the probe, whereas the latter was devoid of any stimulus repetition. Thus, the correct response in the prime was always different from that in the probe in the ignored repetition and the control trials (see Figure 1.1 for an illustration of the paradigm).

Figure 1.1

Illustration of the auditory four-alternative negative priming paradigm and the specific erroneous probe response with the previously executed prime response



Note. The figure was taken from the manuscript of Study Three. In the figure, primes are shown for the ignored repetition (upper) and the control (lower) conditions with an identical probe. Prime and probe targets (in black) are presented on the side cued by a “click”, distractors (in grey) are presented on the opposite side. Correct responses are indicated by black-framed keys and black hand symbols below the keys. The grey hand symbol in this example indicates a potential probe error with the previously executed prime response (here “frog”). Such errors are more often committed in ignored repetition than in control trials.

Given that unique keys were assigned to the four environmental sounds, probe responses can be categorized as: (1) correct response to the probe target; (2) incorrect response to the probe distractor; (3) incorrect response with the previously executed prime response (as shown in the probe in Figure 1.1); (4) incorrect response with the remaining fourth response option. Mayr and Buchner (2006) found that participants were more likely to commit erroneous probe responses with the previously executed prime response in the ignored repetition trials as compared with the control trials. This result indicates that the repetition of the prime distractor stimulus can directly retrieve the previously executed prime response. Since it is assumed that the stimulus and response elements that were bound together into an S-R episode can be retrieved by re-encountering one of them, this finding suggests that the distractor stimulus was integrated with the response into an S-R episode during the prime processing.

1.2 The Role of Context in S-R Binding and Retrieval

As compared with the target and the distractor stimulus, the so-called contextual stimulus did not receive that much attention in previous studies of S-R binding and retrieval. Unlike the target and the distractor, the context is an additional stimulus without any assignment of response keys throughout the whole course of the experiment (Mayr et al., 2018). It mainly functions as a background of the central task of responding to the target. In this sense, the context is considered as task-irrelevant. The influence of such a task-irrelevant stimulus on behavior has been intensively investigated in the field of memory (for a review, see Smith & Vela, 2001) and in the field of learning (for a review, see Bouton, 2010). For example, in studies of animal associative learning, the context was found to function as an “occasion setter” which modulates the association between the other stimuli and the behavior (e.g., Bouton, 1984). However, in the field of S-R binding and retrieval, it remains unclear whether and how such a task-irrelevant stimulus influences the binding between the other stimuli and the response. Moreover, it is also unclear how a contextual stimulus is integrated into an S-R episode. The current thesis was aimed to investigate the different roles of context in S-R binding and retrieval, thereby elucidating the integration of the context as well as the contextual influence on S-R binding.

To this end, theoretical background and empirical evidence that helps to specify the role of context in S-R binding and retrieval are introduced in the following parts of Chapter 1. Specifically, the context is considered either as an

element that can be involved in different *binding structures* in an S-R episode, or as a segmentation factor that may influence the integration of the other stimuli with the response into an S-R episode. These possible roles of the context were investigated in three studies. An overview of the three studies is presented at the end of Chapter 1 and these studies are fully reported in Chapter 2 to 4. Finally, in Chapter 5, findings from these studies are summarized and possible implications for future research are discussed.

Context as an Element in S-R Episodes

As mentioned earlier, the influence of contextual information on behavior has been intensively investigated in the learning literature (for reviews, see Bouton, 2010; Bouton & Todd, 2014). Studies in animal learning specified different functions the contextual stimulus perform in the formation of associations. In some cases, the contextual stimulus itself can directly elicit the previously learned behavior in a similar way as the conditional stimulus (CS), which indicates that the context may be associated with the conditional response (e.g., rats can establish the so-called contextual fear of the Skinner box in which they were shocked, indicated by behavior like freezing or avoidance, Bouton, 1984; Fanselow, 1980). In other cases, the contextual stimulus modulates the association between the CS and the learned behavior (e.g., exposure to the context in which the rats were shocked before can increase their fear of the CS, even after an extinction manipulation, Bouton, 1984; Bouton & King, 1986). Transferring these findings into S-R binding and retrieval, it is reasonable to assume that the context

can be directly bound with the response into an S-R episode, or the context may modulate the binding between the other stimulus and the response.

The “direct” binding between a stimulus and a response is assumed to form a unitary structure. This type of binding is referred to as a *binary binding* or an *elemental binding* (Hommel, 2004; Moeller, Frings, et al., 2016), which is the commonly observed binding structure in previous studies (e.g., Hommel, 1998, 2004; Singh & Frings, 2020; it can also be a binding between two features of a stimulus, as found by Kahneman et al., 1992, or a binding between two responses, i.e., the so-called *response-response binding*, Moeller & Frings, 2019). However, interestingly, Mayr et al. (2018) observed a binding structure involving the contextual stimulus that cannot be categorized as a binary binding. The authors employed the four-alternative negative priming paradigm in the auditory modality, and additionally presented a sine tone together with the target and distractor sound pair, which acted as the context. The context could repeat or change between the prime and the probe presentations. The results replicated the previous finding of a binary binding between the distractor stimulus and the response by Mayr and Buchner (2006), but showed that the repetition of the context tones could not directly retrieve the previously executed prime response, which indicates that the context was not involved in a binary binding with the response in the prime. However, repeating the context significantly facilitated the retrieval of the previously executed prime response induced by the repetition of the prime distractor stimulus. In other words, the context modulated the binding between

the distractor and the response. This significant contextual modulation suggests that the context may be involved in a *higher-order binding* (Hommel, 1998) together with the prime distractor stimulus and the response. Specifically, it is assumed that the context and the prime distractor stimulus form a compound, and the whole compound is bound with the response in the prime episode (Qiu et al., 2022). Thus, this type of higher-order binding that the context is involved in is also referred to as a *configural binding* (Moeller, Frings, et al., 2016).

Given that the binary binding is the commonly found binding structure, the finding of the contextual involvement in a configural binding by Mayr et al. (2018) leads to the question whether the context can also be bound in a binary fashion with the response into an S-R episode. If so, what determines the binding structure (binary vs. configural) that a contextual stimulus is involved in? Across four experiments, Study One and Two answered these questions by pinpointing two determinants (namely, saliency and inter-trial variability) that influence the integration of the contextual stimulus into an S-R episode.

Context as an Event Segmentation Factor of S-R Episodes

As mentioned above, previous studies in S-R binding and retrieval mainly focused on the integration of the target and the distractor into an S-R episode. Several factors (such as saliency, temporal proximity, and spatial proximity) that influence the binding of these stimuli with responses were proposed and were empirically tested, based on which the so-called *binding principles* were

established (e.g., Dutzi & Hommel, 2009; Frings & Rothermund, 2011; Hommel, 2005; Moeller et al., 2012). For example, Frings and Rothermund (2011) manipulated whether the target and the distractor can be perceived as belonging to the same object or not (e.g., presenting the letters D, F, and D horizontally creates an impression of them belonging together, whereas presenting these letters vertically may create an impression of three separated letters. Note that in this example, the F is the target and the Ds are the distractors). Across six experiments, results consistently showed that the distractor was only integrated into an S-R episode when it could be perceptually grouped with the target, indicating a binding principle of *perceptual grouping*.

Perceptual grouping is also a fundamental and common mechanism underlying human information processing (Paine & Gilden, 2013). Most of the studies investigating perceptual grouping were from the field of Gestalt psychology, which focuses mainly on principles (e.g., similarity, common fate) that fosters a perception of association among stimuli (for reviews, see Wagemans, Elder, et al., 2012; Wagemans, Feldman, et al., 2012). However, studies investigating the so-called *temporal grouping* were mainly from the field of *event perception* (for a recent review, see Zacks, 2020). The main topic of this field is how human beings segment the continuous information stream received by the brain into meaningful units (or say, gestalts, Zacks, 2020), which are perceived as events (e.g., the morning routine can be segmented as events like eating breakfast and brushing teeth). Zacks and Tversky (2001, p 3) define an event as “a segment

of time at a given location that is conceived by an observer to have a beginning and an end”. This definition points out the kernel of event perception, namely, the perceived beginnings and ends of events, which are referred to as *event boundaries*.

The perception of event boundaries was originally tested using the *unitization* task (e.g., Newton, 1973), in which short videos of daily activities were shown to participants. Participants were required to press a key at their own discretion whenever they thought an event ended and the next event started. Newton (1973) found that participants tended to agree on the same locations of event boundaries. This finding was replicated in other studies, which further showed that participants consistently experienced the same event boundaries in a retest session as they had experienced before in a viewing session of the same videos one year ago (e.g., Speer et al., 2003; Zacks et al., 2001). Together, these findings show that the perception of event boundaries is a stable and general phenomenon.

Several factors were found to effectively indicate event boundaries (see Zacks, 2020 for a summary), one of which is the change of the context. Such an event boundary indexed by context change has been found to influence associative memory (e.g., DuBrow & Davachi, 2013; Heusser et al., 2018; Pu et al., 2022; Wang & Egner, 2022). For example, Pu et al. (2022) presented to-be-remembered items on a colored background which acted as the context. A change of the context color indicated an event boundary. Results showed impaired temporal order

memory of items across such an event boundary, as compared with the baseline condition when there was no manipulation of event boundaries (i.e., the context color remains the same throughout the whole course). This result is consistent with the previous findings that crossing an event boundary weakens the associations of information (e.g., DuBrow & Davachi, 2013; Paine & Gilden, 2013; Speer & Zacks, 2005). Furthermore, results also showed a facilitated temporal order memory of items belonging to the same event (i.e., sharing the same context) as compared with the baseline condition, suggesting strengthened associations. Transferring these findings into S-R binding and retrieval, the stimulus and the response that are enclosed by the same context may more likely or more strongly be bound together into an S-R episode, as compared with those elements that are separated by different contexts (i.e., a context change happens between the stimulus presentation and the response execution). This possible influence of event segmentation by context on S-R binding was examined in Study Three, which provides supportive evidence for a binding principle of common context.

1.3 Overview of the Studies

In the current thesis, three studies were conducted to investigate the role of context in S-R binding and retrieval. Specifically, the role of context as an element that can be involved in different binding structures (binary vs. configural) of an S-R episode was investigated in Study One and Two, whereas the role of context as an event segmentation factor which may impact the binding between another

stimulus (here the distractor) and the response was investigated in Study Three. The aforementioned four-alternative negative priming paradigm (Mayr & Buchner, 2006) was employed in Study One, Study Two, and Experiment 1 of Study Three, whereas the distractor-response binding paradigm (Frings et al., 2007) was adopted in the remaining experiments of Study Three for generalization across paradigms. The three studies are briefly described in the following.

Study One and Two

In Study One and Two, following the contextual manipulation in Mayr et al. (2018), an additional contextual sound was presented together with the target and distractor sound pair, which could repeat or change between the prime and the probe presentations. It should be noted that in Mayr et al. (2018), only two sine tones (300 Hz and 700 Hz) comparable in loudness with the target and distractor sound pair were selected as the contextual stimuli. Results from this study suggest a configural binding which involves the context, the prime distractor stimulus and the response, instead of a binary binding between the context and the response. Study One and Two were aimed to investigate whether the context can enter into a binary binding with the response, and to specify under which conditions the context is involved in different binding structures (binary vs. configural), with a focus on the saliency and the inter-trial variability properties of the contextual stimulus.

Saliency, which is defined as a property that reveals how conspicuous a stimulus is when compared with the surroundings (Kayser et al., 2005), has been proposed by Bouton (2010) as a determinant of the functions of the context in animal associative learning. Simply put, the context tends to modulate the association between the CS and the behavior when its saliency level is relatively low, whereas the context of higher saliency may be directly associated with the behavior (e.g., Goddard & Holland, 1996; Holland, 1989; Holland & Haas, 1993). Saliency has been found as an important factor in S-R binding and retrieval as well. For example, Hommel (2004) put forward a saliency principle of binding, according to which, a stimulus is integrated into an S-R episode only if its saliency level exceeds an integration threshold. Taken together, it is possible that the saliency of the context in Mayr et al. (2018) may not have been sufficiently high, which might have led the context to modulate the binding between the distractor stimulus and the response, instead of being directly bound with the response in a binary fashion into an S-R episode. In Study One, to investigate the possible influence of the saliency property on the integration of the context into an S-R episode, the loudness (Experiment 1) as well as the emotional valence (Experiment 2A and 2B) of the contextual stimulus were systematically manipulated (see Table 1.1 for a summary of the specific manipulations). The context of low saliency, following the binding principle of saliency proposed by Hommel (2004), was not expected to be integrated into an S-R episode. As for the context of moderate saliency, it should enter into a configural binding with the

prime distractor stimulus and the response, as found in the previous study by Mayr et al. (2018). The context of high saliency, however, was supposed to be bound with the response in a binary fashion into an S-R episode.

Table 1.1

Manipulations of the context in Study One and Two

Study	Experiment	Manipulation of the context
Study One (saliency)	Experiment 1 (<i>n</i> = 106)	Loudness of the sine tones: (1) softer than the target and the distractor sound pair (low-saliency) (2) comparable to the sound pair (moderate-saliency), as in Mayr et al. (2018) (3) louder than the sound pair (high-saliency)
	Experiment 2A (<i>n</i> = 143) & Experiment 2B (<i>n</i> = 147)	Emotional valence of the human sounds: (1) neutral (categorized as moderate-saliency, see Chapter 2 for reasons) (2) negative (high-saliency)
Study Two (inter-trial variability)	Single experiment (<i>n</i> = 100)	Intertrial-variability of the sine tones: (1) two sine tones as the context (low-variability) (2) eight sine tones as the context (high-variability)

In Study Two, the inter-trial variability of the context was manipulated, following the previous findings by Chao (2009), which indicates that increasing the inter-trial variability of the context may promote the benefit of repeating the context between the prime and the probe on episodic retrieval (please see Chapter 3 for a detailed description of the study). Chao (2009) explained the findings in

terms of attention received by the contextual stimulus during the memory encoding phase in the prime. Simply put, a context of higher inter-trial variability may receive more attention during processing, which makes the context more likely or more strongly be encoded into the prime representation. Thus, the context may function as a more potent retrieval cue of the prime episode. Transferring this finding into S-R binding and retrieval, presumably the higher the inter-trial variability, the more likely the contextual stimulus is bound strongly with the response into an S-R episode. Given that only two sine tones were used as the context in Mayr et al. (2018), the relatively low inter-trial variability may be one of the reasons that the context did not enter into a binary binding with the response. Therefore, in Study Two, the inter-trial variability of the context was increased, by employing eight different sine tones. Participants were either assigned into the low-variability group (in which two out of the eight sine tones were selected as the context) or the high-variability group (in which all of the eight sine tones were used as the context). A pattern of configural binding among the context, the prime distractor stimulus and the response was expected for the low-variability group, whereas a pattern of binary binding between the context and the response was expected for the high-variability group.

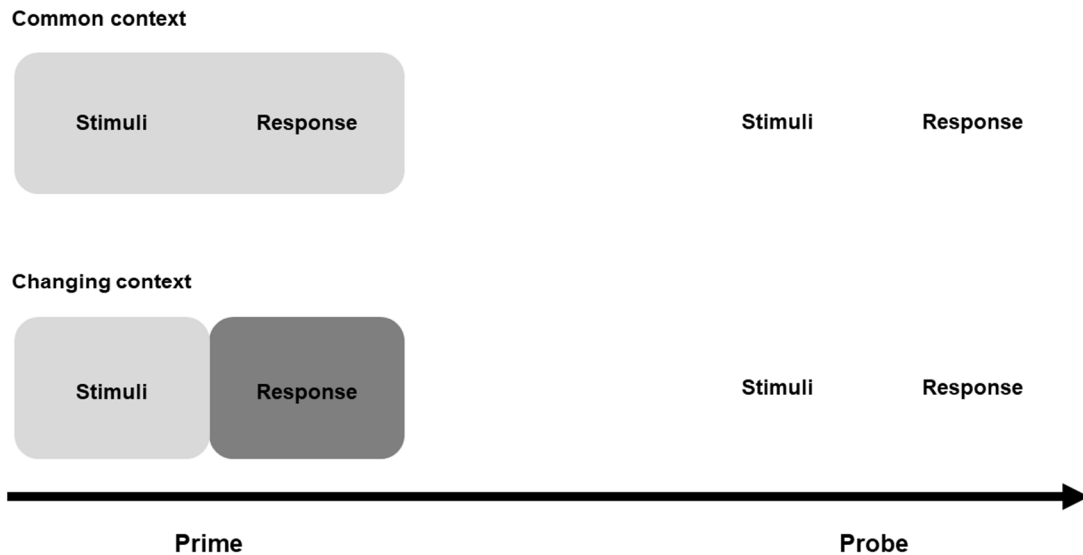
Study Three

Study Three was aimed to investigate the influence of event segmentation by context on S-R binding. Since auditory stimuli develop over time, they may better demarcate the temporal integration window of an S-R episode as compared with

visual stimuli. Thus, sine tones were employed as contextual stimuli in Study Three as well. It has been argued that in the sequence of a prime followed by a probe, the binding process happens in the prime and the after-effects of binding can be observed in the probe (Frings et al., 2020). Therefore, in order to test the influence of event segmentation by context on the binding process, in Experiment 1 ($n = 56$) and 2A ($n = 57$), the context in the prime was manipulated to be either a common context (i.e., the stimulus presentation and the response execution shared the same context) or a changing context (i.e., the first context started with the stimulus presentation and ended after the offset of the presentation, then the second context started and ended when a response was given). However, no additional context tones were displayed in the probe (i.e., the probe “context” was persisting silence). An illustration of the common context and the changing context conditions is presented in Figure 1.2.

Figure 1.2

Illustration of the common context and changing context conditions in Experiment 1 and 2A



Note. This figure was taken from the manuscript of Study Three. In the figure, different context tones are represented by different background shadings. In Experiment 1 and 2A, the context tones could form a common context or a changing context in the prime, whereas no context tones were displayed in the probe.

If the auditory context can demarcate the integration window of an S-R episode, the stimulus and the response sharing a common context should be more likely or more strongly bound into an S-R episode, leading to a larger after-effect of such a stronger binding as compared with the changing context condition when these elements are separated by different contexts. This hypothesis was tested

using the four-alternative negative priming paradigm in Experiment 1. Specifically, if sharing a common context leads to a stronger binding between the distractor stimulus and the response in the prime, repeating the prime distractor stimulus in the probe should more likely retrieve the previously executed prime response, as compared with the changing context condition in which these two elements were separated by different contexts in the prime. In order to generalize the findings in Experiment 1 across paradigms of S-R binding and retrieval (Frings et al., 2020), Experiment 2A was conducted as a conceptual replication of Experiment 1, in which the distractor-response binding paradigm was used (please see Chapter 4 for a detailed description of the paradigm). To anticipate, even though with different paradigms, both Experiment 1 and 2A showed a larger after-effect of binding in the common context than in the changing context condition.

Finally, an alternative account of contextual similarity between the prime and the probe was tested in Experiment 2B ($n = 58$), in which the distractor-response binding paradigm was employed for consistency between Experiment 2A and 2B. The contextual similarity between the encoding phase and the testing phase has been consistently found to benefit successful retrieval (for a review, see Smith & Vela, 2001). If a common context is more similar to the persisting silence than a changing context, the larger after-effect of binding may simply be due to the benefited retrieval of the prime information in the common context than in the changing context condition, regardless of differences in the binding process. This contextual similarity account was examined by manipulating the probe context as

a common context or a changing context, whereas no additional context tones were presented in the prime (in this case, the prime “context” was persisting silence). If the similarity between a common context and the persisting silence is larger than that between a changing context and the persisting silence, an improved retrieval of the prime information in the common context condition as compared with the changing context condition should be observed in Experiment 2B as well. If such an improved retrieval is not observed Experiment 2B, the common and the changing contexts may not significantly differ from each other in terms of similarity with the persisting silence. In this case, contextual similarity between the prime and the probe cannot account for the results in Experiment 1 and 2A. Instead, the results are tentatively attributed to the influence of event segmentation by context on S-R binding, suggesting a binding principle of common context.

Chapter 2: Study One



Saliency determines the integration of contextual information into stimulus–response episodes

Ruyi Qiu¹ · Malte Möller¹ · Iring Koch² · Susanne Mayr¹

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Abstract

When humans perform a task, it has been shown that elements of this task, like stimulus (e.g., target and distractor) and response, are bound together into a common episodic representation called *stimulus–response episode* (or *event file*). Recently, the context, a completely task-irrelevant stimulus, was found to be integrated into an episode as well. However, instead of being bound directly with the response in a binary fashion, the context modulates the binary binding between the distractor and response. This finding raises the questions of whether the context can also enter into a binary binding with the response, and if so, what determines the way of its integration. In order to resolve these questions, saliency of the context was manipulated in three experiments by changing the loudness (Experiment 1) and emotional valence (Experiment 2A and 2B) of the context. All experiments implemented the four-alternative auditory negative priming paradigm introduced by Mayr and Buchner (2006, *Journal of Experimental Psychology: Human Perception and Performance*, 32[4], 932–943). Results showed that the integration of context changed as a function of its saliency level. Specifically, the context of low saliency was not bound at all, the context of moderate saliency modulated the binary binding between the distractor and response, whereas the context of high saliency entered into a binary binding with the response. The current results extend a previous finding by Hommel (2004, *Trends in Cognitive Sciences*, 8[11], 494–500) that there is a saliency threshold which determines whether a stimulus is bound or not, by suggesting that a second threshold determines the specific structure (i.e., binary vs. configural) of the resulting binding.

Keywords Context · Saliency · Stimulus–response episode · Binding

While we perceive a given stimulus as a unit, features of the stimulus (e.g., color and shape of an object or pitch and loudness of a sound) are coded in a distributed fashion in the brain (e.g., Seymour et al., 2009; Stecker et al., 2005). This raises the so-called binding problem, which has stimulated a long and still ongoing research interest (for reviews, see Feldman, 2013; Treisman, 1996). Kahneman et al. (1992) were among the first to investigate feature binding and proposed that an episodic trace was formed to store the features and their relations when processing a stimulus. Similarly, it has been shown that stimuli and responses can also be integrated into a common episodic representation called

stimulus–response episode (or event file, for overviews, see Hommel, 2004; also see the Binding and Retrieval in Action Control [BRAC] framework; Frings et al., 2020). It has been proposed that reencountering one of the elements of an episode will retrieve the whole episode, which may facilitate or impair responding, depending on whether the retrieved episode is compatible with the current processing demands or not.

Binding and retrieval of stimulus–response episodes is assumed to be a general mechanism of human information processing which underlies several empirical phenomena (Frings et al., 2020), the one most relevant to the present purpose is the *negative priming effect*. In a typical negative priming task, participants need to respond to a target stimulus and simultaneously ignore a distractor stimulus. When the distractor stimulus of a first presentation (i.e., the *prime*) reappears as the target in the following presentation (i.e., the *probe*) in so-called *ignored repetition* trials, responses are slowed down and sometimes more error prone as compared

✉ Ruyi Qiu
Ruyi.Qiu@uni-passau.de

¹ Chair of Psychology and Human-Machine Interaction, University of Passau, 94032 Passau, Germany

² Department of Cognitive and Experimental Psychology, RWTH Aachen University, 52056 Aachen, Germany

with trials without any stimulus repetition (so-called *control* trials). The impaired responding in ignored repetition as compared with control trials denotes the *negative priming effect* (Neill, 1977; Tipper, 1985).¹ Based on the instance theory of automatization (Logan, 1988), Neill and Valdes (1992) proposed that by withholding a response to the distractor stimulus in the prime, this stimulus is associated with the so-called *do-not-respond* tag. When the stimulus is repeated as the target in the probe, the do-not-respond tag is retrieved and conflicts with the need to respond to this stimulus in the probe, thus impairing the response speed and/or accuracy.

Alternatively, and in line with BRAC framework of binding and retrieval of stimulus–response episodes, the executed prime response is bound with the other elements of the prime trial (e.g., target and distractor stimuli). Therefore, reencountering the prime distractor stimulus in the probe will retrieve the prime episode, including the prime response. This is exactly what Mayr and Buchner (2006) found. In their experiment, the prime response was always different from the correct probe response. This implies that retrieving the prime response in ignored repetition trials should impair probe responding, thereby leading to the negative priming effect (for a similar explanation, see Rothermund et al., 2005). Mayr and Buchner (2006) used a four-alternative identification task, in which each stimulus was assigned to a unique response key. This allowed the authors to analyze the frequencies of the different probe response types. Specifically, a probe response could be categorized as either a correct response, an erroneous response with the key assigned to the probe distractor, an erroneous execution of the prime response, or an erroneous response with the remaining response option. Results showed an increased probability of committing errors with the former prime response in the ignored repetition as compared with the control condition. Since only elements that were bound together can be retrieved by the repetition of one of them, the effective retrieval of the prime response by the repetition of the prime distractor stimulus indicates that a binding was formed between these elements. The increased probability of committing prime response errors induced by the repetition of the prime stimulus has been coined as the *prime-response retrieval effect*, which is an unambiguous indicator of stimulus–response binding (Frings et al., 2015; Mayr et al., 2018).

In the present article, we adopted the negative priming paradigm and the analysis of the prime–response retrieval effect as a tool to investigate the mechanisms of

stimulus–response binding with respect to the role of context in the integration of stimulus–response episodes.

The role of context in binding and retrieval of stimulus–response episodes

Context can act as an effective retrieval cue. For example, there is consistent evidence from the memory literature showing that the similarity of contextual information between the encoding and testing phases favors successful retrieval (for a review, see Smith & Vela, 2001). Given that stimulus–response episodes are stored in memory and are retrieved from memory, the context may also play an important role in the binding and retrieval of stimulus–response episodes. For instance, Frings and Rothermund (2017) tested the integration of contextual visual features (e.g., color) using the distractor–response binding paradigm, examining the effect of the relationship between distractor repetition and response repetition on performance. In accordance with the rules of figure–ground segmentation (for a review, see Wagemans et al., 2012), they found that features belonging to the figure region (e.g., a confined area on the screen) were bound with the response whereas features belonging to the background did not result in measurable stimulus–response binding effects.

In a recent negative priming study of Mayr et al. (2018), the integration of context into stimulus–response episodes was investigated by means of the before-mentioned four-alternative identification task in the auditory modality (Mayr & Buchner, 2006). The context was a sine tone that was presented together with pairs of task-relevant stimuli (i.e., target and distractor sounds), but it was completely task-irrelevant (i.e., in contrast to targets and distractors, context stimuli were not assigned to a response throughout the experiment). The context tone could be repeated or changed between prime and probe presentations. Results showed no significant prime–response retrieval effect induced by context repetition per se. However, when the context was repeated, the prime–response retrieval effect induced by the repetition of the prime distractor stimulus was significantly larger than when the context was changed (for a similar finding for the distractor–response binding effect with task selection criterion as context, please see Frings et al., 2017). The combined pattern of results—no prime–response retrieval effect induced by context repetition alone on the one hand, and contextual modulation of the prime–response retrieval effect induced by the repetition of the prime distractor stimulus on the other hand—suggests that the context is not bound directly with the response, but that it enters into some kind of higher-order binding with the distractor stimulus and the response (Hommel, 1998).

Evidence of binding among context, stimulus, and response as found by Mayr et al. (2018) fits well into the

¹ Note that the negative priming effect is considered to be rooted in multiple processes (for a review, see Frings et al., 2015), including an inhibition mechanism (Tipper, 1985) as well as an episodic memory process (Mayr & Buchner, 2006; Neill & Valdes, 1992). For the purposes of the present paper, we exclusively focus on the latter.

binding structures proposed by Moeller et al. (2016). The latter authors distinguished between a unitary structure integrating an individual feature and the response (a so-called *binary binding*) and an integration among several features and the response, referred to as *configural binding*. Accordingly, the integration of context found in Mayr et al. (2018) can be categorized as a configural binding—that is, the context and distractor form a compound which is bound with the response. Mayr et al. (2018) replicated the evidence of configural binding of the context in a second experiment. However, it remains an open question whether context is limited to be involved in configural binding structures or it can also enter into a binary binding with the response. The main purpose of the current study was to investigate whether context can be part of different binding structures (either binary or configural) and to pinpoint a factor that determines its binding structure.

Evidence from learning research: The role of context saliency

The impact of context on behavior has been intensively investigated in the learning literature. Interestingly, contextual information also plays various roles in learned behavior (for reviews, see Bouton, 2010; Bouton & Todd, 2014; Pearce & Bouton, 2001). In some cases, the context directly elicits behavior in a similar way as other stimuli. For example, rats established a contextual fear (indicated by behavior like freezing or avoidance) of the Skinner box or chamber where they were shocked (e.g., Bouton, 1984; Fanselow, 1980). In other cases, the context modulates the association between stimulus and behavior. For example, exposure to the same context where the rats were shocked augmented the rats' fear of the conditioned stimulus after the extinction manipulation (e.g., Bouton, 1984; Bouton & King, 1986). Saliency has been proposed as one factor that determines the role of context in learning (Bouton, 2010). Saliency is a stimulus property that reveals how conspicuous the stimulus is when compared with its surroundings (Kayser et al., 2005). Evidence shows that stimuli of relatively low saliency rather modulate learned associations than directly elicit behavior, whereas highly salient stimuli tend to be directly associated with the behavior (e.g., Goddard & Holland, 1996; Holland, 1989; Holland & Haas, 1993).

Saliency also plays a role in binding and retrieval of stimulus–response episodes. For example, the level of saliency was found to determine whether a stimulus is integrated into a stimulus–response episode or not (Dutzi & Hommel, 2009; Hommel, 2004). Moreover, Moeller et al. (2016) found that distinguishable features were involved in binary bindings with a response, whereas features that were hard to separate from each other were involved in configural bindings. If saliency increases the distinguishability of a feature, it

is possible that features of higher saliency are more likely to be directly bound with a response. In contrast, less salient features may be more likely to be involved in configural bindings or even not integrated into a stimulus–response episode at all. With respect to auditory perception, loudness was found to be positively correlated with the perceived saliency level (Kayser et al., 2005). In Mayr et al. (2018), the saliency of the context might have led to a configural binding because the context tones were approximately as loud as the target and distractor sound pair. Presumably, these context tones were not perceived as of high saliency, and thus the context only modulated the binding between distractor and response instead of being directly bound with the response. The present study aimed to test whether saliency influences the binding of contextual information, and to specify under which saliency conditions the context (1) is not at all integrated into a stimulus–response episode, (2) is involved in a configural binding, or (3) is involved in a binary binding.

The current study

The current study adopted the paradigm used by Mayr et al. (2018) and manipulated the saliency level of the context. In Experiment 1, saliency was manipulated by changing the loudness of context tones. Specifically, context tones were softer than the sound pair in the *low-saliency condition*, they were approximately as loud as the sound pair in the *moderate-saliency condition*, and they were louder than the sound pair in the *high-saliency condition*. In addition to perceptual properties, information carried by a stimulus can also influence its saliency (e.g., endowing the stimulus with different identity relevance can change the social saliency; Sui et al., 2012). Therefore, in Experiment 2A, which served as a conceptual replication of Experiment 1, emotionally neutral and negative information (in other words, emotional valence) was used to manipulate the saliency of the contextual stimulus. To further confirm the reliability of the findings in Experiment 2A, Experiment 2B was conducted as a full replication of Experiment 2A.

If saliency modulates the integration of context, low-saliency contexts, even if easily perceivable, may not be integrated at all (Hommel, 2004). Thus, repeating the low-saliency contexts should neither retrieve the prime response directly nor facilitate the retrieval of the prime response induced by the repetition of the prime distractor stimulus. As for moderate-saliency contexts, a replication of the findings by Mayr et al. (2018) is expected: The contextual stimulus should be involved in a configural binding—that is, a larger prime-response retrieval effect induced by the repetition of the prime distractor stimulus should be found when the context is also repeated than when it is changed. High-saliency contexts, on the other hand, may be bound directly with the

response. This binary binding should be indicated by a significant prime-response retrieval effect due to the repetition of the context per se.

Experiment 1

Method

Participants

Of the 134 participants who took part in the experiment, data of 28 participants had to be excluded. Of the excluded participants, 24 were tested on a computer with an incorrectly set system volume, and three quit due to keyboard malfunction. The remaining four participants had excessive error rates ($>.50$) in the ignored repetition and control conditions (as compared with an average error rate of around $.09$), suggesting either inability or unwillingness to follow the instructions. The resulting sample consisted of 106 adults (84 females), most of whom were students at the University of Passau. They ranged in age from 18 to 32 years ($M = 22$, $SD = 2.56$). Participants either were paid 12 euros or received course credit for their participation. This and the following experiment were conducted in accordance with the ethical guidelines of the German Psychological Association (DGPs) and the Professional Association of German Psychologists (Deutsche Gesellschaft für Psychologie, 2016) and with the 1964 Declaration of Helsinki.

Materials

Four 300-ms environmental sounds (frog, piano, drum, and bell) were used as stimuli. Participants heard sounds via headphones (DT110, Beyerdynamic GmbH & Co. KG, Heilbronn, Germany) that were plugged directly into the computer that controlled the experiment. All sounds had an average loudness of approximately 71 dB(A) SPL. Loudness was measured using the NIOSH (2016) app on a cellphone (iPhone 8, Apple Inc., Cupertino, CA, USA) equipped with an external microphone (iMM-6 iDevice Calibrated Measurement Microphone, Dayton Audio, Springboro, USA) while the sounds were played at one side of the headphone. LiveCode (LiveCode 9.5, Runtime Revolution Ltd., Edinburgh, Scotland) was used to program and run the experiment.

In each presentation, a 20-ms metronome click was first played either to the left ear or right ear, indicating the side the participants should pay attention to. After a 500-ms interval, the to-be-attended sound (i.e., target) was played on this side, and a to-be-ignored sound (i.e., distractor) was played simultaneously on the other side. Participants were required to respond to the target sound by pressing an assigned response key, and to ignore the distractor sound.

The response keys were four vertically aligned keys (“9,” “6,” “3,” “;”) on the number pad of a keyboard, assigned to the sounds of “frog,” “piano,” “drum,” and “bell”, respectively. Half of the participants were instructed to use their middle and index fingers of their right hands to press the two distal keys, and the middle and index fingers of their left hands to press the two proximal keys. This arrangement was reversed for the remaining participants.

A context tone was played together with the sound pair. The context was a sine tone of either 300 Hz or 700 Hz, also lasting for 300 ms (including 10-ms attack and decay intervals). Context tones were easily discernable not only from the stimulus sounds, but also from each other. Context tones were played simultaneously to both ears creating the impression to come from a central location. The saliency level of context tones was classified as *low*, *moderate*, or *high*, depending on their loudness. In the low-saliency condition, the context tones were softer than the sound pair but still audible (approximately 58 dB(A) SPL); in the moderate-saliency condition, the tones were approximately as loud as the sound pair (about 72 dB(A) SPL); in the high-saliency condition, the tones were louder than the sound pair (approximately 76 dB(A) SPL). When added to the sound pair presentation, context tones of low saliency only slightly increased the overall loudness (approximately 0.5 dB(A) SPL), the moderately salient context tones increased the overall loudness somewhat more (<2 dB(A) SPL), the context tones of high saliency clearly increased the overall loudness (approximately 7 dB(A) SPL).

To make sure the context of low saliency was audible, and contexts of different saliency levels were distinguishable, two auditory tests were conducted with 16 new participants (13 females). Note that these tests were conducted in retrospect (i.e., after the experiments were finished). These participants were students and employees of the University of Passau, ranging in age from 19 to 40 years ($M = 23.88$, $SD = 6.06$). In the first auditory test, participants listened to a random sequence of trials consisting of either sound pairs without context or sound pairs combined with the low-saliency context. They were required to categorize the trials by an appropriate keypress (key *H* for sound pair without context, key *J* for sound pair with context). The one-sample *t* test of the sensitivity parameter d' ($M = 2.20$) revealed that it was significantly different from zero, $t(15) = 7.52$, $p < .001$, which means that the participants could easily detect the context of low saliency. In the second auditory test, participants listened to a random sequence of trials consisting of sound pairs with context of all three saliency levels and were asked to categorize them via keypress (key *H* for low saliency, key *J* for moderate saliency, and key *K* for high saliency). When calculating the hit and false-alarm rate for the comparison between the context of low and moderate saliency, the incorrect responses of categorizing the context

Table 1 Examples of stimulus configurations of different trial types for Experiments 1, 2A, and 2B

	Ignored repetition		Control		Attended repetition		Attended repetition control	
	Attended ear	Ignored ear	Attended ear	Ignored ear	Attended ear	Ignored ear	Attended ear	Ignored ear
Prime	Frog	Piano	Frog	Bell	Piano	Bell	Frog	Bell
Probe	Piano	Drum	Piano	Drum	Piano	Drum	Piano	Drum

of low or moderate saliency as being highly salient were excluded (around 4% of the trials for the former, around 18% of the trials for the latter). Similarly, in the comparison between the context of moderate saliency and high saliency, the incorrect responses of categorizing the moderately or highly salient context as being low salient were excluded (around 16% of the trials for the former, around 1% of the trials for the latter). The one-sample *t* test showed that both *d'* parameters (between low and moderate saliency, $M = 1.24$; between moderate and high saliency, $M = 2.42$) were significantly different from zero, $t_s > 7.81$, $ps < .001$. Thus, participants could easily distinguish the contexts of different saliency levels.

Each trial comprised a prime presentation and a probe presentation. To create ignored repetition trials, three out of the four sounds were selected as target and distractor in the prime and probe presentations, with the restriction that the prime distractor was identical to the probe target (see Table 1). The parallel control trial for each ignored repetition trial was constructed by replacing the prime distractor with the remaining fourth sound. To prevent participants from anticipating response changes between prime and probe, we added attended repetition trials and their control counterparts. In attended repetition trials, three out of the four sounds were selected as target and distractor, with the restriction that the prime target was identical to the probe target. The parallel control trials were constructed by replacing the prime target with the remaining fourth sound. Since no hypothesis was made for attended repetition trials and their control counterparts, results of them are not reported here.

The basic set of experimental trials contained 48 trials, with 12 trials for each of the four trial types described above.² The basic set was implemented four times: (1) with

a 300-Hz context tone in both prime and probe presentations; (2) with a 700-Hz context tone in both prime and probe presentations; (3) with a 300-Hz context tone in the prime presentation and a 700-Hz context tone in the probe presentation; (4) with a 700-Hz context tone in the prime presentation and a 300-Hz context tone in the probe presentation. Note that Combinations 1 and 2 will be referred to as “context-repeated trials,” whereas Combinations 3 and 4 will be referred to as “context-changed trials.” This 192-trial set was repeated three times as there were three different saliency conditions, resulting in 576 trials in total. These 576 trials were presented in a random sequence in the experiment. For each trial, it was randomly decided on which side the prime target would be presented; the probe target would always be presented on the other side.

Procedure

Participants were familiarized with the experimental sounds and introduced to the task, followed by three training sessions. In the first training, presentations consisted of target and distractor pairs without context tones. Participants had to identify the target sound via key press. Participants had to achieve an accuracy of at least 60% in the preceding 15 training trials to pass the training. If the criterion was missed after 60 trials, participants were offered to quit or to repeat the training. In the second training, sound pairs were presented together with context tones. Participants were instructed that the context tones were task irrelevant and they should focus on the task itself. The criterion of the second training was identical to that of the first one. In the final training, participants responded to six prime–probe sound pair presentations. The timing of these final training trials was identical to the timing of the experimental trials.

An experimental trial started with a 20-ms metronome click, indicating the to-be-attended side. The prime presentation followed the click after a 500-ms cue–target interval. After the prime response, a 500-ms prime–probe interval elapsed, after which, the probe cue was presented on the opposite side of the prime cue. Following the cue–target interval, the probe sound pair was presented. Audio-visual feedback about the correctness of the prime and probe responses was given after each trial, followed by a 1,200-ms intertrial interval. Responses faster than 100 ms and slower

² By generating the ignored repetition and attended repetition trials in the described way, each control trial would have occurred twice, once as a control for an ignored repetition trial and once as a control for an attended repetition trial. To avoid this confounding, the ignored repetition and attended repetition trials and their respective control trials were systematically assigned to two basic sets (referred to as Set 1 and Set 2). In each basic set, none of the control trials was repeated. Participants were randomly assigned to one of these two basic sets. For more details of Set 1 and Set 2, please see Mayr and Buchner (2006).

than 3,000 ms were excluded from the analysis, and participants got warning messages.

The whole experiment comprised 24 blocks with 24 experimental trials in each block. After each block, feedback regarding error rate was presented. Participants were offered rest, and they could start the next block at their own discretion by pressing one of the response keys. The testing lasted for 75–90 minutes.

Design and analysis

The experiment comprised a $2 \times 2 \times 3$ within-subjects design, with trial type (ignored repetition vs. control), context relation (repeated vs. changed), and context saliency (low vs. moderate vs. high) as independent variables. Apart from averaged reaction times and probe error rates, the probe response frequencies were analyzed.

The multinomial processing tree (MPT) model introduced by Mayr and Buchner (2006) was used to estimate and compare the probability of the prime-response retrieval process for the different experimental conditions (see Hu & Batchelder, 1994, for a general introduction to multinomial processing tree modeling). This so-called baseline model (see Fig. 1)

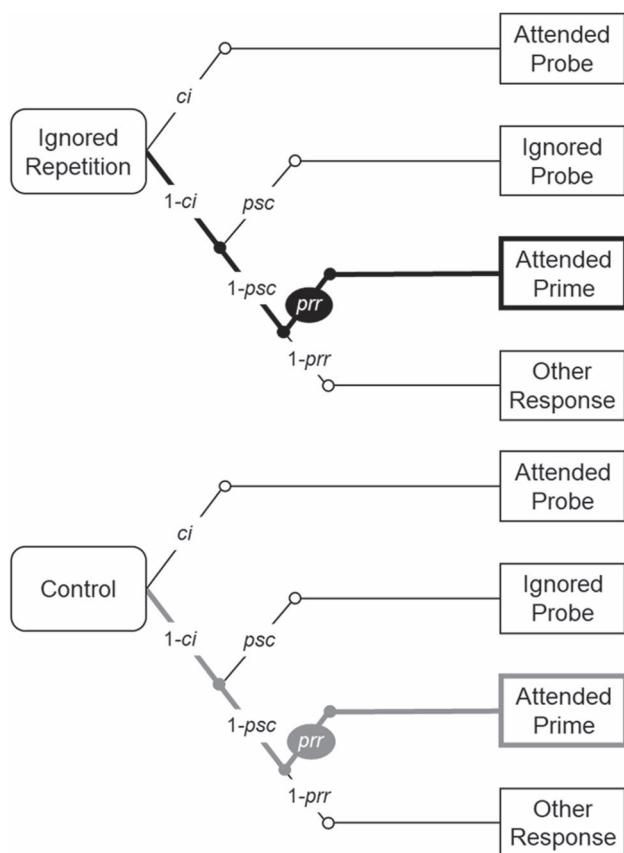


Fig. 1 The baseline multinomial processing tree model for analyzing the probe response in ignored repetition and control trials

describes the occurrence of probe responses in the four-alternative identification task as a result of different processes. Correct identification of the probe target (with probability ci^3) leads to a correct probe response. With probability $1 - ci$, an erroneous response will occur, either for the probe distractor (with conditional probability psc) or, alternatively, with the former prime response key (with conditional probability prr). Finally, if prime-response retrieval does not take place (with conditional probability $1 - prr$) an erroneous response with the remaining fourth response option is given.

The multinomial model allows for probability estimates and hypothesis testing. The stimulus–response binding and retrieval account predicts that the probability of prime response retrieval (i.e., prr) is larger when a stimulus is repeated than when it is changed. Accordingly, the probability of the prr parameter should be larger in ignored repetition trials (prr_{IR}) than in control trials (prr_C). This prediction was tested for each of the 2×3 (Context Relation \times Context Saliency) conditions by calculating the goodness-of-fit of a model with the restriction of equal prr parameters between the ignored repetition and control conditions (i.e., $prr_{IR} = prr_C$). A significant misfit of this restricted model to the empirical data will be evidence for the occurrence of the prime-response retrieval mechanism induced by the repetition of the prime distractor stimulus.

Moreover, we tested whether the context was integrated into stimulus–response episodes and how context saliency influenced the type of context integration (see Fig. 2 for prototypical result patterns of each type of context integration). This was done in two steps: First, we tested for the presence of a binary binding between context and response and, second, for the presence of a configural binding among context, distractor stimulus, and response. A binary binding between context and response would be indicated by a significant prime-response retrieval effect induced by the repetition of the context per se. Therefore, for each of the three saliency conditions, the processing trees of the context-repeated and the context-changed conditions were integrated into one model (i.e., the joint model) and the goodness-of-fit of this joint model with the restriction of equal prr_C parameters between the context-repeated and the context-changed conditions was tested.

Next, the presence of a configural binding among context, distractor stimulus, and response was analyzed for each level of context saliency. Evidence for a configural binding is demonstrated if the prime-response retrieval effect induced by the repetition of the prime distractor stimulus is larger in the context-repeated than in the context-changed

³ For the abbreviation of each parameter, ci means *correct identification*, psc means *probe stimulus confusion*, prr means *prime-response retrieval*.

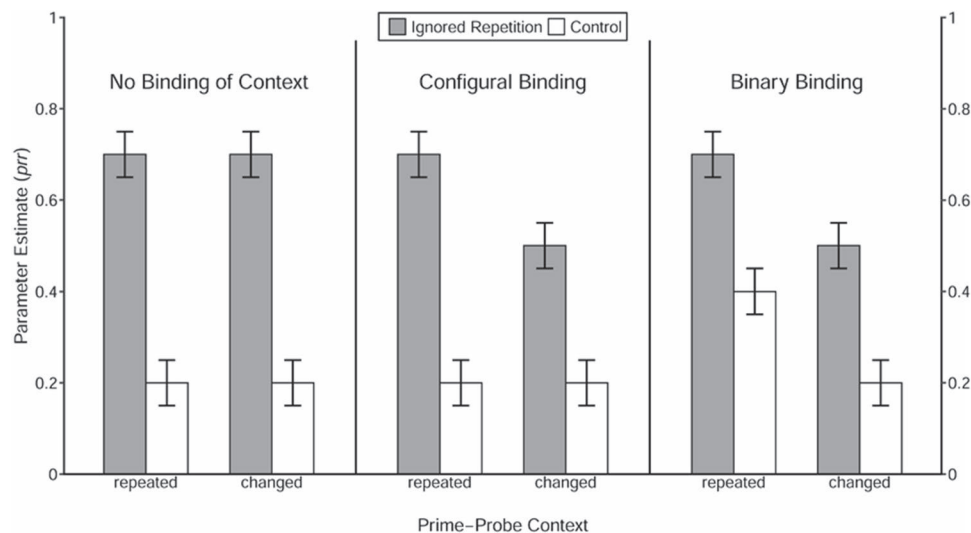


Fig. 2 Example of prototypical result patterns for each type of context integration. *Note.* The *prr* parameter represents the retrieval of the prime response induced by the repetition of stimuli (the distractor and/or the context). The pattern on the left depicts the situation when retrieval of the prime response is not influenced by repetition of the context per se nor by repetition of the distractor and context combination, indicating that the context is not integrated into a stimulus–response episode. The pattern in the middle depicts the situa-

tion when the repetition of the context per se does not improve the retrieval of the prime response, but boosts distractor-induced prime-response retrieval, indicating that the context is involved in a configural binding with the prime distractor stimulus and the response. The pattern on the right depicts the situation when the repetition of the context per se improves the retrieval of the prime response, but does not facilitate distractor-induced prime-response retrieval, indicating that the context is involved in a binary binding with the response

condition. This corresponds to an interaction effect between the factors context relation and trial type. The interaction analysis in MPT modeling requires reparameterization of the joint model (see Knapp & Batchelder, 2004, for details of reparameterization methods of MPT models, and please see the Appendix for detailed description of the reparameterized model and the interaction analysis used in the current study). In the reparameterized model, the prime-response retrieval effect induced by the repetition of the prime distractor stimulus can be represented by the difference between prr_{IR} and prr_C parameters (i.e., $prr_{IR} - prr_C$). All MPT analyses were run with the multiTree software (Moshagen, 2010).

With respect to statistical power considerations, the contextual modulation of the prime-response retrieval effect was of central interest. The difference in the size of the prime-response retrieval effect induced by the repetition of the prime distractor stimulus between context-repeated and context-changed trials found in Mayr et al. (2018) was relatively small ($\omega = .03$). To detect the contextual modulation of a similar size within each context-saliency condition, given desired levels of $\alpha = .05$ and $1 - \beta = .80$, approximately 8,721 trials in total were required for the model analysis. Since each participant maximally contributed 96 trials, that is, 24 trials for each 2×2 (Trial Type \times Context Relation) condition, data had to be collected from 91 participants. We were able to collect usable data from 106 participants (i.e., 10,176 trials); thus, the power was slightly larger than what

we had planned for ($1 - \beta = .86$). Note that in Experiment 1, 2A and 2B, p values for multiple comparisons were reported after Bonferroni-Holm correction (Holm, 1979). All sample size calculations were conducted using the G*Power program (Faul et al., 2009).

Results

Analyses of reaction times and overall error rates

A 2 (trial type: ignored repetition vs. control) \times 2 (context relation: repeated vs. changed) \times 3 (context saliency: low vs. moderate vs. high) repeated-measures multivariate analysis of variance (MANOVA) was applied to reaction times (see Table 2 for the main statistical results as well as Fig. 3 for an overview of the descriptive findings). The statistical analysis revealed a significant main effect of trial type, $F(1, 105) = 62.60, p < .001, \eta_p^2 = .37$. Probe responses were slower in the ignored repetition ($M_{RT} = 990$ ms) than in the control condition ($M_{RT} = 948$ ms), showing a significant negative priming effect in reaction times. There was also a significant main effect of context saliency, $F(2, 104) = 42.20, p < .001, \eta_p^2 = .45$. Probe responses were slower when context saliency was high ($M_{RT} = 1,008$ ms) than when it was moderate ($M_{RT} = 953$ ms), $F(1, 105) = 85.21, p < .001, \eta_p^2 = .45$, and low ($M_{RT} = 946$ ms), $F(1, 105) = 28.55, p < .001, \eta_p^2 = .21$. The difference of reaction times between the moderate-saliency and low-saliency conditions

Table 2 Statistical analysis results of reaction times and error rate of Experiment 1

Experiment	Repeated-measure MANOVA analysis	Results						
		Reaction Times			Error Rate			
		<i>F</i>	<i>p</i>	η_p^2	<i>F</i>	<i>p</i>	η_p^2	
Experiment 1	Main Effect	Trial Type	62.60	<.001	.37	39.91	<.001	.28
		Context Relation	0.31	.58	<.01	12.53	<.01	.11
		Context Saliency	42.20	<.001	.45	11.73	<.001	.18
	Pair-wise Comparison (Context saliency)	Low vs. Moderate	0.69	>.99	.01	0.13	>.99	<.01
		Moderate vs. High	85.21	<.001	.45	23.40	<.001	.18
		Low vs. High	28.55	<.001	.21	11.23	<.01	.10

was not significant, $F(1, 105) = 0.69, p > .99, \eta_p^2 = .01$. Potentially, these results indicate that it was more difficult

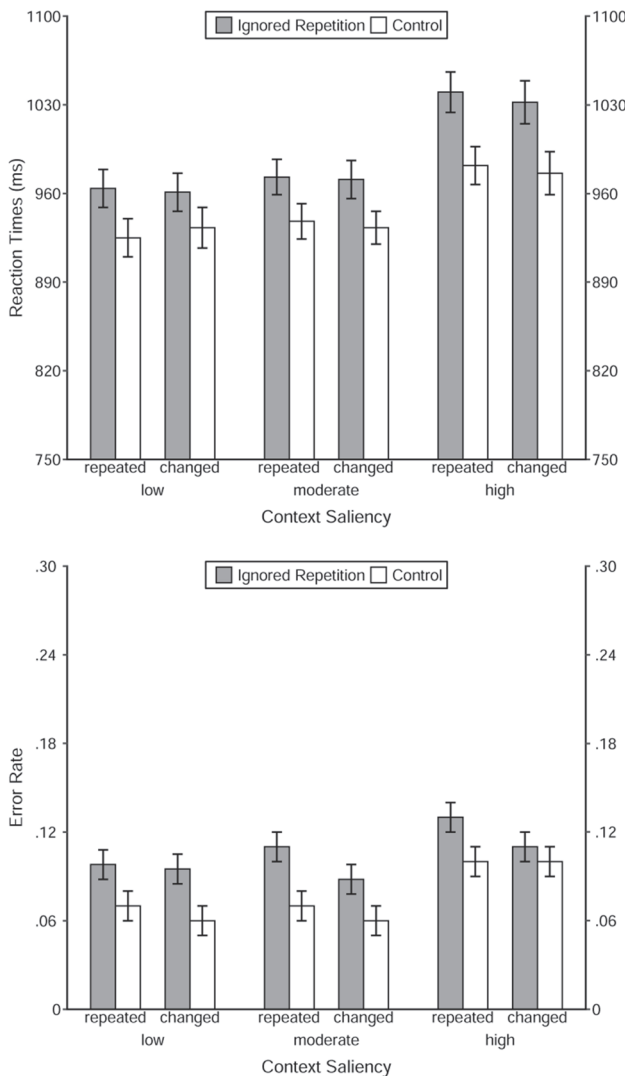


Fig. 3 Reaction times (upper panel) and error rate (lower panel) as function of trial type, context relation, and context saliency in Experiment 1. *Note.* The error bars depict the standard errors of the means

to identify or to focus on the task-relevant stimuli when the context was of high saliency. None of the other main or interaction effects was significant, all F s < 2.46, p s > .09.

The same MANOVA on error rates revealed a significant main effect of trial type, $F(1, 105) = 39.91, p < .001, \eta_p^2 = .28$, with higher error rates in the ignored repetition ($M_{\text{error rate}} = .10$) than in the control condition ($M_{\text{error rate}} = .07$). In other words, there was a significant negative priming effect in error rates. The main effect of context relation was also significant, $F(1, 105) = 12.53, p < .01, \eta_p^2 = .11$, showing that repetition of context in the probe presentation increased the probe error rates (for the context-repeated condition $M_{\text{error rate}} = .10$; for the context-changed condition, $M_{\text{error rate}} = .08$). Furthermore, there was a significant main effect of context saliency, $F(2, 104) = 11.73, p < .001, \eta_p^2 = .18$. The results pattern resembles that of the reaction times, specifically, the error rates were higher when context saliency was high ($M_{\text{error rate}} = .11$) than when it was moderate ($M_{\text{error rate}} = .08$), $F(1, 105) = 23.40, p < .001, \eta_p^2 = .18$, and when it was low ($M_{\text{error rate}} = .08$), $F(1, 105) = 11.23, p < .01, \eta_p^2 = .10$; whereas the difference in error rates between the moderate-saliency and low-saliency conditions was not significant, $F(1, 105) = 0.13, p > .99, \eta_p^2 < .01$. This pattern of results suggests that it might be more difficult to identify or to focus on the task-relevant stimuli when the context saliency was high. None of the interaction effects was significant, all F s < 2.52, p s > .11.

Multinomial analysis of categorial response frequencies

The estimated prime-response retrieval parameters prr_{IR} and prr_C for all conditions are depicted in Fig. 4. Statistical results are summarized in Table 3. The goodness-of-fit tests of the baseline model with the restriction $prr_{IR} = prr_C$ for each of the 2×3 (Context Relation \times Context Saliency) conditions revealed that the restricted model had to be rejected for each context-relation condition, regardless of the saliency level, G^2 s > 6.83, p s < .01, $\omega_s > .03$. These results demonstrate clear evidence that the repetition of the

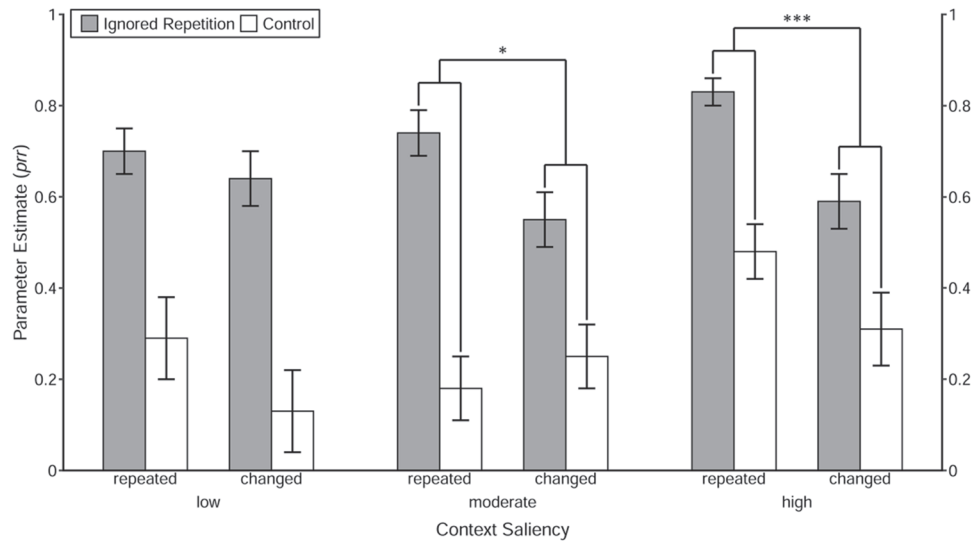


Fig. 4 Probability estimates for the model parameters representing the probability of prime-response retrieval (*prr*) as a function of trial type, context relation, and context saliency in Experiment 1. *Note.* The error bars depict the standard errors of the means. Annotation

shows significant comparisons indicating configural binding of the context. The symbols “*” and “***” indicate $p < .05$ and $p < .001$, respectively

Table 3 MPT model analysis results of Experiment 1

Model	Restriction	Goodness-of-fit test results								
		Low-saliency			Moderate-saliency			High-saliency		
		$G^2(1)$	p	ω	$G^2(1)$	p	ω	$G^2(1)$	p	ω
Baseline	$prr_{IR1} = prr_{C1}$	13.39	<.001	.05	31.68	<.001	.08	25.15	<.001	.07
	$prr_{IR2} = prr_{C2}$	13.70	<.001	.05	9.10	<.01	.04	6.84	<.01	.04
	$prr_{C1} = prr_{C2}$	1.38	.24	.01	0.50	.48	.01	2.56	.11	.02
Reparametrized	$prr_{IR1} - prr_{C1} = prr_{IR2} - prr_{C2}$	0.67	.41	.01	5.63	.02	.02	12.56	<.001	.04

Note. In the restriction equation of each model, 1 means context repetition, 2 means context change

prime distractor stimulus induced the retrieval of the prime response, which indicates that a binary binding was formed between the prime distractor stimulus and the response.

To investigate whether the repetition of context per se induced retrieval of the prime response (indicating evidence for binary binding between the context and the prime response), the prr_C parameters were then compared between the context-repeated and context-changed conditions when the saliency was low, moderate, and high, respectively. With the restriction of equivalence of the prr_C parameters between the context-repeated and context-changed conditions, the model fit the data in the low-saliency condition, $G^2(1) = 1.38$, $p = .24$, $\omega = .01$, and in the moderate-saliency condition, $G^2(1) = 0.50$, $p = .48$, $\omega = .01$. In the high-saliency condition, however, the misfit approached marginal significance, $G^2(1) = 2.56$, $p = .11$, $\omega = .02$. These results indicate

that there was no evidence for binary binding between the context and the prime response when context saliency was low or moderate. When context saliency was high, there was a tendency of binary binding formation.

We then tested whether the retrieval of the prime response induced by the repetition of the prime distractor stimulus was larger for context-repeated than for context-changed trials (indicating evidence for configural binding among context, distractor, and response) under each context-saliency condition. In the interaction analysis, the abovementioned reparametrized model was used (see Appendix). With the restriction of equivalence of the prime-response retrieval effect induced by the repetition of the prime distractor stimulus (i.e., $prr_{IR} - prr_C$) between context-repeated and context-changed trials, the goodness-of-fit tests showed a significant misfit in the moderate-saliency condition, $G^2(1) = 5.63$, p

$= .02$, $\omega = .02$, and in the high-saliency conditions, $G^2(1) = 12.56$, $p < .001$, $\omega = .04$, but not in the low-saliency condition, $G^2(1) = 0.67$, $p = .41$, $\omega = .01$. Together, the results indicated that the context of moderate or high saliency was involved in a configural binding with the prime distractor stimulus and the prime response, whereas the context of low saliency was not.

Discussion

The results showed that the saliency of the context is a crucial determinant in stimulus–response binding. Although a low saliency context was easily perceived (as the additional auditory test revealed), the repetition of this context per se neither led to an increase in prime response errors nor to a larger prime-response retrieval effect induced by the repetition of the prime distractor stimulus. However, the repetition of a moderately salient context significantly increased the prime-response retrieval effect induced by the repetition of the prime distractor stimulus, as compared with the condition without context repetition; but the moderate-saliency context itself did not lead to an increase of errors with the former prime response. As for the high-saliency condition, there was a tendency of a prime-response retrieval effect induced by the repetition of context information alone; and similar to the moderate-saliency condition, the context repetition significantly boosted the commission of prime-response errors due to the repetition of the prime distractor stimulus.

Together, the pattern of results indicates that saliency modulates the integration of context in a stimulus–response episode. Specifically, the results suggest that the context of low saliency was not integrated at all, and that the context of moderate saliency was involved in a configural binding. The context of high saliency, however, tended to be directly bound with the response. The fact that we only found a tendency of binary binding in the high-saliency condition may be due to insufficient context saliency. Possibly, the context was not loud enough to reach a sufficiently high-saliency level to enter into a binary binding. We did not want to exceed 80 dB(A) SPL for the overall sound compound due to ethical reasons. In order to conceptually replicate Experiment 1, saliency was manipulated differently in Experiment 2A and 2B—namely, by changing the value of the information carried by the context.

Experiment 2A

It has been consistently found that stimuli carrying emotional (especially negative or unpleasant) information are more salient than those containing neutral or nonemotional information (e.g., Biggs et al., 2012; Niu et al., 2012;

Ogawa & Suzuki, 2004). Therefore, Experiments 2A and 2B employed spoken vowels with either no (i.e., neutral) or a negative emotional pronunciation. Context sounds were as loud as the sound pair to keep the loudness-driven saliency constant between conditions. Given the comparable loudness, sounds without emotional pronunciation were considered to be as salient as the sound pair, comparable with the moderate saliency condition in Experiment 1. Therefore, the neutral context sounds were categorized as of moderate saliency. Due to their emotional information, the negative context sounds were considered more salient than the sound pair—thus, they were categorized as of high saliency. We expected that the context of high saliency should be bound directly with the response (i.e., binary binding), whereas the context of moderate saliency should be involved in a configural binding, as found for the moderate saliency condition in Experiment 1.

Method

Participants

One hundred and fifty English-speaking participants (71 females) were recruited for the current experiment using Prolific (<https://www.prolific.co>) for online data collection. None of them reported suffering from any kind of hearing problems. Data sets of seven participants had to be rejected because of excessive error frequencies ($>.50$) in ignored repetition and control conditions (as compared with the average of .18), which suggested either inability to perform the task or unwillingness to follow the instructions. Data from the remaining 143 participants entered the analysis. Their age ranged from 18 to 47 years ($M = 29$, $SD = 7.04$). Participants received 3.30 pounds for their participation.

Materials, task, and procedure

Materials, task and procedure were identical to those in Experiment 1 with the following exceptions. Four context sounds (i.e., the vowel “a” pronounced in an angry way as well as the vowel “e” pronounced in a disgusted manner and their neutral counterparts) were recorded from a female speaker using an iPhone 8 cellphone. The sounds were cut to a length of 300 ms and set to the same loudness. We also ran an auditory test to make sure the emotional and neutral context sounds were distinguishable. Participants who took part in the auditory test for Experiment 1 participated in this test, too. They listened to a random sequence of trials consisting of sound pairs with either the emotional context or the neutral context and were required to categorize the contexts as being emotional or neutral by pressing an appropriate key (key *F* for neutral, key *J* for emotional). The one-sample *t* test showed that the d' parameter ($M = 3.20$) was

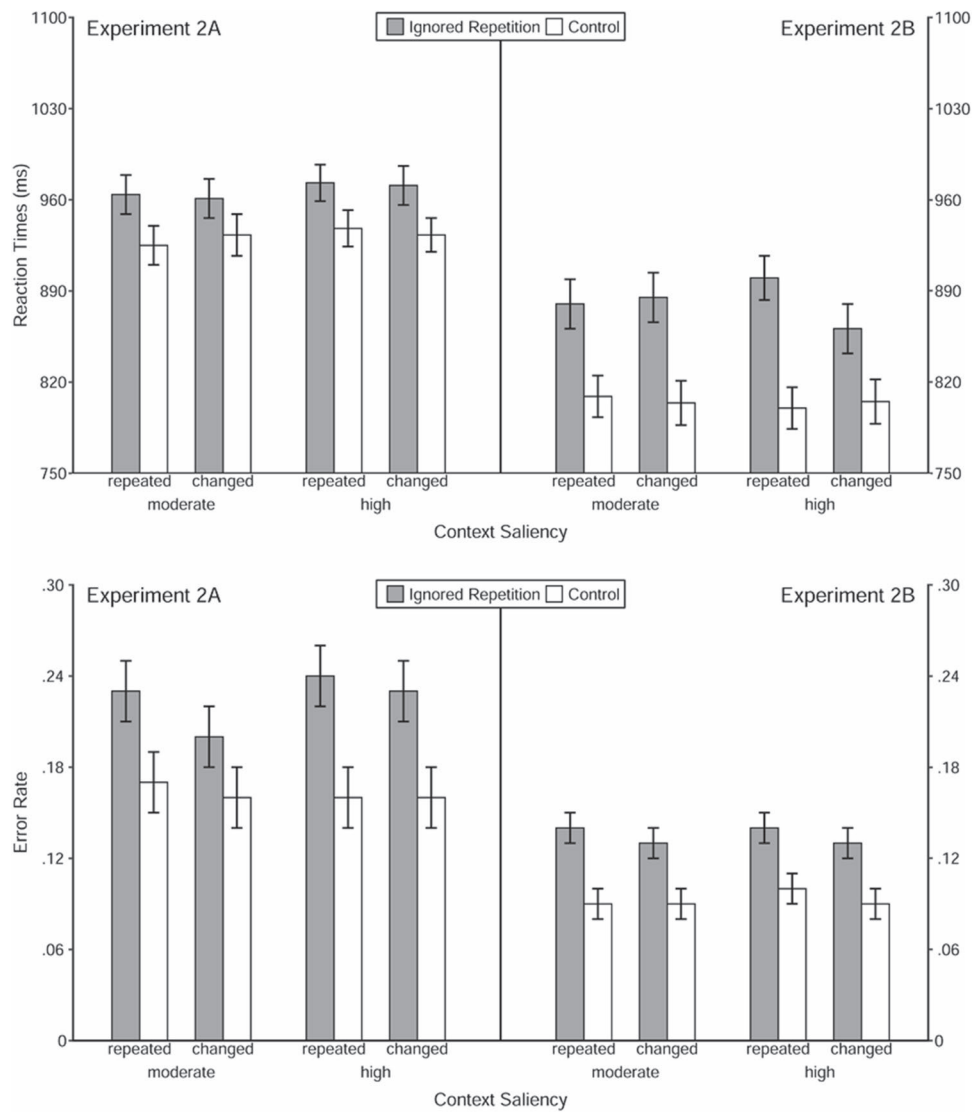


Fig. 5 Reaction times (upper panel) and error rate (lower panel) as function of trial type, context relation, and context saliency in Experiment 2A and 2B. *Note.* The error bars depict the standard errors of the means

Table 4 Statistical analysis results of reaction times and error rate of Experiments 2A and 2B

Experiment	Repeated-measure MANOVA analysis		Results					
			Reaction Times			Error Rate		
			<i>F</i>	<i>p</i>	η_p^2	<i>F</i>	<i>p</i>	η_p^2
Experiment 2A	Main Effect	Trial Type	84.85	<.001	.37	70.34	<.001	.33
		Context Relation	0.96	.33	.01	5.46	.02	.04
		Context Saliency	0.62	.43	<.01	1.20	.28	.01
Experiment 2B	Main Effect	Trial Type	115.65	<.001	.44	52.85	<.001	.27
		Context Relation	1.98	.16	.01	3.88	.05	.03
		Context Saliency	0.21	.65	<.01	0.35	.55	<.01

significantly different from zero, $t(15) = 4.94$, $p < .001$. Therefore, participants could easily distinguish between the emotional and neutral context sounds.

The four stimulus sounds were assigned to four basic keyboard keys, with “frog,” “piano,” “drum,” and “bell” assigned to keys *F*, *V*, *J*, and *N*, respectively. Participants were instructed to respond to the frog and the piano sounds using their middle and index fingers of the left hands, and to respond to the drum and the bell sounds using their middle and index fingers of the right hands.

To shorten the experiment for online data collection, the original 48 trials in the basic set were reduced to 32 trials, with the restriction that stimuli occurred equally often. The basic set was repeated four times (two times in the context-repeated condition and two times in the context-changed condition), resulting in a set of 128 trials. These 128 trials were duplicated (once for each of the two saliency conditions), thus there were 256 trials in total, which were presented in a random sequence.

The experiment was programmed using PsychoPy3 (Peirce et al., 2019), and was hosted on the Pavlovia platform (<https://pavlovia.org>). Participants from Prolific received an invitation to the experiment and were linked to Pavlovia. Participants were first instructed to use a headphone and to adjust the loudness to a comfortable level. After being introduced to the task, participants were familiarized with the four stimulus sounds. The training sessions were similar to those in Experiment 1, but the criterion to pass each training was set to 42% correct in 12 trials to reduce the overall task duration. Timing of the experimental trial was identical to Experiment 1, with the exception that the intertrial interval was prolonged to 2,000 ms. The experiment comprised 16 blocks with 16 experimental trials in each, and it took 30 to 45 minutes to finish.

Design and analysis

Experiment 2A comprised a $2 \times 2 \times 2$ within-subjects design, with trial type (ignored repetition vs. control), context relation (repeated vs. changed), and context saliency (moderate vs. high) as independent variables. Dependent variables were averaged reaction times, overall probe error rates, and, most importantly, probe response frequencies. The analysis of the categorical response frequencies followed the same rationale as in Experiment 1.

The current experiment contained fewer trials in each of the $2 \times 2 \times 2$ (Trial Type \times Context Relation \times Context Saliency) conditions as compared with Experiment 1 (i.e., 16 trials vs. 24 trials). Sample-size calculations followed the rationale of Experiment 1: To detect the contextual modulation of a similar effect size (i.e., $\omega = .03$), given desired levels of $\alpha = .05$ and $1 - \beta = .80$, probe response data had to be collected from 136 participants. The final sample comprised

143 participants (i.e., 9,152 trials), so the power was slightly larger (.82) than originally planned for.

Results

Analysis of reaction times and overall error rates

A 2 (trial type: ignored repetition vs. control) $\times 2$ (context relation: repeated vs. changed) $\times 2$ (context saliency: moderate vs. high) repeated-measures MANOVA was applied to reaction times (see Table 4 for the main statistical results as well as Fig. 5 for an overview of the descriptive finding). The main effect of trial type was significant, $F(1, 142) = 84.85$, $p < .001$, $\eta_p^2 = .37$; the probe responses were slower in ignored repetition trials ($M_{RT} = 963$ ms) than in control trials ($M_{RT} = 878$ ms), revealing a significant negative priming effect in reaction times. However, neither context relation nor context saliency affected reaction times—for the former, $F(1, 142) = 0.96$, $p = .33$, $\eta_p^2 = .01$, for the latter, $F(1, 142) = 0.62$, $p = .43$, $\eta_p^2 < .01$. None of the interaction effects was significant, all $F_s < 0.35$, $p_s > .55$.

The same MANOVA on error rates revealed a significant main effect of trial type as well, $F(1, 142) = 70.34$, $p < .001$, $\eta_p^2 = .33$; probe responding in ignored repetition trials ($M_{\text{error rate}} = .23$) comprised more errors than that in control trials ($M_{\text{error rate}} = .16$), showing a negative priming effect in error rates. The main effect of context relation was significant, $F(1, 142) = 5.46$, $p = .02$, $\eta_p^2 = .04$, with a higher error rate when context was repeated ($M_{\text{error rate}} = .20$) than when it was changed ($M_{\text{error rate}} = .19$), which replicates the findings in Experiment 1. The main effect of context saliency was not significant, $F(1, 142) = 1.20$, $p = .28$, $\eta_p^2 = .01$. None of the interaction effects reached the significance level, either—all $F_s < 2.92$, $p_s > .08$.

Multinomial analysis of categorical response frequencies

Estimated *prr* parameters are depicted in Fig. 6. Statistical results are summarized in Table 5. First, it was tested whether the repetition of the prime distractor stimulus induced the retrieval of the prime response, suggesting that a binary binding between prime distractor and response had been formed. Results of the goodness-of-fit tests of the baseline model with the restriction $prr_{IR} = prr_C$ showed evidence for the binary binding between prime distractor and response when context saliency was high, no matter whether the context was repeated, $G^2(1) = 4.40$, $p = .04$, $\omega = .03$, or changed, $G^2(1) = 6.25$, $p = .01$, $\omega = .04$. However, when context saliency was moderate, increased retrieval of the prime response due to repetition of the prime distractor stimulus was only found in the context-repeated condition, $G^2(1) = 4.53$, $p = .03$, $\omega = .03$, but not in the context-changed condition, $G^2(1) = 0.77$, $p = .38$, $\omega = .01$.

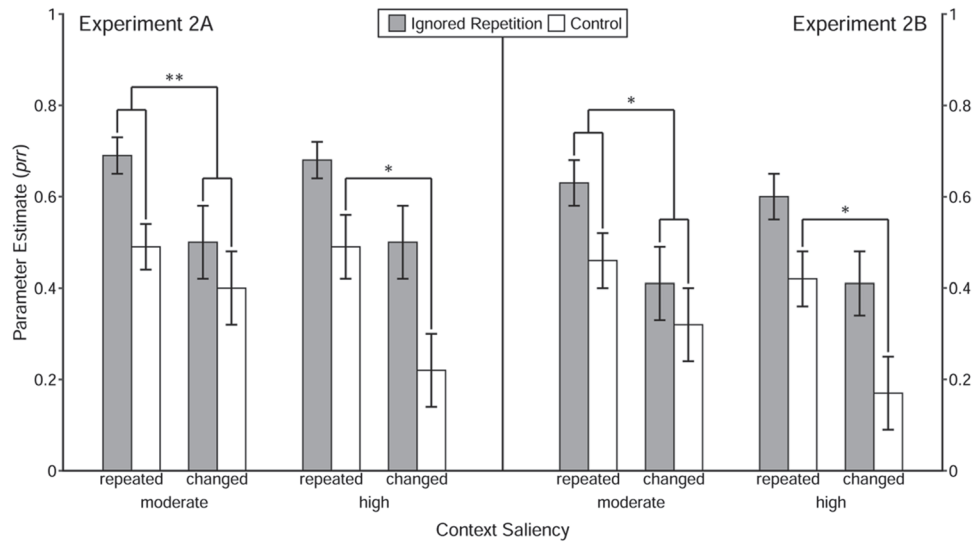


Fig. 6 Probability estimates for the model parameters representing the probability of prime-response retrieval (*prr*) as a function of trial type, context relation, and context saliency in Experiment 2A and 2B. *Note.* The error bars depict the standard errors of the means. Annota-

tion shows significant comparisons indicating configural and binary binding of the context. The symbols “*” and “**” indicates $p < .05$ and $p < .01$, respectively

Table 5 MPT model analysis results of Experiments 2A and 2B

Experiment	Model	Restriction	Goodness-of-fit test results					
			Moderate saliency			High saliency		
			$G^2(1)$	p	ω	$G^2(1)$	p	ω
Experiment 2A	Baseline	$prr_{IR1} = prr_{C1}$	4.53	.03	.03	4.40	.04	.03
		$prr_{IR2} = prr_{C2}$	0.77	.38	.01	6.25	.01	.04
		$prr_{C1} = prr_{C2}$	0.64	.42	.01	5.86	.02	.03
	Reparametrized	$prr_{IR1} - prr_{C1} = prr_{IR2} - prr_{C2}$	7.82	<.01	.03	0.37	.54	.01
Experiment 2B	Baseline	$prr_{IR1} = prr_{C1}$	5.29	.02	.04	4.49	.03	.03
		$prr_{IR2} = prr_{C2}$	1.80	.18	.02	5.03	.02	.03
		$prr_{C1} = prr_{C2}$	0.51	.47	.01	4.04	.04	.02
	Reparametrized	$prr_{IR1} - prr_{C1} = prr_{IR2} - prr_{C2}$	4.66	.03	.02	0.18	.67	<.01

Note. In the restriction equation of each model, 1 means context repetition, 2 means context change.

Then, to investigate whether it is solely the repetition of context that induced retrieval of the prime response (indicating evidence of binary binding between the context and the prime response), a restricted model with equivalent prr_C parameters in the context-repeated and the context-changed conditions was tested. Results revealed a significant misfit of the restricted model in the high-saliency condition, $G^2(1) = 5.86, p = .02, \omega = .03$, but not in the moderate-saliency condition, $G^2(1) = 0.64, p = .42, \omega = .01$. This suggests that the context of high saliency was involved in a binary binding with the response, whereas the context of moderate saliency was not.

Finally, a reparametrized model was used to test the configural binding hypothesis. With the restriction of

equivalence of the prime-response retrieval effect (i.e., $prr_{IR} - prr_C$) between context-repeated and context-changed trials, the goodness-of-fit tests showed a significant misfit in the moderate-saliency condition, $G^2(1) = 7.82, p < .01, \omega = .03$, but not in the high-saliency condition, $G^2(1) = 0.37, p = .54, \omega = .01$. These results indicate that the context of moderate saliency was involved in a configural binding with the prime distractor stimulus and the prime response, whereas the context of high saliency was not.

Discussion

Experiment 2A demonstrates that the repetition of a highly salient context per se significantly increases the

probability of retrieving the prime response as compared with a condition without context repetition. In contrast, the repetition of a context of moderate saliency did not retrieve the prime response on its own but increased the prime-response retrieval effect induced by the repetition of the prime distractor stimulus as compared with a changed context.

The results of Experiment 2A replicate the findings from Experiment 1, again revealing evidence of configural binding among the moderately salient context, the prime distractor, and the response. Furthermore, the results provide evidence for a binary binding between the highly salient context and the response (for which only a tendency was found in Experiment 1). In sum, results from Experiment 2A underline the conclusion from Experiment 1 that the specific binding between context and other elements of an episode is determined by context saliency. Specifically, a context of high saliency is involved in a binary binding with the response, whereas a context of moderate saliency is involved in a configural binding among several elements (stimuli and response).

Experiment 2B

Method

Participants

Among the 150 German-speaking participants (66 females), 30 of whom were students of the University of Passau, the remaining participants were from the Prolific platform. Data sets of three participants had to be excluded because of exceeding error rates ($>.5$) in ignored repetition and control conditions (as compared with the average of around .11), which suggests either unwillingness or inability to follow the instruction. The remaining 147 participants whose data sets entered into the analysis ranged in age from 18 to 41 years ($M = 26$, $SD = 5.62$). Students from the University of Passau received course credit for their participation, whereas participants from the Prolific platform received 3.30 pounds monetary reward.

Materials, task, procedure, and design

Materials, task, procedure and design were identical to those in Experiment 2A. To detect the contextual modulation of a similar effect size as in Experiment 2A (i.e., $\omega = .03$), given desired levels of $\alpha = .05$ and $1 - \beta = .80$, probe response data had to be collected from a sample of 136 participants. The final sample comprised 147 participants (i.e., 9,408 trials), so the power was slightly larger than what we had planned for ($1 - \beta = .83$).

Results

Analysis of reaction times and overall error rates

A 2 (trial type: ignored repetition vs. control) \times 2 (context relation: repeated vs. changed) \times 2 (context saliency: moderate vs. high) repeated-measures MANOVA was applied to reaction times and error rates. The main effect of trial type was significant in reaction times, $F(1, 146) = 115.65$, $p < .001$, $\eta_p^2 = .44$, and in error rates, $F(1, 146) = 52.85$, $p < .001$, $\eta_p^2 = .27$. The probe responses were slower and more error prone in ignored repetition trials ($M_{RT} = 883$ ms, $M_{\text{error rate}} = .13$) than in control trials ($M_{RT} = 805$ ms, $M_{\text{error rate}} = .09$), revealing a negative priming effect in both dependent measures. The manipulation of context (i.e., context relation or context saliency) did not affect reaction times, whereas a marginally significant main effect of context relation was found in error rates, $F(1, 146) = 3.88$, $p = .05$, $\eta_p^2 = .03$, with a relatively higher error rate when the context was repeated ($M_{\text{error rate}} = .12$) than when it was changed ($M_{\text{error rate}} = .11$). None of the interaction effects was significant, all F s < 3.74 , p s $> .05$.

Multinomial analysis of categorical response frequencies

Firstly, the prime-response retrieval effect induced by the repetition of the prime distractor stimulus was investigated. With the restriction $prr_{IR} = prr_C$, the restricted model had to be rejected when the context saliency was high, regardless of whether the context was repeated, $G^2(1) = 4.49$, $p = .03$, $\omega = .03$, or changed, $G^2(1) = 5.03$, $p = .02$, $\omega = .03$. When context saliency was moderate, the restricted model had to be rejected only when the context was repeated, $G^2(1) = 5.29$, $p = .02$, $\omega = .04$, but not when the context was changed, $G^2(1) = 1.80$, $p = .18$, $\omega = .02$.

Then, the prime-response retrieval effect induced by the repetition of the context per se was investigated. To this end, a restricted model with equivalent prr_C parameters in the context-repeated and the context-changed conditions was tested. Results revealed a significant misfit of the restricted model in the high-saliency condition, $G^2(1) = 4.04$, $p = .04$, $\omega = .02$, but not in the moderate-saliency condition, $G^2(1) = 0.51$, $p = .47$, $\omega = .01$. This suggests that the context of high saliency was involved in a binary binding with the response, whereas the context of moderate saliency was not.

Finally, a reparametrized model was used to test the configural binding hypothesis. With the restriction of equivalence of the prime-response retrieval effect (i.e., $prr_{IR} - prr_C$) between context-repeated and changed trials, the goodness-of-fit tests showed a significant misfit in the moderate-saliency condition, $G^2(1) = 4.66$, $p =$

.03, $\omega = .02$, but not in the high-saliency condition, $G^2(1) = 0.18$, $p = .67$, $\omega < .01$. These results indicate that the context of moderate saliency was involved in a configural binding with the prime distractor stimulus and the prime response, whereas the context of high saliency was not.

Discussion

With a different sample of participants, Experiment 2B showed the identical results pattern as in Experiment 2A. Specifically, the prime-response retrieval effect induced by the repetition of the context per se was significant in the high-saliency condition, but not in the moderate-saliency condition. However, the contextual modulation of the prime-response retrieval effect induced by the repetition of the prime distractor stimulus was significant in the moderate-saliency condition, but not in the high-saliency condition. Together, results in Experiment 2B show again, that the context of high saliency is involved in a binary binding with the response, whereas the context of moderate saliency is involved in a configural binding together with the prime distractor stimulus and the response.

General discussion

The goal of the current study was to elucidate the integration of context in a stimulus–response episode, with a focus on the role of saliency. To this end, the saliency of an auditory context was manipulated by changing its loudness (Experiment 1) and emotional valence (Experiments 2A and 2B). Despite the different ways of the saliency manipulation, the results of all experiments showed a similar pattern of results in the moderate-saliency condition: the prime-response retrieval effect induced by the repetition of the prime distractor stimulus was larger when the context was repeated than when it was changed, but the context repetition alone did not retrieve the prime response. This constitutes a replication of the findings reported by Mayr et al. (2018). More importantly, in the high-saliency condition, results from Experiments 2A and 2B show that the repetition of the context did not increase the prime-response retrieval effect induced by the repetition of the prime distractor stimulus, but it retrieved the prime response on its own. Note that in the high-saliency condition of Experiment 1, results only revealed a tendency of such a direct response retrieval induced by context repetition, presumably due to insufficient context saliency. On the other hand, the repetition of the highly salient context in Experiment 1 boosted the prime-response retrieval effect induced by

the repetition of the prime distractor. As for the low-saliency condition, results from Experiment 1 show that repetition of context per se did not retrieve the prime response, and that repetition of context did not boost the probability of retrieving the prime response induced by the repetition of the prime distractor stimulus, either. Taken together, Experiments 1, 2A, and 2B provide empirical evidence that saliency is a determinant of context integration. Specifically, context of low saliency is not integrated into a stimulus–response episode at all, context of moderate saliency is involved in a configural binding, whereas context of (sufficiently) high saliency enters into a binary binding with the response.

The integration of context as a function of saliency level is consistent with proposed assumptions about binding principles (Hommel, 2004). Following this notion, a binary binding between a task-irrelevant stimulus and a response is only formed when the stimulus is salient enough to pass a certain integration threshold. If this threshold is missed, the stimulus will not be integrated at all (e.g., Dutzi & Hommel, 2009). This pattern describes what we found in the (sufficiently) high-saliency versus low-saliency conditions in the current study. However, the findings of configural binding structures in Experiments 1, 2A, and 2B might extend this binding principle: If a stimulus passes the basic integration threshold (and is therefore bound), a second saliency threshold will then determine the specific binding structure (i.e., binary vs. configural). When the saliency of a stimulus is sufficient to be integrated but misses the threshold for binary binding, it will enter into a configural binding. Otherwise, it will be bound with the response in a binary fashion.

The distinction between binary and configural bindings based on the saliency level may result from the influence of saliency on the perception of a stimulus—that is, whether the stimulus is perceived as an individual object or not. Referring to the figure–ground segmentation literature, there is evidence that saliency determines whether a part of a stimulus is perceived as a *figural element/object* or the *background* of other parts (Hoffman & Singh, 1997; Wagemans et al., 2012). In essence, with other properties being equal, the more salient part will be assigned the status as the “figure” in a display. Transferring this finding into the auditory modality, it is likely that the auditory contextual stimulus of high saliency will be perceived as an individual object, whereas the stimulus of relatively lower saliency may be perceived as the background of the other stimuli. Furthermore, given that the latter is presumably more similar to the other stimuli (in the sense of saliency level operationally defined by loudness and emotional valence in the current

study) than the former, the latter may be more likely to be perceptually grouped with the other stimuli (Wagemans et al., 2012), thereby forming a compound.⁴ Together, the “figure” object, which is presumably distinguishable from other stimuli, is more likely to enter a binary binding with the response (Moeller et al., 2016), whereas the “background” may be involved in a configural binding as a part of a compound. This notion fully conforms to what we found in the current study.

The current findings bear resemblance to findings in learning—namely, *configural* and *elemental* associations in classical conditioning (for a review, see Pearce & Bouton, 2001). While the former assumes an association between a compound of elements with a reinforcer (Shanks et al., 1998), the latter assumes unitary association between each element and the reinforcer (Rescorla & Wagner, 1971). Recently, these two types of associations were found to coexist but to be supported by different neural systems (for a review, see Honey et al., 2014). For example, Iordanova et al. (2009) found that healthy rats could form both elemental and configural association, but lesions in the hippocampus left rats reliant on elemental associations, which means the hippocampus is involved in configural but not in elemental associations. For another example, the retrosplenial cortex, which is involved in contextual fear conditioning, was found to contribute more to the configural approach (Todd et al., 2017). Assuming an overlap between the mechanisms involved in binding and conditioning, the distinction by the second saliency threshold that decides whether the context is involved in configural or binary binding might have a neural basis. With that being said, future studies are required to investigate the neural basis of our findings.

Note that the current study did not reveal significant contextual modulation of the negative priming effect in reaction times or in overall error rates. This is consistent with the previous study by Mayr et al. (2018), in which the prime-response retrieval process was found to be the only mechanism underlying the negative priming effect that was sensitive to contextual modulation. However, it is noteworthy that in the visual modality the contextual modulation of the negative priming effect has been consistently found (e.g., Chao, 2009; Chao & Yeh, 2008), reasons for this difference between modalities should be investigated in future studies.

To sum up, the current study manipulated the saliency property of context to investigate its influence on the

integration of context in stimulus–response episodes. Results show that only contextual stimuli of sufficient saliency can be integrated into a stimulus–response episode, entering into either a configural or a binary structure, depending on the context saliency level. Taken together, the current study provides detailed insights into the architecture of bindings between completely task-irrelevant features and actions, and thus sheds light on how contextual information influences human behavior.

Appendix

Standard statistical testing procedures of MPT models only concern testing the equivalence between model parameters. To analyze interaction effects—in this case, whether the prime-response retrieval effect (as the difference between the *pr* parameters in the ignored repetition condition, represented by “IR,” and the control condition, represented by “C”) is larger in the context repeated than in the context changed condition—requires a so-called reparameterization (see Knapp & Batchelder, 2004). This process introduces new parameters to represent certain effects. With these new parameters, it can be tested whether certain effects (here: $pr_{IR} - pr_C$) differ between conditions (here, the context-repeated vs. the context-changed condition). The interaction analysis used in the current study is described in the following.

The reparameterization is applied to the baseline model introduced by Mayr and Buchner (2006) for testing the prime-response retrieval effect (see Fig. 1 in the main text). Assuming a joint model of the two context-relation conditions (repeated vs. changed), the *pr* parameters in each baseline model can be presented with the subscript “REP” for the context-repeated condition, and the subscript “CH” for the context-changed condition, respectively.

Referring to Knapp and Batchelder (2004), there are two basic methods to reparametrize MPT models, called Method A and B, respectively. If we have two parameters of interest, θ_1 and θ_2 (with the order restriction $0 \leq \theta_1 \leq \theta_2 \leq 1$) in the original model, according to Method A, a new parameter α can be introduced to reparametrize the original model, with $\alpha = \theta_1 / \theta_2$. As for Method B, instead, a new parameter β can be introduced to reparametrize the original model, with $\beta = (\theta_2 - \theta_1) / (1 - \theta_1)$. Method A and B can be applied additively if necessary, as long as the resulting reparametrized model is statistically equivalent to the original model (i.e., results of the goodness-of-fit test of these models with the same set of empirical data should be identical) and the reparametrized model itself is identifiable. Both Method A

⁴ We thank an anonymous reviewer for this idea that similarity breeds perceptual grouping, which may result in a compound of the distractor stimulus and the response in the so-called configural binding.

and B are used for the current analysis. The procedure is described in detail in the following.

First, Method B is applied to the joint model to represent the prime-response retrieval effects (i.e., the difference between the prr_{IR} and the prr_C parameters) with the context repeated (i.e., $prr_{IR_REP} - prr_{C_REP}$) or changed (i.e., $prr_{IR_CH} - prr_{C_CH}$). The resulting model is called the β -reparametrized model. In the β -reparametrized model for each saliency condition, there are two β parameters, one for the context-repeated condition ($\beta_{REP} = [prr_{IR_REP} - prr_{C_REP}] / [1 - prr_{C_REP}]$) and one for the context-changed condition ($\beta_{CH} = [prr_{IR_CH} - prr_{C_CH}] / [1 - prr_{C_CH}]$). For empirical data from each saliency condition of the current experiments, the goodness-of-fit test of the β -reparametrized model yielded the same result as the one for the joint model, $G^2(0) = 0$. The local identifiability test (repeatedly estimating 1,000 times) using multiTree (Moshagen, 2010) showed almost no deviations in any of the parameter estimates (all deviations ≤ 0.00001). Similarly, the simulated identifiability test yielded an average deviation smaller than 0.00001. In the β -reparametrized model, the prime-response retrieval effect in the context-repeated (i.e., $prr_{IR_REP} - prr_{C_REP}$) and context-changed conditions (i.e., $prr_{IR_CH} - prr_{C_CH}$) can be represented as follows:

$$prr_{IR_REP} - prr_{C_REP} = \beta_{REP} \cdot (1 - prr_{C_REP}), \quad (1)$$

$$prr_{IR_CH} - prr_{C_CH} = \beta_{CH} \cdot (1 - prr_{C_CH}). \quad (2)$$

To determine whether the prime-response retrieval effect in the context-repeated condition is different from that in the context-changed condition, we tested whether the quotient of $(prr_{IR_REP} - prr_{C_REP})$ and $(prr_{IR_CH} - prr_{C_CH})$ equals 1. Combining Eqs. 1 and 2, the following relation is tested:

$$\frac{\beta_{REP}}{\beta_{CH}} \cdot \frac{1 - prr_{C_REP}}{1 - prr_{C_CH}} = 1. \quad (3)$$

If the prr_{C_REP} parameter is statistically equivalent to the prr_{C_CH} parameter in the joint model, a nested model with an additional restriction $\beta_{REP} = \beta_{CH}$ can be built to test whether the β parameters are equal as well. Note that this nested model is equivalent to a model with the restriction $(prr_{IR_REP} - prr_{C_REP}) = (prr_{IR_CH} - prr_{C_CH})$. This nested model analysis was applied in the low-saliency, moderate-saliency, and high-saliency conditions in Experiment 1 as well as the moderate-saliency condition in Experiments 2A and 2B, because the

restricted model with the restriction $prr_{C_REP} = prr_{C_CH}$ did not yield significant misfit with the empirical data in these conditions.

When the model with the restriction $prr_{C_REP} = prr_{C_CH}$ has to be rejected for the empirical data, which is the case in the high-saliency condition of Experiments 2A and 2B, the nested model mentioned above can no longer test whether Eq. 3 is satisfied or not. Thus, further reparameterization is required, which is described in the following.

An equal transformation of Eq. 3 will be:

$$\frac{\beta_{CH}}{\beta_{REP}} = \frac{1 - prr_{C_REP}}{1 - prr_{C_CH}}. \quad (4)$$

If Eq. 4 is satisfied, then Eq. 3 is satisfied as well, which means there is no statistical difference between $(prr_{IR_REP} - prr_{C_REP})$ and $(prr_{IR_CH} - prr_{C_CH})$. Instead, if Eq. 4 is not satisfied, then Eq. 3 will not be satisfied, indicating that $(prr_{IR_REP} - prr_{C_REP})$ and $(prr_{IR_CH} - prr_{C_CH})$ are statistically different from each other.

To test whether Eq. 4 is satisfied or not, quotients on the left and right side of Eq. 4 need to be represented by new parameters, because MPT model analysis does not allow for directly testing the equivalence of two quotients of model parameters, but allows for testing the equivalence of two model parameters. Here, Method A can be applied to the β -reparametrized model to represent these quotients with two new α parameters. Specifically, we can get an α_{beta} parameter which equals $(\beta_{CH} / \beta_{REP})$, and an α_{prr_C} parameter which equals $(1 - prr_{C_REP}) / (1 - prr_{C_CH})$. Equation 4 can then be represented as:

$$\alpha_{beta} = \alpha_{prr_C}. \quad (5)$$

Now, with these two new α parameters, we get a fully reparametrized model. This fully reparametrized model yielded the same model fit as the joint model for empirical data from the high-saliency condition in Experiment 2A, $G^2(0) = 0$, and in Experiment 2B, $G^2(0) = 0$. In addition, the local identifiability test using multiTree showed almost no deviations in any of the parameter estimates (all deviations ≤ 0.00005). Similarly, the simulated identifiability test yielded an average deviation smaller than 0.00001. With this fully reparametrized model, we can directly test the difference between $(prr_{IR_REP} - prr_{C_REP})$ and $(prr_{IR_CH} - prr_{C_CH})$ by restricting $\alpha_{beta} = \alpha_{prr_C}$. Parameter estimates in the joint and reparametrized models are displayed in Appendix Tables 6, 7 and 8 for Experiment 1, 2A, and 2B, respectively.

Table 6 Parameter estimates from the joint and reparametrized models for Experiment 1

	Context Repeated						Context Changed						New Parameters																	
	Control			Control			Ignored Repetition			Control			<i>prr</i>	<i>psc</i>	<i>ci</i>	<i>prr</i>	<i>psc</i>	<i>ci</i>	<i>prr</i>	<i>psc</i>	<i>ci</i>	<i>prr</i>	<i>psc</i>	<i>ci</i>	β_{CH}	β_{REP}	α_{beta}	α_{prrC}	G^2	
	<i>prr</i>	<i>psc</i>	<i>ci</i>	<i>prr</i>	<i>psc</i>	<i>ci</i>	<i>prr</i>	<i>psc</i>	<i>ci</i>	<i>prr</i>	<i>psc</i>	<i>ci</i>																		<i>prr</i>
Joint Model (low-saliency condition)																														
0.90	0.58	0.70	0.94	0.82	0.29	0.29	0.91	0.67	0.64	0.87	0.13	0.95	0.87	0.13	0.95	0.87	0.13	0.95	0.87	0.13	0.95	0.87	0.13	0.95	0.87	0.13	0.95	0.87	0.13	0
	(0.01)	(0.03)	(0.05)	(0.01)	(0.03)	(0.09)	(0.01)	(0.03)	(0.06)	(0.03)	(0.09)	(0.01)	(0.03)	(0.06)	(0.01)	(0.03)	(0.09)	(0.01)	(0.03)	(0.06)	(0.01)	(0.03)	(0.09)	(0.01)	(0.03)	(0.06)	(0.01)	(0.03)		
β -reparametrized Model (low-saliency condition)																														
0.90	0.58	0.94	0.94	0.82	0.29	0.29	0.91	0.67	0.64	0.87	0.13	0.95	0.87	0.13	0.95	0.87	0.13	0.95	0.87	0.13	0.95	0.87	0.13	0.95	0.87	0.13	0.95	0.87	0.13	0
	(0.01)	(0.03)	(0.01)	(0.03)	(0.09)	(0.09)	(0.01)	(0.03)	(0.06)	(0.03)	(0.09)	(0.01)	(0.03)	(0.06)	(0.01)	(0.03)	(0.09)	(0.01)	(0.03)	(0.06)	(0.01)	(0.03)	(0.09)	(0.01)	(0.03)	(0.06)	(0.01)	(0.03)		
Joint Model (moderate-saliency condition)																														
0.90	0.65	0.74	0.93	0.79	0.18	0.18	0.92	0.69	0.55	0.71	0.25	0.94	0.71	0.25	0.94	0.71	0.25	0.94	0.71	0.25	0.94	0.71	0.25	0.94	0.71	0.25	0.94	0.71	0.25	0
	(0.01)	(0.03)	(0.05)	(0.01)	(0.03)	(0.07)	(0.01)	(0.03)	(0.06)	(0.04)	(0.07)	(0.01)	(0.03)	(0.06)	(0.01)	(0.03)	(0.07)	(0.01)	(0.03)	(0.06)	(0.01)	(0.03)	(0.07)	(0.01)	(0.03)	(0.06)	(0.01)	(0.03)		
β -reparametrized Model (moderate-saliency condition)																														
0.90	0.65	0.93	0.93	0.79	0.18	0.18	0.92	0.69	0.55	0.71	0.25	0.94	0.71	0.25	0.94	0.71	0.25	0.94	0.71	0.25	0.94	0.71	0.25	0.94	0.71	0.25	0.94	0.71	0.25	0
	(0.01)	(0.03)	(0.01)	(0.03)	(0.07)	(0.07)	(0.01)	(0.03)	(0.06)	(0.04)	(0.07)	(0.01)	(0.03)	(0.06)	(0.01)	(0.03)	(0.07)	(0.01)	(0.03)	(0.06)	(0.01)	(0.03)	(0.07)	(0.01)	(0.03)	(0.06)	(0.01)	(0.03)		
Joint Model (high-saliency condition)																														
0.88	0.59	0.83	0.91	0.68	0.48	0.48	0.90	0.72	0.59	0.82	0.31	0.92	0.82	0.31	0.92	0.82	0.31	0.92	0.82	0.31	0.92	0.82	0.31	0.92	0.82	0.31	0.92	0.82	0.31	0
	(0.01)	(0.03)	(0.03)	(0.01)	(0.03)	(0.06)	(0.01)	(0.03)	(0.06)	(0.03)	(0.08)	(0.01)	(0.03)	(0.06)	(0.01)	(0.03)	(0.08)	(0.01)	(0.03)	(0.06)	(0.01)	(0.03)	(0.08)	(0.01)	(0.03)	(0.06)	(0.01)	(0.03)		
β -reparametrized Model (high-saliency condition)																														
0.88	0.59	0.91	0.91	0.68	0.48	0.48	0.90	0.72	0.59	0.82	0.31	0.92	0.82	0.31	0.92	0.82	0.31	0.92	0.82	0.31	0.92	0.82	0.31	0.92	0.82	0.31	0.92	0.82	0.31	0
	(0.01)	(0.03)	(0.01)	(0.03)	(0.06)	(0.06)	(0.01)	(0.03)	(0.06)	(0.03)	(0.08)	(0.01)	(0.03)	(0.06)	(0.01)	(0.03)	(0.08)	(0.01)	(0.03)	(0.06)	(0.01)	(0.03)	(0.08)	(0.01)	(0.03)	(0.06)	(0.01)	(0.03)		

Note. The degree of freedom of G^2 is 0

Table 7 Parameter estimates from the joint and reparametrized models for Experiment 2A

Context Repeated				Context Changed				New Parameters								
Ignored Repetition				Ignored Repetition				Control								
<i>ci</i>	<i>psc</i>	<i>pr</i>	<i>ci</i>	<i>psc</i>	<i>pr</i>	<i>ci</i>	<i>psc</i>	<i>pr</i>	<i>ci</i>	<i>psc</i>	<i>pr</i>	β_{CH}	β_{REP}	α_{beta}	α_{prc}	G^2
Joint Model (moderate-saliency condition)																
0.80	0.72	0.69	0.87	0.83	0.50	0.81	0.75	0.49	0.88	0.84	0.41					0
(0.01)	(0.02)	(0.04)	(0.01)	(0.02)	(0.08)	(0.01)	(0.02)	(0.05)	(0.01)	(0.02)	(0.08)					
β -reparametrized Model (moderate-saliency condition)																
0.80	0.72		0.87	0.83	0.50	0.81	0.75		0.88	0.84	0.41	0.14	0.38			0
(0.01)	(0.02)		(0.01)	(0.02)	(0.08)	(0.01)	(0.02)		(0.01)	(0.02)	(0.08)	(0.15)	(0.13)			
Joint Model (high-saliency condition)																
0.81	0.69	0.68	0.86	0.84	0.50	0.83	0.81	0.49	0.87	0.87	0.23					0
(0.01)	(0.02)	(0.04)	(0.01)	(0.02)	(0.08)	(0.01)	(0.01)	(0.07)	(0.01)	(0.02)	(0.08)					
β -reparametrized Model (high-saliency condition)																
0.81	0.69		0.86	0.84	0.50	0.83	0.81		0.87	0.87	0.23	0.34	0.37			0
(0.01)	(0.02)		(0.01)	(0.02)	(0.08)	(0.01)	(0.01)		(0.01)	(0.02)	(0.08)	(0.11)	(0.13)			
Fully Reparametrized Model (high-saliency condition)																
0.81	0.69		0.86	0.84		0.83	0.81		0.87	0.87	0.23	0.37	0.93	0.65		0
(0.01)	(0.02)		(0.01)	(0.02)		(0.01)	(0.01)		(0.01)	(0.02)	(0.08)	(0.13)	(0.44)	(0.12)		

Note. The degree of freedom of G^2 is 0

Table 8 Parameter estimates from the joint and reparametrized models for Experiment 2B

Context Repeated				Context Changed				New Parameters								
Ignored Repetition				Ignored Repetition				Control								
<i>ci</i>	<i>psc</i>	<i>pr</i>	<i>ci</i>	<i>psc</i>	<i>pr</i>	<i>ci</i>	<i>psc</i>	<i>pr</i>	<i>ci</i>	<i>psc</i>	<i>pr</i>	β_{CH}	β_{REP}	α_{beta}	α_{prC}	G^2
Joint Model (moderate-saliency condition)																
0.87	0.70	0.63	0.92	0.78	0.40	0.89	0.70	0.46	0.92	0.80	0.32					0
(0.01)	(0.03)	(0.05)	(0.02)	(0.03)	(0.08)	(0.01)	(0.03)	(0.06)	(0.01)	(0.03)	(0.08)					
β -reparametrized Model (moderate-saliency condition)																
0.87	0.70		0.92	0.78	0.40	0.89	0.70		0.92	0.80	0.32	0.20	0.38			0
(0.01)	(0.03)		(0.02)	(0.03)	(0.08)	(0.01)	(0.03)		(0.01)	(0.03)	(0.08)	(0.13)	(0.12)			
Joint Model (high-saliency condition)																
0.87	0.67	0.60	0.91	0.76	0.41	0.89	0.72	0.42	0.92	0.86	0.17					0
(0.01)	(0.03)	(0.05)	(0.01)	(0.03)	(0.07)	(0.01)	(0.03)	(0.06)	(0.01)	(0.03)	(0.08)					
β -reparametrized Model (high-saliency condition)																
0.87	0.67		0.91	0.76	0.41	0.89	0.72		0.92	0.86	0.17	0.30	0.33			0
(0.01)	(0.03)		(0.01)	(0.03)	(0.07)	(0.01)	(0.03)		(0.01)	(0.03)	(0.08)	(0.10)	(0.12)			
Fully Reparametrized Model (high-saliency condition)																
0.87	0.67		0.91	0.76		0.89	0.72		0.92	0.86	0.17			0.93	0.72	0
(0.01)	(0.03)		(0.01)	(0.03)		(0.01)	(0.03)		(0.01)	(0.03)	(0.08)			(0.46)	(0.11)	

Note. The degree of freedom of G^2 is 0

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Chapter 3: Study Two



Inter-Trial Variability of Context Influences the Binding Structure in a Stimulus-Response Episode

RESEARCH ARTICLE

RUYI QIU

MALTE MÖLLER

IRING KOCH

SUSANNE MAYR

*Author affiliations can be found in the back matter of this article

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ABSTRACT

There is strong evidence that stimuli and responses are bound together in a direct (*binary*) fashion into an episodic representation called *stimulus-response episode* (or *event file*). However, in an auditory negative priming study in which participants were required to respond to the target stimulus and to ignore the distractor stimulus, context information (i.e., a completely task-irrelevant stimulus) was found to rather modulate the binding between the distractor stimulus and the response, instead of entering into a binary binding with the response itself (Mayr et al., 2018). The current study demonstrates that simply increasing the variability of the context across trials leads to a binary binding between the context and the response. The same auditory negative priming task was implemented, and participants were either assigned to the high-variability group (8 different context sounds) or the low-variability group (2 different context sounds). For the low-variability group, results replicated previous findings of contextual modulation of the binding between the distractor stimulus and the response. For the high-variability group, however, repetition of the context per se retrieved the prime response, indicating a binary binding between the context and the response. Together, the current findings provide evidence that the inter-trial variability of context information is a determinant of how context is bound in a stimulus-response episode. Possible underlying mechanisms are discussed.

CORRESPONDING AUTHOR:

Ruyi Qiu

Chair of Psychology and Human-Machine Interaction, University of Passau, 94032, Passau, Germany

Ruyi.Qiu@uni-passau.de

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The human brain encodes different perceptual features (e.g., color, shape, pitch, and loudness) of stimuli in a distributed fashion (e.g., Seymour et al., 2009; Stecker et al., 2005). To achieve a coherent perception of the world requires mechanisms that bind features (e.g., Kahneman et al., 1992; Treisman, 1996). Apart from the perceptual features, a multitude of findings suggests that action features (e.g., a keypress response) are bound as well (for an overview of feature binding across perception and action, please see Hommel, 2004). It is assumed that the stimulus and the response can be integrated into a common episodic representation, referred to as a stimulus-response (S-R) episode (or an event file). Upon reencountering a feature stored in an S-R episode, the whole episode is retrieved, which either facilitates or impairs performance, depending on whether the retrieved information is compatible with the current processing requirements or not. The so-called *S-R binding and retrieval* processes have been proved to be a common mechanism underlying human information processing and action control (for a recent review of the binding and retrieval in action control, BRAC, please see Frings et al., 2020). Previous findings further indicate that the binding process usually results in a so-called binary structure, which links the individual stimulus and the response (e.g., Hommel, 1998, 2004; Moeller et al., 2016; Singh & Frings, 2020).

Supplementing the relevance of S-R bindings in human action, the binary binding between a previously ignored stimulus and the executed response was found to be one of the causes underlying the *negative priming effect* (referred to as the prime-response retrieval account, Mayr & Buchner, 2006; for a similar account, please see Rothermund et al., 2005).¹ Mayr and Buchner (2006) used an auditory identification task, in which participants were required to respond to a target sound via an appropriate keypress while ignoring a simultaneously presented distractor sound. Four environmental sounds were used as target and distractor stimuli, and each of the sounds was assigned to a unique response key. In the so-called *ignored repetition* trials, the distractor stimulus of the previous presentation (i.e., the *prime*) was used as the target in the following presentation (i.e., the *probe*). Probe reaction times were longer and probe error rates were higher in these ignored repetition trials than in trials devoid of any stimulus repetition (i.e., the *control* trials), resulting in the so-called negative priming effect. The further analysis of probe error frequencies showed that the participants were more likely to commit errors with the prime response in ignored repetition trials as compared with control trials. This finding reveals that the repetition of the prime distractor stimulus in the probe retrieves the executed prime response, indicating that these elements were bound together into the prime episodic representation (see **Figure 1** for illustration of the prime-response retrieval error). Since the retrieved prime response is incompatible with the required response in the probe, the emerging response conflict has to be overcome before a correct response can be given, contributing to the negative priming effect. The significant increase of prime response errors induced by the repetition of a stimulus has been coined the *prime-response retrieval effect*, which is considered as an unambiguous indicator of the (binary) binding between a stimulus and the response (Frings et al., 2015; Mayr et al., 2018).

Interestingly, in a recent study using the aforementioned four-alternative auditory negative priming task, an additional task-irrelevant stimulus that served as context was found to modulate the binding between the prime distractor stimulus and the response, instead of being bound in a binary fashion with the response itself (Mayr et al., 2018). A sine tone presented together with the target and distractor sounds was used as the context stimulus. The context tone could repeat or change between the prime and the probe. Results showed that the sole repetition of the context tone in the probe did not increase errors with the prime response (i.e., the prime-response retrieval effect induced by the sole repetition of the context was not significant). However, the prime-response retrieval effect induced by the repetition of the prime distractor stimulus was significantly larger when the context was *additionally* repeated than when it was changed. In other words, the context did not retrieve the prime response on its own, but increased the retrieval of the prime response induced by the repetition

¹ Note that there are several possible processes underlying the negative priming effect (for a review, see Frings et al., 2015). Apart from the memory-based processes (e.g., Neil & Valdes, 1992) which are mainly focused on in the current paper, an inhibition mechanism has also been discussed as a reason for the emergence of the effect (Tipper, 1985).

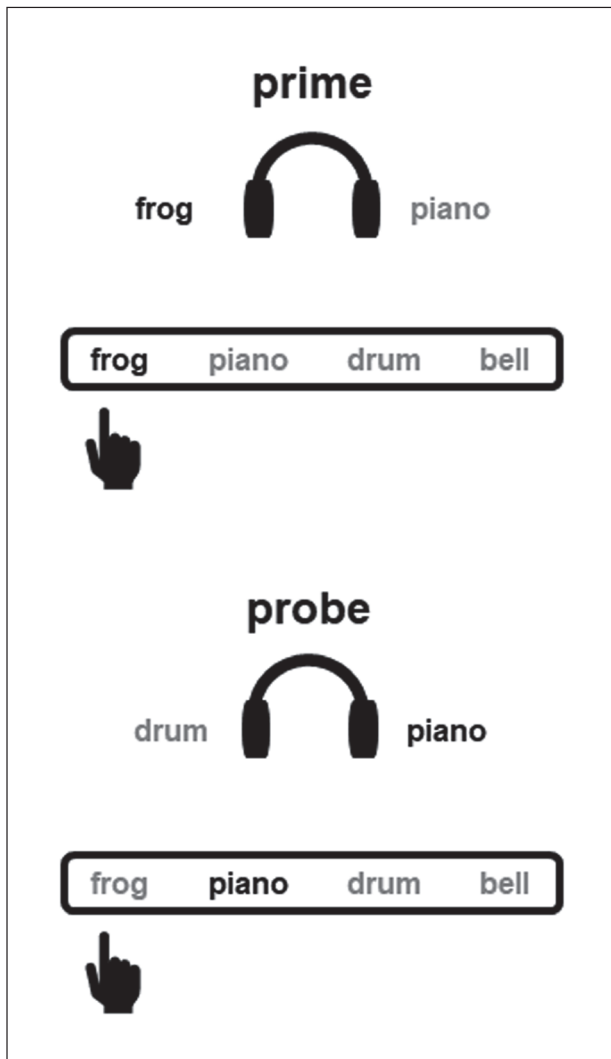


Figure 1 Illustration of the erroneous probe response with the previously executed prime response in ignored repetition trials. Note: Targets and correct responses are in black, distractors and incorrect responses are in grey.

of the prime distractor stimulus. This finding cannot be explained by presumed binary bindings between stimuli and responses. Instead, it suggests that the context is involved in a higher-order binding (Hommel, 1998; Singh & Frings, 2020), which includes more than two elements (context, distractor, and response) in an episodic representation (Qiu et al., 2022). This novel finding leads to the questions whether context information can be bound in a binary fashion with the response as well, and if so, what determines the binding structure (i.e., binary vs. higher-order) involving context. The main purpose of the current study was to investigate if the inter-trial variability of context could influence whether it enters into a binary binding with the response or not. To this end, the four-alternative auditory negative priming task was employed as the vehicle to test the influence of context variability on the prime-response retrieval effect (induced by the repetition of the context and by the repetition of the prime distractor stimulus).

THE ROLE OF INTER-TRIAL CONTEXTUAL VARIABILITY IN NEGATIVE PRIMING

It is well-established in the memory literature that contextual information is encoded and the repetition of the encoded contextual information can improve successful retrieval (for a review, see Smith & Vela, 2001). Substantiating the contribution of memory-related processes, the negative priming effect was also found to be influenced by the manipulation of context repetition (e.g., Fox & De Fockert, 1998; Neill, 1997). Typically, a larger negative priming effect was found when the context was repeated than when it was changed, which is referred to as the *contextual similarity effect*. Chao (2009) investigated the contextual similarity effect with a focus on the inter-trial variability of context. A visual negative priming task was used, in which symbols (i.e., the context stimuli) and distractor letters flanked the central target letter (e.g., A @ B @ A). The symbols could repeat or change between the prime and the probe. In

the low-variability condition, two different symbols served as the context, whereas sixteen different symbols were used in the high-variability condition. Results showed a significant negative priming effect in the high-variability condition when the prime context was repeated in the probe, but not when the context was changed. As for the low-variability condition, no significant negative priming effect was obtained, regardless of the context relation between the prime and the probe. An attention hypothesis was put forward by Chao (2009) for these results. It was assumed that more frequently changing context stimuli receive more attention during processing, ultimately leading to stronger encoding of the context information in memory (e.g., Chun & Turk-Browne, 2007; Logan, 1988; Uncapher et al., 2011). As a consequence, the context presumably acted as a more potent retrieval cue to the prime episode in the high- as compared with the low-variability condition, leading to the significant contextual similarity effect in the former. Additionally, according to the *cue overload* assumption (Watkins & Watkins, 1975), Chao (2009) also assumed that individual context stimuli in the low- as compared with the high-variability condition are associated with more (and different) representations. In this sense, context in the low-variability condition might be a less efficient retrieval cue of the most recent prime information as it is connected to several other episodes in memory as well. Since evidence suggests that it is the most recently formed S-R bindings that mainly matter in the current S-R retrieval process (e.g., Giesen et al., 2020; Schmidt et al., 2016), we suppose that cue overload may not play an important role in modulating the S-R binding and retrieval component of the negative priming effect, whereas attention can be a potential modulator of these episodic memory processes (Moeller & Frings, 2014).

In fact, only two context stimuli were used in the study by Mayr et al. (2018), resembling the low-variability condition employed by Chao (2009). However, a significant contextual modulation of the prime-response retrieval effect induced by the repetition of the prime distractor stimulus (i.e., the S-R binding and retrieval component of the negative priming effect) was found in Mayr et al. (2018). To reiterate, the prime-response retrieval effect was larger when the context was additionally repeated than when it was changed, but sole context repetitions did not increase the likelihood to perform the former prime response in the probe. Referring to the attention hypothesis by Chao (2009), it is possible that the context stimuli in Mayr et al. (2018) did not receive sufficient attention during processing to form a binary binding with the prime response. Instead, the context modulated the binding between the prime distractor stimulus and the response, which presumably is due to the fact that the context stimulus was less discriminable from other stimuli in the prime episode, thereby entering into a so-called configural binding with prime stimuli and the response (see Moeller et al., 2016 for evidence that discriminability determines binding structure).

CURRENT STUDY

To test the attention-related hypothesis, in the present experiment, the identical four-alternative auditory negative priming task as in Mayr et al. (2018) was implemented, and a total of eight different sine tones were used as the context. Participants were randomly assigned to either the high-variability group (in which all of the eight sine tones were used as the context), or the low-variability group (in which two out of the eight sine tones were randomly selected as the context throughout the whole experiment). It was expected that in the high-variability group, the repetition of the context per se should retrieve the prime response (i.e., a significant prime-response retrieval effect induced by the repetition of the context should emerge), which indicates a binary binding between the context and the response. However, in the low-variability group, no significant prime-response retrieval effect induced by the repetition of the context per se should be found. Instead, the repetition of the context may promote the prime-response retrieval process induced by the repetition of the prime distractor stimulus, as shown in the previous study (Mayr et al., 2018). This would indicate the formation of a configural binding among context, distractor, and response.

METHOD

PARTICIPANTS

One hundred and three participants took part in the experiment, most of whom were students at the University of Passau. Eleven of these participants were tested offline, whereas the

remaining ninety-two participants were tested online on the Pavlovia platform (<https://pavlovia.org>) due to the onset of the Covid-19 pandemic. Data of three participants had to be excluded because of excessive error rates (over 50%) in more than half of the experimental conditions (as compared with an average of 17%), which suggests either unwillingness or inability to follow the instructions. The resulting sample of 100 adults (15 males, 1 non-binary) ranged in age from 19 to 31 years ($M = 21.88$, $SD = 2.36$). Participants either received course credit or a monetary compensation of 10 € for their participation. The experiment was conducted in accordance with the ethical guidelines of the German Psychological Association (DGPs) and the Professional Association of German Psychologists (Deutsche Gesellschaft für Psychologie, 2016) and with the 1964 Declaration of Helsinki.

MATERIALS

Four sounds (frog, piano, drum, and bell) with a duration of 300 ms (including on- and off-ramps) were used as target and distractor stimuli. All sounds had an average loudness of approximately 71 dB (A) SPL. NIOSH (2016) on a cellphone (iPhone 8, Apple Inc., Cupertino, USA) equipped with an external microphone (iMM-6 iDevice Calibrated Measurement Microphone, Dayton Audio, Springboro, USA) was used to measure the loudness while the sounds were played on one side of a stereo headphone (DT110, Beyerdynamic GmbH & Co. KG, Heilbronn, Germany). The offline test was programmed by LiveCode (LiveCode 9.5, Runtime Revolution Ltd., Edinburgh, Scotland), whereas the online test was programmed using Psychopy3 (Peirce et al., 2019).

Each presentation started with a 20-ms metronome click either played to the right or left ear. Then, a target sound was played on the side indicated by the metronome click, and a distractor sound was simultaneously played on the other side. Participants were asked to identify the target sound by an appropriate keypress and to ignore the distractor sound. In the offline test, the response keys were “9”, “6”, “3” and “,” on the number pad of the keyboard. These keys were assigned to frog, piano, drum, and bell sounds, respectively. In the online version of the experiment, four common letter keys *F*, *V*, *J*, and *N* (assigned to frog, piano, drum, and bell sounds) were selected as response keys to avoid the potential lack of a number pad on privately owned computer systems. All participants were instructed to use the middle and index fingers of their left and right hands to press the keys. Specifically, for the offline test, five participants were instructed to use the middle and index fingers of their right hands to press the two distal keys (i.e., “9” and “6”), and the middle and index fingers of their left hands to press the two proximal keys (i.e., “3” and “,”). This arrangement was reversed for the remaining six participants.

An additional sine tone, presented together with the target and distractor sound pair, served as context. The context tone was played simultaneously to both ears to create the impression to originate from a central location. The context tone could be (1) 150 Hz, (2) 300 Hz, (3) 400 Hz, (4) 500 Hz, (5) 600 Hz, (6) 700 Hz, (7) 800 Hz and (8) 900 Hz in frequency. The context tones lasted for 300 ms, including 10-ms attack and decay intervals, and they were approximately equal in loudness as target and distractor sounds. When added to the target and distractor sound pair, the context tones only slightly increased the overall loudness (i.e., within 3 dB(A)).

Twelve context tone pairs were created with the restrictions that each pair only comprised frequencies with even or odd labels (e.g., 300 Hz and 500 Hz or 400 Hz and 800 Hz). With at least 200 Hz difference in frequency, the context tones in a pair could be easily distinguishable from each other. Among these twelve pairs of context tones, the frequencies of occurrence were balanced (i.e., each context tone appeared three times). All twelve pairs of context tones were used in the high-variability group, whereas in the low-variability group, a randomly chosen context sound pair was employed.

Each trial comprised a prime presentation and a probe presentation. Ignored repetition trials were created by selecting three out of the four sounds as the target and distractor in the prime and probe presentations, with the probe target identical to the prime distractor. Replacing the prime distractor with the remaining fourth sound in each ignored repetition trial created a parallel control trial. Note that if only ignored repetition trials and their corresponding control trials were used, participants may learn to expect no response repetition between the prime and the probe. Therefore, attended repetition trials and their parallel control trials were added.

The attended repetition trials also required three out of the four sounds to be the target and distractor in the prime and probe presentations, but the restriction was that the probe target was identical to the prime target. Accordingly, the parallel control trials were constructed by replacing the prime target with the remaining fourth sound. Since no hypothesis was made for attended repetition trials and their parallel control trials, their results will not be reported. However, the data were uploaded to PsychArchives for those who are interested.

The basic set of experimental trials contained 48 trials, with 12 trials for each of the four trial types described above.² The basic set was implemented for eight times, four times with the context repeated in the prime and the probe, and four times with the context changed between the prime and the probe. The resulting 384 experimental trials were presented in a random sequence. In each trial, the side where the prime target would be presented was randomly decided, whereas the probe target would always be presented on the opposite side. This was done to avoid identity-location feature mismatches in the ignored repetition condition, which has been discussed as one reason for the emergence of the negative priming effect (Park & Kanwisher, 1994).

PROCEDURE

Participants were first informed to use headphones. After being familiarized with the experimental sounds, participants were introduced to the general task. A training phase followed, which included three sessions: In the first session, participant learned about the target and distractor sound pairs without context tones. The task was to identify the target sound by pressing the appropriate key and to ignore the distractor sound. For the offline test, accuracy had to be at least 60% in the 15 subsequent trials to pass this training phase. If the criterion was missed after 60 trials, participants were offered to quit the experiment or to repeat the training. For the online test, the accuracy criterion to pass was set to 33 % in 12 subsequent trials to reduce the overall task duration. If the criterion was missed, participants could either quit the experiment or repeat the training. In the second session, sound pairs were presented together with context tones. Prior to the training session, participants were informed that the context tones were task-irrelevant, and were instructed to focus on the task itself. The criterion to pass the second training session was identical to the first session. Finally, participants responded to six or ten prime and probe trials in the offline or the online version of the experiment, respectively. The timing of the training trials in this session was identical to that of the experimental trials (see *Figure 2*).

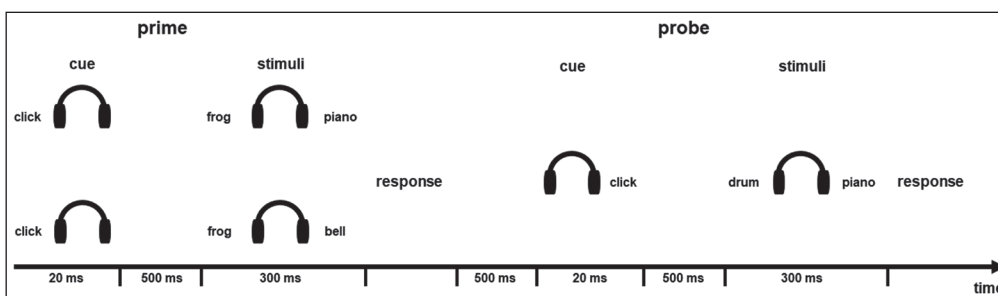


Figure 2 Example of the trial procedure. Primes are shown for the ignored repetition (upper) and control (lower) conditions with an identical probe.

Note: The contextual stimuli are not presented in the figure. The response interval was 100–3000 ms.

Each experimental trial started with the 20-ms metronome click, which cued the side where the prime target would be presented. Following a 500-ms cue-target interval, the prime sound pair was presented. The prime response was followed by a 500-ms prime-probe interval, after which the probe cue was presented on the opposite side of the prime cue. After another 500-ms interval, the probe sound pair was presented. Participants received audio-visual feedback about the correctness of the prime and the probe responses after each trial. The intertrial interval was set to 1200 ms. Responses faster than 100 ms and slower than 3000 ms were counted as

² Note that the full permutation of the four sounds actually leads to 24 trials for each trial type, resulting in a complete set of 96 trials. However, in this set of 96 trials, the ignored repetition trials and the attended repetition trials always share an identical set of control trials, which means that each control trial would have occurred twice. Therefore, the ignored repetition and attended repetition trials were systematically assigned to two basic sets, with the restriction that none of the control trial was repeated in one set. It was randomly decided which basic set each participant was assigned to. Please see Mayr and Buchner (2006) for more details about the basic sets.

invalid and were excluded from analyses, and participants received warning message about them.

The experiment comprised 16 blocks with 24 experimental trials in each block. After each block, the overall error rate for the block was presented on the screen. Participants could either take a rest or start the next block at their own discretion by pressing one of the response keys (in the offline test) or the space key (in the online test). The testing lasted for approximately 60 minutes, for both online and offline versions.

DESIGN & ANALYSIS

The experiment was a 2×2×2 mixed design with Trial Type (ignored repetition vs. control), Context Relation (repeated vs. changed) as the within-subject variables, and Context Variability (low vs. high) as the between-subject variable. The dependent variables were averaged reaction times, overall probe error rates, and most importantly, probe response frequencies.

In order to have enough power to observe the basic negative priming effect, sample size was calculated with the purpose to detect a medium-sized effect (i.e., $f = 0.25$, as defined by Cohen, 1988) of context variability on the contextual modulation of the negative priming effect. The calculations were conducted using the G*Power program (Faul et al., 2009). Given desired levels of $\alpha = \beta = .05$, and an assumed correlation of $\rho = .2$ (estimated from Mayr et al., 2018) between the negative priming effects in context repeated and changed conditions, data had to be collected from 86 participants. The final sample comprised 100 participants, so the power was slightly larger (.97) than what was originally planned for. P-values of multiple comparisons were reported after Bonferroni-Holm correction (Holm, 1979).

To estimate the conditional probability of prime response errors based on the probe response frequency data, the multinomial processing tree (MPT) model introduced by Mayr and Buchner (2006) was implemented (see **Figure 3** for a description of the model in the ignored repetition and the control conditions). Henceforth, this specific model is referred to as the baseline

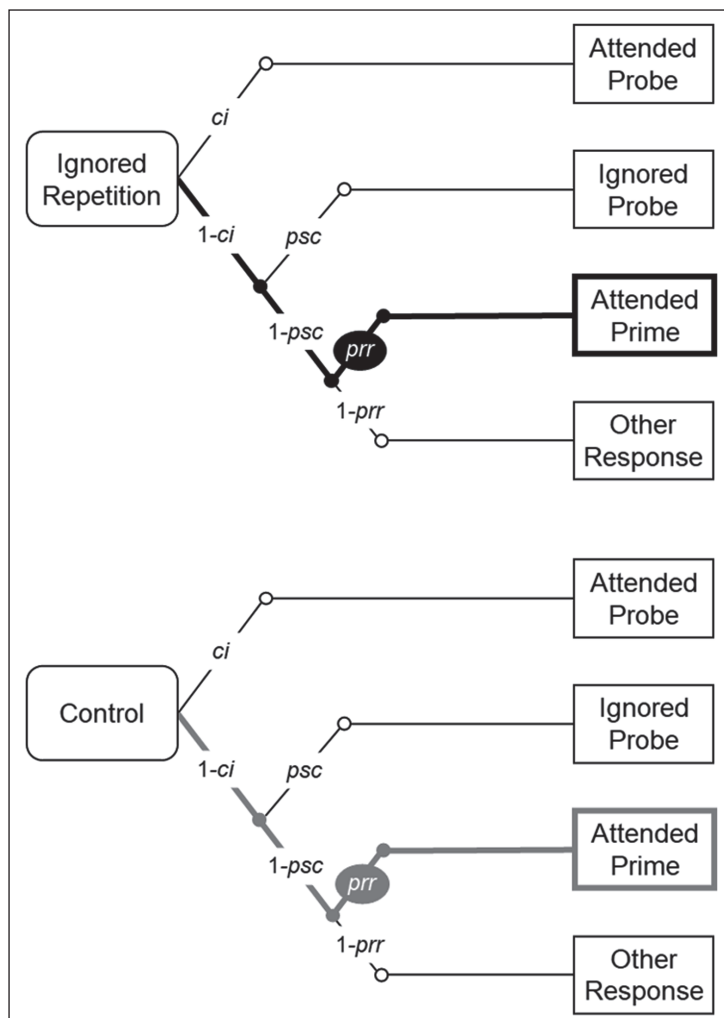


Figure 3 The multinomial processing tree model in the ignored repetition and the control conditions.

Note: The figure was taken from Qiu et al. (2022).

model. There are four possible probe response categories in the baseline model, namely, (1) the correct response (correct identification, represented by the probability parameter ci), (2) incorrect response to the probe distractor (the probe stimulus confusion error, represented by the probability parameter psc), (3) incorrect response to the prime target (the prime-response retrieval error, represented by the probability parameter prr), and (4) incorrect response with the remaining response option. To investigate the prime-response retrieval effect induced by the repetition of the prime distractor stimulus, a restriction of the equivalence of the prr parameters between the ignored repetition condition and the control condition (i.e., $prr_{IR} = prr_C$) is added to the baseline model. A significant misfit between this restricted model and empirical data will be evidence for the prime-response retrieval effect induced by the repetition of the prime distractor stimulus, indicating a binary binding between the prime distractor stimulus and the response.

When testing the integration of the context, the baseline models in the context repeated and changed conditions were integrated into a joint model, for each Context Variability group. The binary binding between the context and the response was tested first, with the restriction of the equivalence of the prr_C parameters between the context repeated and changed conditions. If the restricted model has to be rejected (i.e., significantly misfits the empirical data), the prime-response retrieval effect induced by the repetition of the context alone is significant, which is evidence for the binary binding between the context and the response.

Finally, the contextual modulation of the binding between the prime distractor stimulus and the response was investigated. The analysis corresponds to an interaction analysis between the Context Relation and Trial Type. The interaction analysis in MPT modeling requires reparameterization of the joint model (see Knapp & Batchelder, 2004 for details of MPT model reparameterization methods; please see the Appendix of Qiu et al., 2022 for detailed description of the reparameterized model and the interaction analysis used in the current study). In the reparameterized model, the prime-response retrieval effect induced by the repetition of the prime distractor stimulus can be represented by the difference of the prr parameters between the ignored repetition and the control conditions, that is, $prr_{IR} - prr_C$. If the goodness-of-fit test suggests a significant difference of ($prr_{IR} - prr_C$) between the context repeated and changed conditions, it is assumed to be evidence for the involvement of context in a configural binding, as found in Mayr et al. (2018). The model analysis described above were run with the multiTree software (Moshagen, 2010).

RESULTS

REACTION TIMES AND ERROR RATES

A 2 (Trial Type: ignored repetition vs. control) \times 2 (Context Relation: repeated vs. changed) \times 2 (Context Variability: low vs. high) mixed models MANOVA was applied to probe reaction times and error rates (see **Figure 4** for an overview of descriptive findings). The results showed a significant main effect of Trial Type in reaction times, $F(1, 98) = 37.54, p < .001, \eta_p^2 = .28$, and in error rates, $F(1, 98) = 46.39, p < .001, \eta_p^2 = .32$. Probe responses were slower and more error prone in ignored repetition than in control trials, revealing a typical negative priming effect (Neill & Valdes, 1992; Tipper, 1985). Moreover, there was a significant interaction between

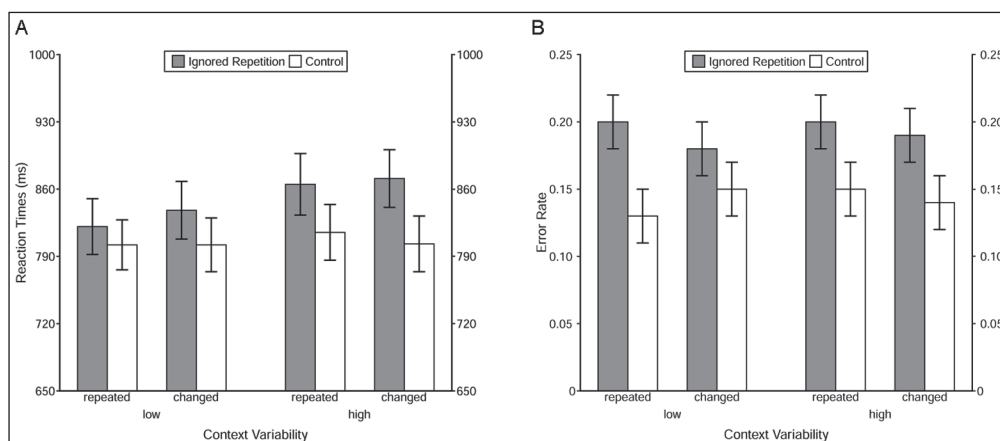


Figure 4 Descriptive findings in reaction times and error rates. Note: **A)** Reaction times as a function of Trial Type, Context Relation and Context Variability; **B)** Error rates as a function of Trial Type, Context Relation and Context Variability. The error bars depict the standard errors of the means.

Trial Type and Context Variability in reaction times, $F(1, 98) = 4.93, p = .03, \eta_p^2 = .05$. Further analysis showed that the negative priming effect was significant in the high- as well as the low-variability group, but the effect was larger for the former, $F(1, 49) = 33.42, p < .001, \eta_p^2 = .41$, than for the latter, $F(1, 49) = 7.97, p = .04, \eta_p^2 = .14$. No other interaction or main effects, neither in reaction times nor in error rates, were significant, all $F_s < 3.01, p_s > .08$.

MPT MODEL RESULTS

The estimated value of the prr parameters under each $2 \times 2 \times 2$ condition is depicted in **Figure 5**. The prime-response retrieval effect induced by the repetition of the prime distractor stimulus in each of the 2 (Context Relation) \times 2 (Context Variability) conditions was tested first. Results showed that with the restriction $prr_{IR} = ppr_c$, the restricted model always had to be rejected, $G^2_s > 18.95, p_s < .001, \omega_s > .06$, revealing evidence for the prime-response retrieval process induced by the repetition of the prime distractor stimulus.

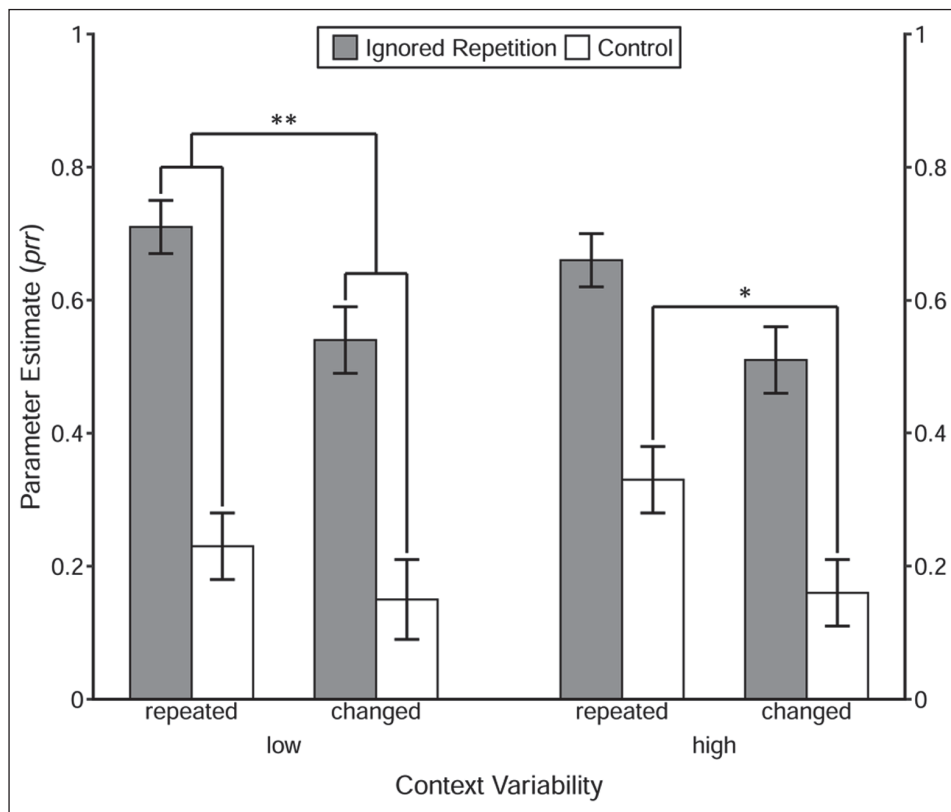


Figure 5 Probability estimates for the model parameters representing the probability of prime-response retrieval (prr) as a function of Trial Type, Context Relation and Context Variability. Note: The error bars depict the standard errors of the parameter estimates. Annotation shows significant comparisons indicating configural and binary binding of the context. The symbols “***” and “*” indicate $p < .01$ and $p < .05$, respectively.

Then, the prime-response retrieval effect induced by the repetition of the context per se was tested with the restriction of equivalence of the prr_c parameters between the Context Relation conditions, in each of the Context Variability groups. The goodness-of-fit test showed that only in the high-variability group, the restricted model had to be rejected, $G^2(1) = 5.19, p = .02, \omega = .03$. However, in the low-variability group, the restricted model did not yield a significant misfit, $G^2(1) = 1.10, p = .29, \omega = .01$.

Finally, the contextual modulation of the prime-response retrieval effect induced by the repetition of the prime distractor stimulus was investigated using the interaction analysis of MPT modeling. The interaction analysis showed that in the low-variability group, the prime-response retrieval effect induced by the repetition of the prime distractor stimulus was larger when the context was repeated than when the context was changed, $G^2(1) = 6.73, p < .01, \omega = .03$. However, no significant contextual modulation was found in the high-variability group, $G^2(1) = 0.09, p = .77, \omega < .01$.

DISCUSSION

In the current study, the influence of stimulus inter-trial variability on the binding structure of the context in an S-R episode was investigated. The variability property of context was manipulated by using either two different sine tones or eight different sine tones as the context. In the

former condition which equals the study by Mayr et al. (2018) with respect to the composition of the context stimuli, results replicated the previous finding that the sole repetition of the context did not lead to a significant prime-response retrieval effect. Also in line with Mayr et al. (2018), a larger prime-response retrieval effect induced by the repetition of the prime distractor stimulus was found when the context was additionally repeated than when the context was changed. In the high-variability condition of the context, however, results showed that the repetition of the context per se induced a significant prime-response retrieval effect, which is evidence for the binary binding between the context and the response. Together, the current study reveals that the inter-trial variability is a determinant of the binding structure of context in an S-R episode.

The current results are in line with the attention hypothesis proposed by Chao (2009). Assuming that increasing the variability of the context leads to an increase of attention allocated to the context stimulus during processing, in the high-variability group, the presumably better encoded context stimulus may be more strongly/likely integrated into an episodic representation directly with the response, resulting in a binary binding structure. In the low-variability group, on the other hand, with less attention during processing, the context may be less discriminable from other stimuli in the prime episode, thereby entering into a configural binding with the prime distractor stimulus and the response (Moeller et al., 2016). This combined pattern of results—binary binding in the high-variability group and configural binding in the low-variability group—presumably is due to the fact that the manipulation of the inter-trial variability in the current study influenced the perceived novelty of the context stimulus. The more frequently changing context may be perceived as more novel, thereby attracting more attention (e.g., Ernst et al., 2020; Parmentier, 2008). Thus, increasing the variability can lead to a binary binding between the context and the response, as shown in the current study.

Note that the current results also reveal that the context is integrated into an S-R episode regardless of its inter-trial variability. Assuming the manipulation of the inter-trial variability influenced attention allocated to the contextual stimulus, the current results are in line with previous findings that attention does not determine whether a stimulus is integrated into an S-R episode or not (e.g., Giesen et al., 2012; Hommel, 2005; Hommel & Colzato, 2004; Moeller & Frings, 2014). However, the current result patterns (i.e., binary binding in the high-variability group and configural binding in the low-variability group) further extend these previous findings, as it suggests that attention may influence the specific structure of the binding that a stimulus is involved in. Presumably, with more attention, the stimulus is more likely to be bound in a binary fashion with the response, otherwise it may enter into some kind of a higher-order binding with other stimuli and the response.

Another possible reason for the current result patterns comes from the *figure-ground segmentation* literature (for a review, see Wagemans et al., 2012).³ It was found that the so-called “figural” stimulus presented in a confined area on the screen entered into a binary binding with the response, whereas the “ground” which covered the whole screen did not (Frings & Rothermund, 2017). Transferring the “figure” and the “ground” into the auditory modality, the former may be in analogy with an individual auditory object, whereas the latter may be in analogy with a background sound of other stimuli. If the manipulation of the inter-trial variability influences whether the context is perceived as an individual object or a background of other stimuli, then the context of high variability may more likely be perceived as an individual object, thereby entering into the binary binding with the response (Frings & Rothermund, 2017). The context of low variability, on the other hand, may more likely be perceived as the background of other stimuli. Therefore, it forms a “compound” with the other stimuli and enters into the configural binding with the prime distractor stimulus and the response (see Qiu et al., 2022 for a similar explanation). With that being said, whether and how the inter-trial variability influences the figure-ground perception of the contextual stimulus requires further investigation in future studies.

Finally, in the current study, the Context Relation factor did not affect the negative priming effect, neither in reaction times nor in error rates (note that some previous studies also reported insignificant influence of Context Relation on the negative priming effect, e.g., Eben et al., 2020; Wong, 2000). Instead, an influence of Context Variability was found on the negative priming effect, with a larger negative priming effect when the context variability was high than when it was low. This result is different from what was found by Chao (2009), which showed a

3 We thank the anonymous reviewer for this possible alternative account.

significant negative priming effect only when the context was repeated in the high-variability condition. However, the current result is consistent with the previous finding that the prime-response retrieval process is the only mechanism underlying the negative priming effect that is sensitive to the contextual modulation in the auditory modality (Mayr et al., 2018). Prospective studies are required to investigate whether and how the difference in modality influences the role of context in negative priming.

To sum up, the current study investigated the binding structure of the context in an S-R episode by manipulating the inter-trial variability of context. Results show that with high variability, the context enters into a binary binding with the response; whereas with low variability, the context is involved in a so-called configural binding with the distractor stimulus and the response. Together, the current study indicates that the inter-trial variability of context is a determinant of its binding structure in an S-R episode, thereby providing insights into the influence of contextual information on action control.

DATA ACCESSIBILITY STATEMENT

The data and programming code for data analysis of the experiment are available on <https://doi.org/10.23668/psycharchives.5605>. The experiment was not preregistered. This work is part of the doctoral dissertation by Ruyi Qiu.

ETHICS AND CONSENT

The experiment was approved by the University Research Ethics Committee of the University of Passau (reference number: I-07.5090/2019).

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COMPETING INTERESTS

The authors have no competing interests to declare.

AUTHOR AFFILIATIONS

Ruyi Qiu  orcid.org/0000-0003-4157-146X

Chair of Psychology and Human-Machine Interaction, University of Passau, 94032, Passau, Germany

Malte Möller  orcid.org/0000-0002-8705-2780

Chair of Psychology and Human-Machine Interaction, University of Passau, 94032, Passau, Germany

Iring Koch  orcid.org/0000-0001-9664-8220

Department of Cognitive and Experimental Psychology, RWTH Aachen University, 52056, Aachen, Germany

Susanne Mayr  orcid.org/0000-0001-9947-8319

Chair of Psychology and Human-Machine Interaction, University of Passau, 94032, Passau, Germany

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Chapter 4: Study Three

The Influence of Event Segmentation by Context on Stimulus-Response Binding

Ruyi Qiu¹, Malte Möller¹, Iring Koch², Christian Frings³, & Susanne Mayr¹

1. Chair of Psychology and Human-Machine Interaction, University of Passau, 94032, Passau, Germany

2. Chair of Psychology I: Cognitive and Experimental Psychology, RWTH Aachen University, 52056, Aachen, Germany

3. Cognitive Psychology Unit, University of Trier, 54286, Trier, Germany

Correspondence: Ruyi Qiu, (+49) 015222452576, Ruyi.Qiu@uni-passau.de, Chair of Psychology and Human-Machine Interaction, University of Passau, 94032, Passau, Germany

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Abstract

A core characteristic of auditory stimuli is that they develop over time. Referring to the *event segmentation theory* (Zacks et al., 2007), we assume that the on- and offset of a contextual sound indicates the start and end of an event. As a consequence, stimuli and responses appearing within a common auditory context may be integrated more likely/strongly, forming so-called event files, than those appearing in different auditory contexts. In two experiments, this hypothesis was tested using the negative priming paradigm and the distractor-response binding paradigm. In prime-probe presentations, participants identified target sounds via keypresses while ignoring distractor sounds. Additional sine tones acted as context in the prime, whereas the probe context was silence. In the common context condition, the context started with the prime sounds and ended with the prime response. In the changing context condition, the context started with the prime sounds but changed to another tone after the offset of the prime sounds. Results from both experiments revealed a larger stimulus-response binding effect in the common than in the changing context condition. We conducted a control experiment to test the alternative account of contextual similarity between the prime and the probe. Together, our results show that common context can temporally segment stimuli and responses into event files, providing evidence of common context as a binding principle.

Keywords: event segmentation, auditory context, event file, stimulus-response binding

Public significance statement

Humans are exposed to a continuous stream of information, but experience and remember structured temporal units called *events*. Given the pronounced temporal characteristic of auditory stimuli, the on- and off-set of these stimuli may support the segmentation of events. The current study investigated this in a micro view: whether stimuli and responses occurring with the same background sound (compared to occurring with different background sounds) are more likely or strongly processed as belonging to the same event. Results showed that the on- and offset of a background sound can demarcate the integration window of event files, which are transient representations of stimulus-response episodes. The findings further suggest that sharing contextual information is one principle for stimuli and responses to be integrated into a common event file representation.

Introduction

Human beings perceive a given stimulus as a unit, even though perceptual features of the respective stimulus (e.g., color and shape of an object, pitch and intensity of a sound) are coded in a distributed fashion in the human brain (e.g., Seymour et al., 2009; Stecker et al., 2005). Therefore, the so-called *binding problem* requires mechanisms that bind the distributed features together, which has raised long and still ongoing research interest (for reviews, see Feldman, 2013; Treisman, 1996). Evidence shows that not only perceptual features can be bound into a unit but that perceptual and action features (e.g., performing a keypress response) can be bound together as well. The feature binding across perception and action forms an episodic representation referred to as an *event file* or a *stimulus-response episode* (for overviews, see Hommel, 2004; also see the *Binding and Retrieval in Action Control* framework, BRAC, Frings et al., 2020). Once a stimulus and an executed response are integrated into an event file, the event file will be retrieved by reencountering the stimulus or the response individually. Facilitation (or impairment) of performance can be observed if the retrieved information is compatible (or incompatible) with the current processing requirements. This so-called binding and retrieval process of event files has been documented as a general mechanism underlying human information processing (Frings et al., 2020).

One question regarding this general mechanism is what determines whether the given features are integrated into an event file or not. To answer the question,

several binding principles have been put forward. From the perspective of feature weighting, the saliency principle of binding was proposed by Hommel (2004) and was tested empirically (e.g., Dutzi & Hommel, 2009; Schmalbrock et al., 2021). In a nutshell, research on this topic suggests that perceptual features that are salient enough will be integrated with responses into event files (Qiu et al., 2022). From the perspective of perceptual grouping, the proximity principle of binding was put forward and was corroborated by empirical evidence (e.g., Hommel, 2005; Moeller et al., 2012; van Dam & Hommel, 2010), which shows that perceptual features and responses that occur in spatial or temporal proximity tend to be bound together. Derived from the *event segmentation theory* (Zacks et al., 2007), a new binding principle, namely, the common context principle, is tested in the current study.

Event segmentation

Humans experience a continuous stream of (sensory) information, but perceive and remember discrete temporal units called *events* (e.g., brushing the teeth and eating breakfast may be perceived as two segmented events of the daily routine in the morning). The essence of segmenting the continuous experience into discrete events is the perception of event boundaries (i.e., the end of an event and the beginning of the next event). *Unitization* studies, in which participants watched movies of daily activities and were required to judge the occurrence of event boundaries via keypresses (i.e., subjectively determine when an event ends and the next event begins), revealed that participants not only showed a high degree

of agreement on the positions of event boundaries (e.g., Newton, 1973), but also consistently experienced the same boundaries in a retest session as they had perceived before in an initial viewing session of the same movie (e.g., Speer et al., 2003). These findings indicate that event segmentation is a common mechanism underlying human beings' organization of the continuous world. Zacks et al. (2007) proposed the event segmentation theory to describe this mechanism, according to which a working memory representation of the current event called the *event model* guides the processing of the continuous information stream. When the current event model no longer fits into what is happening now, resulting in accumulated prediction errors, the event model is updated. As a consequence of the update, an event boundary is perceived and the event is segmented.

Several after-effects of event segmentation have been found in previous studies. For example, Bangert et al. (2019) asked participants to judge the temporal proximity of items presented across an event boundary or within an event in a movie of daily activities and found that items separated by an event boundary were perceived as temporally farther apart as compared with items belonging to the same event. In the same vein, Speer and Zacks (2005) asked participants to read narrative texts in which a temporal adverbial indicated an event boundary (e.g., “an hour later”) or not (e.g., “a moment later”). Results showed that participants were less accurate in judging whether a probe word occurred in the sentences preceding the temporal adverbial when the adverbial indicated an event boundary than when it did not. Similarly, Ezzyat and Davachi

(2011) used an adapted version of the narrative texts from Speer and Zacks (2005) and found that the associative memory of sentences was impaired when they appeared on the opposite sides of an event boundary than when they were part of the same event. The impact of event segmentation on memory was also observed when using an implicit measurement (Paine & Gildea, 2013). The authors implemented an irrelevant feature priming task, in which a task-irrelevant feature of the target stimulus was repeated or changed between the prime and the probe presentations, to investigate the influence of the event boundary (e.g., indicated by inserting a short rest between the prime and the probe, which lasted for 400 ms) on working memory. Results showed a decreased priming effect when the prime and the probe were placed on the opposite sides of the event boundary than when they were placed within the same event, indicating that the prime and the probe were strongly associated in the latter but not in the former condition (Paine & Gildea, 2013). Taken together, the above-mentioned findings suggest that crossing an event boundary results in weaker associations of information than belonging to one event (see DuBrow & Davachi, 2013, for a similar conclusion).

Transferring this property of event segmentation to the binding process of event files, perceptual features and responses that are enclosed into the same event should be more likely bound together, as compared with perceptual features and responses that are separated into different events. This hypothesis was tested in the current study by applying the temporal segmentation of events by context.

The role of context in event segmentation

To reiterate, event segmentation is assumed to result from an update of the current event model, which is due to a mismatch between what is happening now and the prediction made by the current event model. Updating of an event model can be driven by several factors (Zacks et al., 2007), one of which is the distinctive sensory change (e.g., significant movement changes like velocity and orientation, Zacks, 2004). In line with this bottom-up driven event segmentation, context change was found to effectively indicate event boundaries. For example, Heusser et al. (2018) presented to-be-remembered items on a colored background which acted as the context. The change of the background color indicated an event boundary. Results showed impaired temporal order memory of items across an event boundary as compared with items belonging to the same event. This impact on temporal order memory of items was found for the change of implicit context as well (e.g., item category, DuBrow & Davachi, 2013; task set, Wang & Egner, 2022). Moreover, the perceived temporal distance between items (Ezzyat & Davachi, 2014) as well as the performance of serial recall of items (DuBrow & Davachi, 2016) was also found to be influenced by context change. These findings of after-effects on perception and memory corroborate that the context can effectively segment events. Therefore, in the current study, the context was manipulated to investigate the influence of event segmentation on stimulus-response binding.

Given that auditory stimuli develop over time, the auditory context may better demarcate the temporal integration window of event files as compared with

a visual context. The current study thus employed sine tones as the context, which were not assigned to any response, thereby being response-irrelevant throughout the course of the experiment. We expect that the stimulus and the response sharing the same context may be perceived as belonging to one event. Therefore, the stimulus and the response enclosed by the same context are more likely to be bound together into an event file, as compared with the stimulus and the response that are separated by different contexts, which may be perceived as belonging to different events.

Rationale of the present experiments

The general idea of the current study was to apply an event segmentation factor (i.e. context) to stimulus-response binding. In particular, the BRAC framework (Frings et al., 2020) argues that, in prime-probe sequences, stimulus-response binding in the prime leads to the creation of an event file (Hommel, 2004), which is – upon feature repetition – retrieved in the probe, thereby moderating probe performance. Thus, manipulations modulating the binding process aim at processing in the prime. In two experiments (Experiment 1 and 2A), we used established stimulus-response binding tasks and manipulated event file binding in the prime. To foreshadow the results, in comparison to a changing auditory context, a common auditory context furthered the binding between stimuli and responses and led to larger binding effects. An additional control experiment (Experiment 2B) was conducted to test whether contextual similarity between the prime and the probe could account for the current findings.

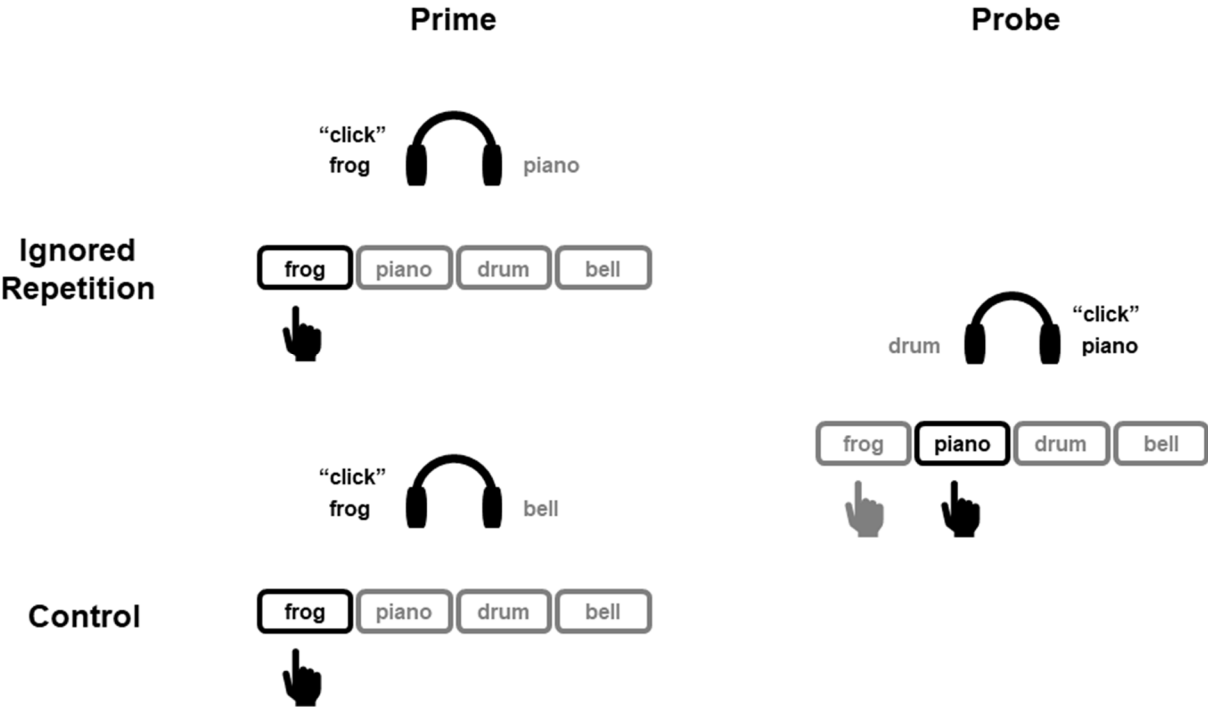
Experiment 1

Several paradigms have been used to detect after-effects of stimulus-response binding (for a review, Frings et al., 2020), one of which is the *four-alternative negative priming paradigm* developed by Mayr and Buchner (2006). The authors used four environmental sounds as target and distractor stimuli, each sound was assigned to a unique response key. Each presentation contained a target and a distractor and participants were required to identify the target via an appropriate keypress and to ignore the simultaneously presented distractor. Each trial comprised two consecutive presentations (i.e., a *prime* followed by a *probe*). In the so-called *ignored repetition* trials, the distractor stimulus in the prime was used as the target in the probe. So-called *control* trials were devoid of any stimulus repetitions between the prime and the probe (see Figure 1 for an illustration of the four-alternative negative priming task). Since the four sounds were assigned to different response keys, the frequencies of the different probe responses can be analyzed. The authors found that participants were more likely to commit erroneous probe responses by repeating the former prime response in ignored repetition trials than in control trials. This result was taken as evidence that the repetition of the prime distractor stimulus in the probe retrieves the prime response, suggesting a binding between these features during the prime processing. The retrieval of the prime response in ignored repetition trials will conflict with correct probe responding, thereby leading to impairment of performance in ignored repetition trials as compared with control trials, which denotes the

negative priming effect (Neill & Valdes, 1992; Tipper, 1985)¹. The larger (conditional) probability of committing the prime response error induced by the repetition of a stimulus has been coined the *prime-response retrieval effect*, which is an unambiguous indicator of the binding between a stimulus and the response (Frings et al., 2015; Mayr et al., 2018; Qiu et al., 2022).

Figure 1

Illustration of the four-alternative negative priming paradigm of Experiment 1



Note. Primes are shown for the ignored repetition (upper) and the control (lower) conditions with an identical probe. Prime and probe targets (in black) are presented on the side cued by a “click”, distractors (in grey) are presented on the opposite side. Correct responses are indicated by black-framed keys and black

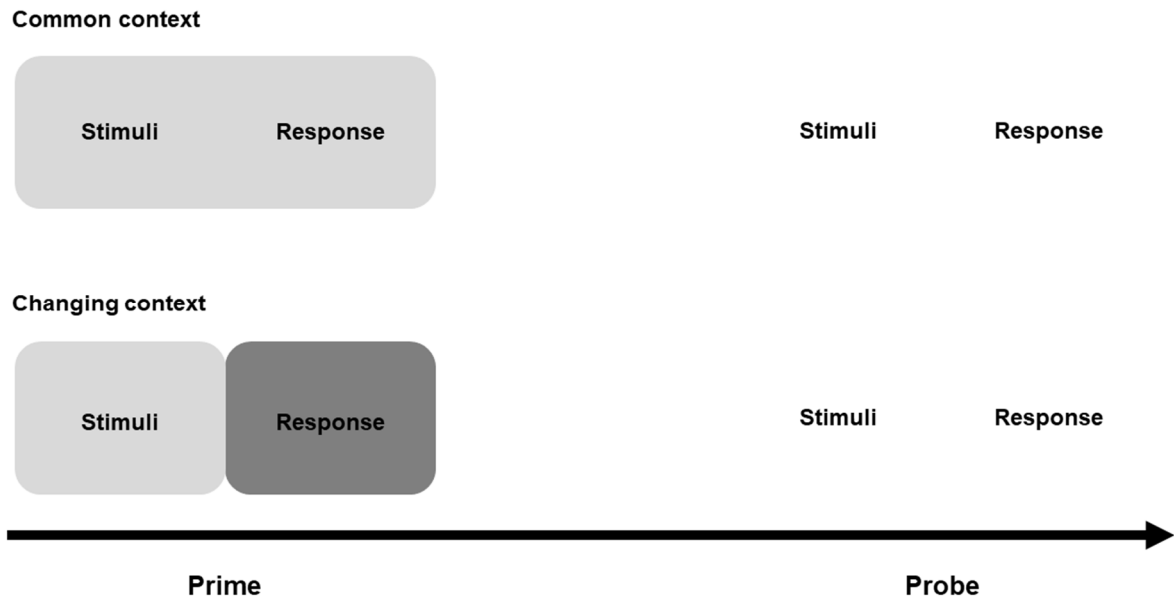
¹ Note that the negative priming effect has been proven to be rooted in several processes (Frings et al., 2015). Apart from the memory-based processes, which are most relevant in the present article, distractor inhibition during target selection, which persists from prime to probe, may also contribute to the emergence of the effect (Tipper, 1985).

hand symbols below the keys. The grey hand symbol in this example indicates a potential probe error with the previously executed prime response (here “frog”). Such errors are more often committed in ignored repetition than in control trials.

The prime-response retrieval effect was found in both the visual and the auditory modality, but appeared to be more pronounced in the latter (Mayr & Buchner, 2006). Therefore, Experiment 1 implemented the four-alternative negative priming task in the auditory modality. As mentioned earlier, given that auditory stimuli (as compared with visual ones) may be more suitable to demarcate the temporal integration window of event files, sine tones were used as the context to segment events. The context tones were presented in addition to the target and distractor sound pair in the prime, to test the influence of event segmentation by context on the binding process. In the so-called *common context* condition, the prime stimuli and the response were enclosed by the same context tone (see Figure 2 for an illustration). In the so-called *changing context* condition, the prime stimuli and the response were accompanied by different context tones, that is, a context change occurred between the stimulus presentation and the response execution. If sharing a common context segments the prime distractor stimuli and the response into one event, these features should be more likely (or strongly) bound together into an event file, resulting in a larger prime-response retrieval effect in the common context condition as compared with the changing context condition.

Figure 2

Illustration of the common context and the changing context conditions in Experiment 1 and 2A



Note. Different context tones are represented by different background shadings. In Experiment 1 and 2A, the context tones could form a common context or a changing context in the prime, whereas no context tones were displayed in the probe.

Method

Participants

Fifty-nine adults (42 females) participated in the experiment for 10 € monetary reward, most of whom were students at the University of Passau. Data of 53 participants had to be collected to reach the desired levels of $\alpha = .05$, $1 - \beta = .80$ (see the *Design and analysis* section for further details of the sample size

calculation). Their age ranged from 19 to 35 years ($M = 24$, $SD = 2.92$). Data of three participants had to be excluded due to their error rates exceeding 50% in several experimental conditions (as compared with an average of 9%), which suggested either inability or unwillingness to follow the instruction. This and the following experiments were conducted in accordance with the ethical guidelines of the German Psychological Association (DGPs) and the Professional Association of German Psychologists (Deutsche Gesellschaft für Psychologie, 2016) and with the 1964 Declaration of Helsinki².

Materials and task

Four environmental sounds (i.e., frog, piano, drum, and bell) were used as stimuli, which lasted for 300 ms. The sounds were played via headphones (DT110, Beyerdynamic GmbH & Co. KG, Heilbronn, Germany) plugged into the computers which controlled the experiment. The loudness level of each sound was approximately 71 db (A). The NIOSH (2016) app on a cellphone (iPhone 8, Apple Inc., Cupertino, the USA) equipped with an external microphone (iMM-6 iDevice Calibrated Measurement Microphone, Dayton Audio, Springboro, the USA) was

² These experiments were part of a larger research project which was approved by the University Research Ethics Committee of the University of Passau (reference number: I-07.5090/2019). There were some deviations from the approved version. First, Experiment 1 had been started before ethical approval was granted. Second, all experiments had been planned as lab studies, due to the COVID-19 pandemic Experiment 2A and 2B had to be run online. This necessitated some changes: Informed consent forms had to be approved by mouse click instead of signing them. It was not possible to compensate participants that aborted the experiments prematurely, participants were informed about this fact. Participants in Experiment 2B were primarily recruited via Prolific, and only to a small extent among University of Passau students. In Experiment 2B, the monetary compensation of 3,75 GBP for a 45 min testing was somewhat lower than the standard compensation. We believed this to be a fair compensation given participants did not have to come to the lab

used to measure the loudness while the sound was played (in a loop) at one side of the headphone.

Each presentation started with a 20-ms metronome click sound played either to the left ear or to the right ear, indicating the side of the to-be-attended sound (target). The to-be-ignored sound (distractor) would be played on the other side. Participants were required to identify the target sound by an appropriate keypress and to ignore the simultaneously presented distractor sound. The response keys were four vertically aligned keys (“9”, “6”, “3”, “;”) on the number pad of the keyboard, which were assigned to the sounds of frog, piano, drum, and bell, respectively. Participants were instructed to use their middle and index fingers of both hands to press the keys. Twenty-nine participants used their left hands to respond to the frog and piano sounds, and right hands to respond to the drum and bell sounds. This arrangement was reversed for the remaining participants.

Each trial comprised a prime and a probe presentation. In the prime, the target and distractor sound pair was presented with context tones, whereas in the probe the sound pair was presented alone (i.e., the probe “context” was persisting silence). The context tones were 300 Hz and 700 Hz sine tones, which were easily distinguishable from the stimulus sounds as well as from each other. When added to the sound pair, the context tone only slightly increased the overall loudness (on average less than 5 db (A) SPL). The context tone was played binaurally to create the impression of being played from the central location. In the common context

condition, the context tone started with the prime sound pair and ended with the prime response. In the changing context condition, the first context tone started and ended with the prime sound pair. After the offset of the first context sound, the second context tone started and ended with the prime response.

There were four trial types. To generate the ignored repetition trials, three out of the four stimulus sounds were selected as the target and the distractor in the prime and the probe presentations, with the restriction that the prime distractor was identical to the probe target. The parallel control trial for each ignored repetition trial was constructed by replacing the prime distractor with the remaining fourth stimulus. The attended repetition trials were implemented to prevent participants from anticipating no response repetition between the prime and the probe. To create the attended repetition trials, three out of the four stimulus sounds were used as the target and the distractor in the prime and the probe presentations, with the restriction that the prime target was identical to the probe target. The parallel control trials were generated by replacing the prime distractor with the remaining fourth stimulus. Since no hypothesis was made for the attended repetition trials and their parallel control trials, results of these trials will not be reported.

The basic set of trials comprised 48 trials, with 12 trials for each trial type described above³. The basic set was implemented four times, twice in the common context condition (with the 300 Hz context tone or with the 700 Hz context tone), and twice in the changing context condition (first with the 300 Hz context tone and then with the 700 Hz context tone or vice versa). These 192 trials were duplicated and were presented in a random sequence in the experiment. In order to avoid identity-location feature mismatches in the ignored repetition condition (which has been discussed as one reason for the emergence of the negative priming effect, Park & Kanwisher, 1994), it was randomly decided in each trial whether the prime target was played on the left or on the right side, whereas the probe target was always played on the opposite side.

Procedure

Participants adjusted the headphones after they were seated in front of the computer. Then, they were introduced to the sounds and task, followed by three training sessions. In the first training session, participants learned about the target and distractor sound pair without the context tone. They were required to identify the target via keypress and to simultaneously ignore the distractor. Participants needed to achieve an accuracy of over 60% within the preceding 15 training trials to pass the training session. If the criterion was not met after 60 trials, participants

³ Note that ignored repetition and attended repetition trials share the same control trials. To avoid that each control trial was played twice, the ignored repetition trials and the attended repetition trials were assigned to two basic sets (Set 1 and Set 2). Within each set, there were no repetitions of control trials. Participants were randomly assigned to Set 1 or Set 2. For details about the basic sets, please see Mayr & Buchner (2006).

could either quit or repeat the training. In the second training session, the target and distractor sound pairs were presented with the context tones. Participants were informed that the context tone was task-irrelevant and that they should focus on the task per se. The criterion to pass the second training was identical to that of the first session. If the participant passed the second training session successfully, they would then respond to 6 prime-probe trials. The timing of these trials was identical to that of the experimental trials.

Each experimental trial started with the 20-ms metronome click sound which cued the to-be-attended side, followed by a 500-ms cue-stimulus interval and the prime presentation. After the prime response, a 500-ms prime-probe interval elapsed. Then, a 20-ms metronome click sound would be presented on the opposite side, indicative of the side where the probe target would be presented. After a 500-ms cue-stimulus interval, the probe sound pair was played. Audio-visual feedback about the correctness of the prime and probe responses was presented after the probe response, followed by a 1200-ms intertrial interval.

Before entering the experiment session, participants were told to respond as accurate as possible and at the same time, as fast as possible. Responses faster than 100 ms or slower than 3000 ms were treated as invalid by the experimental program and participants received specific warning messages for them. There were 16 blocks in the experiment, each block comprised 24 trials. After each block, participants took a rest and received a summary of their performance in this block.

Participants started the next block at their own discretion by pressing one of the response keys. The whole experiment lasted for 45-60 minutes.

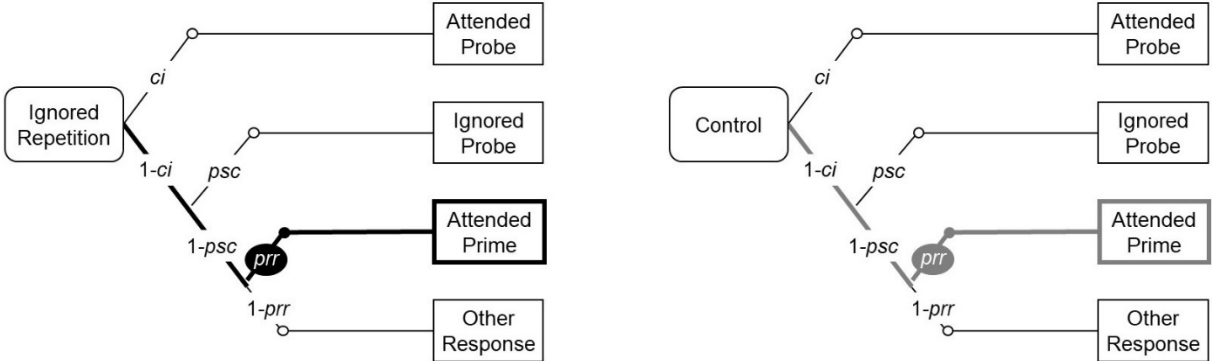
Design and analysis

This experiment comprised a 2 (Trial Type: ignored repetition vs. control) × 2 (Prime Context: common vs. changing) within-subject design. Apart from the averaged probe reaction times and overall probe error rates, probe response frequencies were analyzed.

The multinomial processing tree (MPT) model (for a general introduction of the method, please see Hu & Batchelder, 1994) introduced by Mayr and Buchner (2006) was used to analyze the probe response frequency data (henceforth, this model is called the baseline model, see Figure 3 for a description of the baseline model).

Figure 3

The baseline model for analyzing probe response frequencies



Note. The figure was taken from (Qiu et al., 2022), which is conceptually equivalent to Figure 3 in Mayr and Buchner (2006). The baseline model includes

two “trees”, one for the ignored repetition condition, one for the control condition. Each “branch” of the “tree” leads to a possible probe response category, including the correct response and three types of errors. Note that the label of each category indicates the stimulus that is responded to. For example, “Attended Probe” is the probe target stimulus, thus, this represents a correct probe response. The parameters on the branches reflect the (conditional) probabilities of the presumed cognitive processes, which will lead to specific behavior outcomes (here the probe responses). When feeding the empirical frequency data into the model, the (conditional) probabilities can be estimated and compared between conditions.

In the baseline model, probe responses in the ignored repetition condition (in the following represented by the abbreviation “IR”) as well as those in the control condition (represented by the abbreviation “C”) can be categorized as (1) correct response (correct identification, with probability ci); (2) erroneous response to the probe distractor (probe stimulus confusion, with probability p_{sc}); (3) erroneous execution of the prime response (prime-response retrieval, with probability p_{rr}); (4) erroneous response with the remaining fourth response option. To investigate whether the conditional probability of committing a prime response error is larger in the ignored repetition than in the control condition (i.e., the so-called prime-response retrieval effect), a restriction of $p_{rr_{IR}} = p_{rr_C}$ should be added to the baseline model. A significant misfit of the restricted model against the empirical data will be evidence for the retrieval of the prime response induced by the

repetition of the prime distractor stimulus. We expected a contextual modulation of the prime-response retrieval effect. To test whether the size of the prime-response retrieval effect is modulated by Prime Context, the baseline model of each Prime Context condition is combined into a joint model so that the *prr* parameters can be compared between context conditions. The analysis is done by two steps. Firstly, the *prr_C* parameters are compared between the common context and the changing context conditions. Secondly, based on the statistical equivalence of the *prr_C* parameters between Prime Context conditions, one can further compare the *prr_{IR}* parameters between these conditions. This analysis tests the equivalence of the *prr_{IR}* parameters between the common context and the changing context conditions, given the (statistical) equivalence of the *prr_C* parameters between these conditions. A significant misfit of the model against the empirical data in step 2 will indicate that the prime-response retrieval effect is modulated by Prime Context. The abovementioned model analyses were conducted with the multiTree software (Moshagen, 2010).

G*Power (Faul et al., 2009) was used for sample size calculation in this and the following experiments. In order to achieve sufficient power to detect a medium sized contextual modulation of the negative priming effect in reaction times and/or error rates (i.e., $f = 0.25$, as in G*Power 3.0), given the desired levels of $\alpha = .05$, $1 - \beta = .80$, and an assumed correlation of $\rho = .2$ (estimated from Mayr et al., 2018), data from 53 participants had to be collected. The final sample

comprised 56 participants, thus the power was slightly larger ($1 - \beta = .83$) than what was originally planned for.

Results

Analysis of probe reaction times and overall probe error rates

Trials with response times shorter than 100 ms or longer than 3000 ms were treated as invalid and were excluded from the analysis of reaction times (approximately 0.5%). Trials with responses faster than 400 ms in the prime (approximately 0.1%) were not included, either, which ensured that participants always experienced the change of the prime context in the changing context condition in the remaining trials. Furthermore, only trials with correct responses in both the prime and the probe were included in the analysis of probe reaction times. In total, approximately 17% of all trials were excluded from the analysis of probe reaction times. As for the analysis of overall probe error rates, only trials with valid and correct responses longer than 400 ms in the prime were included, leaving approximately 10% of trials excluded.

The 2 (Trial Type: ignored repetition vs. control) \times 2 (Prime Context: common vs. changing) repeated-measured MANOVA on reactions times showed a significant main effect of Trial Type, $F(1, 55) = 12.77, p < .001, \eta_p^2 = .19$. Probe responses were 25 ms slower in the ignored repetition condition than in the control condition, revealing a negative priming effect. Neither the main effect of Prime Context nor the interaction effect was significant, $F_s < 2.34, p_s > .13$.

The same MANOVA on overall error rates revealed no significant main or interaction effects, all $F_s < 1.02$, $p_s > .31$. Please see Table 1 for mean reaction times and error rates in each 2×2 condition.

Table 1

Mean probe RTs (ms) and overall probe error rates (%) with SE in parenthesis in Experiment 1

Prime Context	Trial Type	
	Ignored Repetition	Control
Common	953 (18)	921 (18)
	8.4 (1.0)	8.3 (1.0)
Changing	943 (19)	926 (19)
	9.3 (1.0)	8.1 (1.1)

Note. The overall error rates contain all types of errors in the probe, including the erroneous execution of the prime response.

MPT model analysis of probe response frequencies

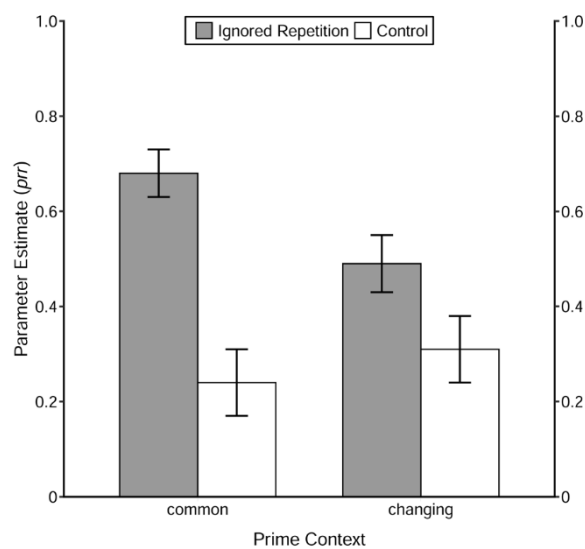
Invalid trials as well as trials with incorrect prime responses or prime responses faster than 400 ms were not included in the model analysis, which took up around 11% of all trials.

To investigate the prime-response retrieval effect induced by the repetition of the prime distractor stimulus, the goodness-of-fit of the baseline model with the restriction $prr_C = prr_{IR}$ under each Prime Context condition was tested (estimated results of the prr parameters are depicted in Figure 4). The restricted model had to be rejected for the common context condition, $G^2(1) = 19.13$, p

$< .001$, $\omega = .06$, revealing a significant prime-response retrieval effect, but not for the changing context condition, $G^2(1) = 3.60$, $p = .06$, $\omega = .03$. These results show clear evidence of prime-response retrieval processes induced by the repetition of the prime distractor stimulus in the common context but not in the changing context condition.

Figure 4

Probability estimates for the prr parameters as a function of Trial Type and Prime Context



Note. Error bars depict the standard errors of the parameter estimates.

To further corroborate the difference of the prime-response retrieval effect between the common context and the changing context conditions, the baseline models for these conditions were combined into a joint model to compare the prr parameters between context conditions. Firstly, the prr_C parameters were set to be

equal between context conditions. The restricted model with the restriction of the equivalence of the prr_C parameters fit the data very well, $G^2(1) = 0.43$, $p = .51$, $\omega = .01$. Based on the statistical equivalence of the prr_C parameters, the prr_{IR} parameters were further compared between context conditions. With the additional restriction of equivalence of the prr_{IR} parameters, the restricted model had to be rejected, $G^2(1) = 4.89$, $p = .03$, $\omega = .02$, indicating that the prime-response retrieval effect induced by the repetition of the prime distractor stimulus was larger in the common context than in the changing context condition.

Discussion

Experiment 1 demonstrated a larger prime-response retrieval effect induced by the repetition of the prime distractor stimulus in the common context than in the changing context condition. These results suggest that sharing a common context can strengthen the binding between a stimulus and the response as compared with being separated by different contexts, supporting a binding principle of common context.

Experiment 1 also showed a significant negative priming effect (in reaction times), which was not modulated by Prime Context. However, it has to be noted that multiple mechanisms were found to underlie the negative priming effect (see Frings et al., 2015 for a review). Prime-response retrieval is just one process that is responsible for the emergence of the negative priming effect (Mayr & Buchner, 2006), but is the only process pertaining to the current purpose as it is a clear

indication of stimulus-response binding. Moreover, previous findings also reveal that in the auditory modality, the negative priming effect in reaction times is insensitive to context manipulation (Mayr et al., 2018). Together, the current result of non-significant contextual modulation of the negative priming effect in reaction times does not seem surprising. With that being said, a significant contextual modulation of the negative priming effect in reaction times was previously observed in the visual modality (e.g., Chao, 2009; Chao & Yeh, 2008), possible reasons for the modality differences may be a topic for future studies.

To sum up, Experiment 1 provides evidence for the binding principle of common context by showing a larger prime-response retrieval effect in the common context than in the changing context condition. To conceptually replicate the findings in Experiment 1 and to further corroborate and generalize these findings across paradigms investigating stimulus-response binding and retrieval (see Frings et al., 2020 for a review), Experiment 2A was conducted, in which the *distractor-response binding (DRB)* paradigm was implemented.

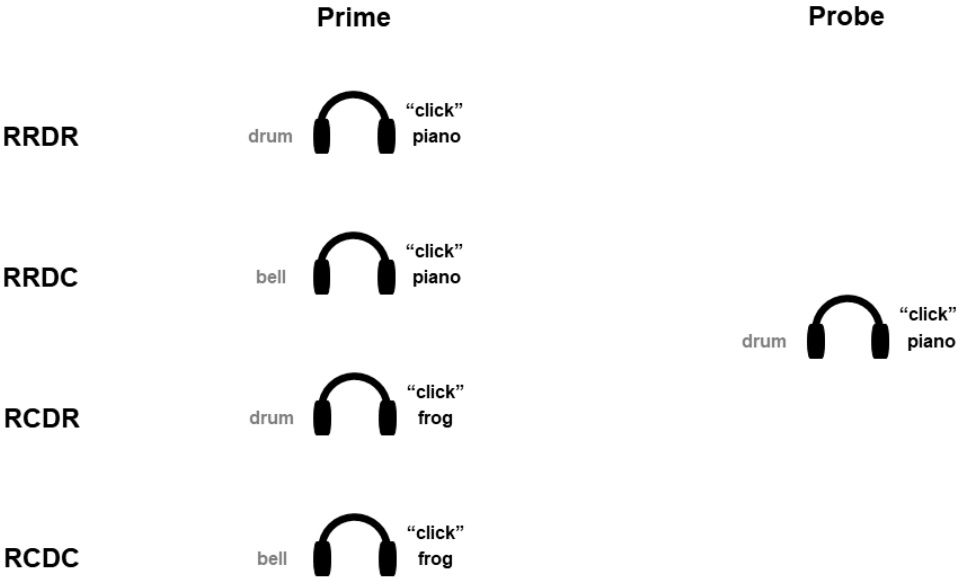
Experiment 2A

The DRB paradigm is a well-established tool to investigate binding between the prime distractor stimulus and the response (Frings et al., 2020; Frings et al., 2007). Similar to the negative priming task, each trial in a typical DRB task is comprised of a prime presentation and a probe presentation. Each presentation contains a target stimulus and a distractor stimulus and participants are required to respond

to the target stimulus and to ignore the distractor stimulus simultaneously. The required response as well as the distractor stimulus are independently repeated or changed between the prime and the probe, leading to four different trial types, namely, trials with response repetition and distractor repetition (RRDR), trials with response repetition and distractor change (RRDC), trials with response change and distractor repetition (RCDR), and trials with response change and distractor change (RCDC). An example of the four trial types is presented in Figure 5.

Figure 5

An exemplary illustration of the four trial types in the DRB paradigm as used in Experiment 2A and 2B



Note. Targets (displayed on the side cued by a “click”) are in black, distractors are in grey.

Following the rationale of the DRB paradigm (Frings et al., 2007), the distractor and the response are bound together into an event file in the prime. As a consequence, when the prime distractor stimulus is repeated (as distractor) in the probe, the prime response is retrieved. If the retrieved prime response is identical to the required probe response (i.e., in trials with a response repetition), performance is typically facilitated, leading to faster responding in DR trials as compared with DC trials. If the retrieved prime response is incompatible with the probe processing requirement (i.e., in trials with a response change), performance is impaired, resulting in slower responding in DR trials as compared with DC trials. The performance differences (facilitation vs. impairment) across conditions will lead to a significant interaction between the response relation and the distractor relation in the prime and the probe, which has been coined the *distractor-response binding (DRB) effect*⁴. The DRB effect is observed in reaction times and/or in overall error rates (whereas the prime-response retrieval effect in Experiment 1 is based on an analysis of the categorical response data, and more specifically, the frequency of probe errors with the previously executed prime response).

Following our hypothesis of the binding principle of common context, the binding between the prime distractor stimulus and the response should be stronger in the common context condition than in the changing context condition. As a

⁴ Note that previous studies also reported no impairment of performance when the distractor stimulus was repeated as compared with changed in the RC condition. The resulting ordinal instead of disordinal interaction between the response relation and the distractor relation was also considered as evidence for distractor-response binding in the prime episode (e.g., Frings & Moeller, 2012; Moeller et al., 2012; Singh et al., 2016).

consequence, a larger DRB effect should be found in the former than in the latter condition.

Method

Participants

Fifty-eight students (52 female, 1 non-binary) from the University of Passau took part in the experiment for course credit. As in Experiment 1, data of 53 participants were required to reach the desired levels of $\alpha = .05$, $1 - \beta = .80$ (see the *Design and analysis* section for further details of the sample size calculation). Data of one participant had to be excluded due to error rates exceeding 50% in several experimental conditions (as compared with an average of 7%), suggesting either inability or unwillingness to follow the instruction. The resulting sample consisted of 57 participants, ranging in age from 19 to 25 years ($M = 21$, $SD = 1.16$).

Materials and task

Identical stimuli from Experiment 1 were used, except that the high pitch context tone was changed from 700 Hz to 600 Hz, so that it was more distinguishable from the piano sound. This replacement only slightly changed the overall loudness (< 1 db (A) SPL). Moreover, in the changing context condition, the first context tone ended 100 ms after the offset of the target and distractor sound pair, so that the change of the prime context was better experienced.

The experiment was programmed using PsychoPy 3 (Peirce et al., 2019). Due to the impact of Covid-19 situation on laboratory data collection, the experiment was hosted on the Pavlovia platform (<https://pavlovia.org>). Participants received an invitation link via e-mail which directed them to the experiment. In the experiment, participants were asked to identify the target sound by an appropriate keypress and to ignore the simultaneously presented distractor sound. Since not every private keyboard is equipped with an external number pad, the sounds were assigned to four common letter keys. Specifically, the frog sound was assigned to the key *F*, the piano sound was assigned to the key *V*, the drum and the bell sounds were assigned to the key *J* and *N*, respectively. Participants were asked to use their middle and index fingers of both hands to respond.

As in Experiment 1, each trial comprised a prime and a probe presentation, but the trial types were different. According to whether the prime response and the prime distractor stimulus were repeated or changed in the probe, the trials were labeled as RRDR, RRDC, RCDR and RCDC. In the basic set of experiment trials, each trial type comprised 24 trials. The 96-trial basic set was implemented four times (twice for the common context condition, twice for the changing context condition), resulting in 384 trials, which were presented in a random sequence. The prime target was randomly played on the left side or on the right side, and the probe target was always played on the same side. The side where the target would be presented was indicated by the 20-ms metronome click sound.

Procedure

After the introduction to the sounds and the task, three training sessions followed, which were similar to those in Experiment 1. The only difference was that the criterion to pass the first two training sessions was accuracy of 33% in 12 trials to reduce the overall task duration. If the participants failed in any training session, the program ended and they were offer to quit or try again. In the final training session, participants experienced 10 prime-probe trials. The timing of these trials and of the experimental trials was identical to that in Experiment 1, but with longer intertrial interval (i.e., 2000 ms), so that participants could be better prepared for the upcoming trial.

The experiment comprised 16 blocks, each comprised 24 trials. After each block, participants took a rest and the summary of their performance in the block was presented. They started the next block at their own discretion by pressing the space key. The experiment lasted for approximately 45 minutes.

Design

The experiment comprised a $2 \times 2 \times 2$ within-subject design with Response Relation (repeated vs. changed), Distractor Relation (repeated vs. changed), and Prime Context (common vs. changing) as independent variables. The dependent variables were probe reaction times and overall probe error rates. To detect a medium sized (i.e., $f = 0.25$) contextual modulation of the DRB effect in reaction times and/or in error rates, given the desired levels of $\alpha = .05$ and $1 - \beta = .80$, and an assumed correlation of $\rho = .2$, data had to be collected from 53 participants.

The final sample comprised 57 participants, thus, the power was slightly larger ($1 - \beta = .83$) than originally planned for.

Results

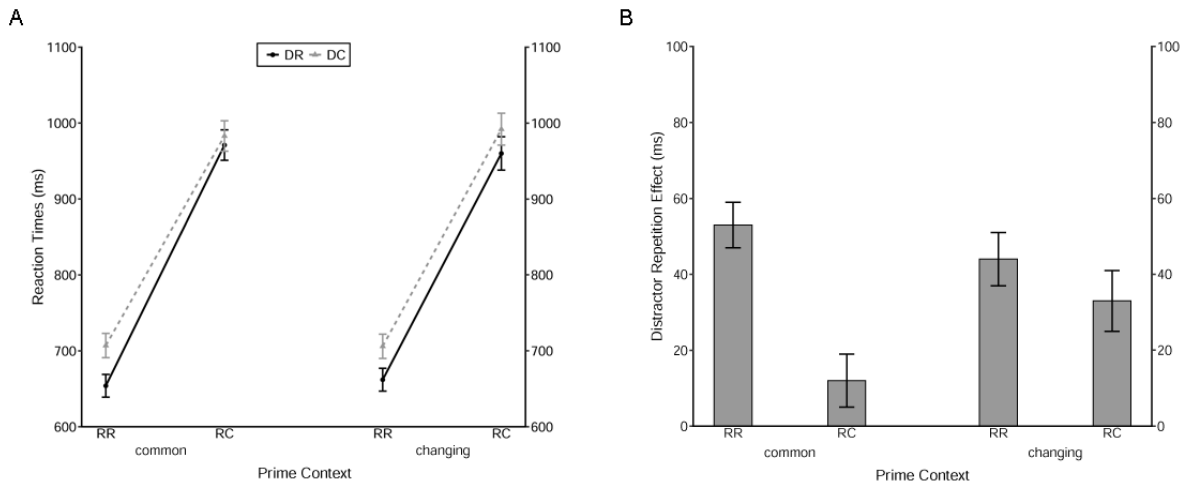
Analysis of probe reaction times

Trials with responses faster than 400 ms which accounted for approximately 2% of all trials were excluded from the analysis of probe reaction times (to ensure that participants experienced the change of the prime context in the changing context condition). To keep in line with previous studies which investigated the stimulus-response binding and retrieval by means of the distractor-response binding paradigm (e.g., Frings et al., 2007; Moeller & Frings, 2011; Moeller et al., 2016; Moeller et al., 2012), we further excluded trials with reaction times longer than 1.5 interquartile ranges above the third quartile of the distribution of the participant (Tukey, 1977), covering approximately 9% of all trials. Furthermore, only trials with correct responses in both the prime and the probe were included in the analysis of probe reaction times. Due to these criteria, approximately 21% of all trials were excluded from the analysis of probe reaction times. The 2 (Response Relation: repeated vs. changed) \times 2 (Distractor Relation: repeated vs. changed) \times 2 (Prime Context: common vs. changing) MANOVA on probe reaction times showed significant main effects of Response Relation, $F(1, 56) = 672.35, p < .001, \eta_p^2 = .92$, and of Distractor Relation $F(1, 56) = 108.56, p < .001, \eta_p^2 = .66$. Reaction times were longer when the response or the distractor was

changed than repeated (see Table 2 for mean reaction times and error rates in each $2 \times 2 \times 2$ condition, and Figure 6 for an overview of the descriptive findings in reaction times). The main effect of Prime Context was not significant, $F(1, 56) = 0.08, p = .78, \eta_p^2 < .01$. The two-way interaction between Response Relation and Distractor Relation was significant, $F(1, 56) = 11.39, p < .01, \eta_p^2 = .17$, showing a significant general DRB effect (26 ms, the DRB effect is calculated as the difference of the distractor repetition effect between response repetition trials and response change trials, e.g., Moeller et al., 2016). More importantly, the three-way interaction of Response Relation, Distractor Relation and Prime Context was also significant, $F(1, 56) = 5.37, p = .02, \eta_p^2 = .09$, revealing a significant modulation of the DRB effect by Prime Context. A 2×2 MANOVA with Response Relation and Distractor Relation as within-subject variables was conducted for the common context and changing context conditions, respectively. Results revealed a significant interaction effect in the common context condition, $F(1, 56) = 22.30, p < .001, \eta_p^2 = .29$, showing a significant DRB effect (41 ms), but not in the changing context condition (11 ms), $F(1, 56) = 1.09, p = .30, \eta_p^2 = .02$. Further analysis in the common context condition showed a significant main effect of Distractor Relation when the response was repeated, $F(1, 56) = 91.78, p < .001, \eta_p^2 = .62$, but not when the response was changed between the prime and the probe, $F(1, 56) = 3.07, p = .51, \eta_p^2 = .05$. No other interaction effects were significant, both $Fs < 0.75, ps > .39$.

Figure 6

Descriptive findings in probe reaction times in Experiment 2A



Note. A) Reaction times as a function of Response Relation, Distractor Relation and Prime Context; B) Distractor repetition effect (calculated as the difference between distractor change and distractor repetition trials) as a function of Response Relation and Prime Context. The error bars depict the standard errors of the means.

Analysis of overall probe error rates

Only trials with correct responses in the prime and with prime reaction times longer than 400 ms were included in the analysis of probe error rates, excluding approximately 10% of all trials.

The 2 (Response Relation: repeated vs. changed) \times 2 (Distractor Relation: repeated vs. changed) \times 2 (Prime Context: common vs. changing) MANOVA on probe error rates revealed significant main effect of Response Relation, $F(1, 56) = 80.69, p < .001, \eta_p^2 = .59$, and Distractor Relation, $F(1, 56) = 18.01, p < .001$,

$\eta_p^2 = .24$. The error rates were higher when the response or the distractor was changed than repeated. None of the other main or interaction effects was significant, with all $F_s < 1.66$, $p_s > .20$.

Table 2

Mean probe RTs (ms) and overall probe error rates (%) with SE in parenthesis in Experiment 2A

Prime Context			Response Relation	
			Repetition	Change
Common	Distractor	Repetition	654 (14)	971 (19)
		Relation	1.2 (0.3)	6.7 (1.1)
		Change	707 (15)	983 (18)
			2.9 (0.6)	7.6 (1.1)
Changing	Distractor	Repetition	662 (15)	960 (19)
		Relation	1.1 (0.4)	5.9 (0.8)
		Change	706 (16)	992 (21)
			3.1 (0.7)	7.1 (0.8)

Discussion

Experiment 2A varied the temporal extension of an irrelevant context stimulus in the DRB paradigm and demonstrated a larger DRB effect in the common context condition than in the changing context condition, which conceptually replicates the findings from Experiment 1. The significant DRB effect in the common context condition was mainly driven by the facilitation of performance in DR trials (as compared with DC trials) when the response was also repeated. However,

no impairment of the performance in DR trials (as compared with DC trials) when the response was changed between the prime and the probe was observed. This pattern of an asymmetrical DRB effect – significant distractor repetition effect in the response repetition condition and non-significant distractor repetition effect in the response change condition – has been found repeatedly (e.g., Frings & Moeller, 2012; Moeller et al., 2012; Singh et al., 2016). It has been attributed to the interplay between two processes, namely, the retrieval of event files on the one hand and the inhibition of the distractor stimulus on the other hand (Frings & Moeller, 2012). According to the authors, the effective inhibition of the distractor stimulus benefits the correct probe response regardless of whether the response is the same or different in the prime and the probe, whereas the impact of the distractor-induced retrieval of the prime response depends on whether the prime response is compatible with the correct probe response or not. If these processes both work in the same direction (i.e., in trials with a response repetition), performance will be facilitated. However, if these processes work in opposite directions (i.e., in trials with a response change), they may neutralize each other, leading to a non-significant effect on performance. The resulting asymmetrical pattern, which has been repeatedly found before, is exactly what we observed in the current study.

Taken together, results from Experiment 2A show again, that sharing a common context, as compared with being separated by different contexts, leads

to a stronger binding between a stimulus and the response, which suggests a binding principle of common context.

However, contextual similarity between the encoding and the testing phases can influence successful retrieval (for a review, see Smith & Vela, 2001). Therefore, it is possible that contextual similarity between the prime and the probe, and not the differences in binding, may underlie the modulation of the prime-response retrieval effect and the DRB effect. In this vein, it might be argued that the common context in the prime is perceived as more similar to the persisting silence in the probe than the changing prime context. In this case, better retrieval in the common context condition may lead to a larger prime-response retrieval effect and a larger DRB effect, as we observed in Experiment 1 and 2A, respectively. This contextual similarity account was tested in Experiment 2B. Based on the conceptually identical results from Experiment 1 and 2A, we suppose that the four-alternative negative priming paradigm and the DRB paradigm pinpoint the same stimulus-response binding and retrieval processes (Frings et al., 2020). Experiment 2B was planned as an online experiment on the Pavlovia platform. The DRB paradigm was selected for consistency between experiments (as Experiment 2A [DRB] had been an online experiment, too, whereas Experiment 1 [NP] had been run as a lab experiment).

Experiment 2B

Experiment 2B was conducted to test the alternative account of contextual similarity between the prime and the probe for the larger after-effects of binding in the common context than in the changing context condition. To this end, the prime context (i.e., common or changing context) and the probe context (i.e., persisting silence) in Experiment 1 and 2A were reversed in the current experiment: The prime context was persisting silence whereas the probe context was either a common or a changing context. If the persisting silence is more similar to a common context than a changing context, contextual similarity should benefit retrieval, leading to a larger DRB effect in the common (probe) context than in the changing (probe) context condition.

Method

Participants

Fifty-eight participants (41 female, 3 non-binary) participated in the experiment. 50 participants were recruited from Prolific (<https://www.prolific.co>). The remaining eight participants were students of the University of Passau. As in Experiment 2A, data of 53 participants were required to reach the levels of $\alpha = .05$, $1 - \beta = .80$ (see the *Design and analysis* section for details of the sample size calculation). Their age ranged from 18 to 36 years ($M = 23$, $SD = 5.10$). Participants either received a monetary reward of 3.75 pounds or course credit for their participation.

Materials and procedure

The stimuli and the procedure were the same as that of Experiment 2A, with the above-mentioned exception that the context was systematically varied in the probe.

Design

The experiment comprised a $2 \times 2 \times 2$ within-subject design with Response Relation (repeated vs. changed), Distractor Relation (repeated vs. changed), and Probe Context (common vs. changing) as independent variables. The dependent variables were probe reaction times and overall probe error rates. As in Experiment 2A, data had to be collected from 53 participants to detect a medium sized (i.e., $f = 0.25$) contextual modulation of the DRB effect ($\alpha = .05$ and $1 - \beta = .80$). The final sample comprised 58 participants, so the power was slightly larger ($1 - \beta = .84$) than the desired level.

Results

Analysis of probe reaction times

Following the same criterion as in Experiment 2A, trials with responses faster than 400 ms (in order to ensure that participants experienced the probe context change in the changing context condition), as well as trials with too slow responses (i.e., reaction time longer than 1.5 interquartile ranges above the third quartile of the distribution of the participants) were excluded from the analysis of probe reaction times, which accounted for approximately 11% of all trials.

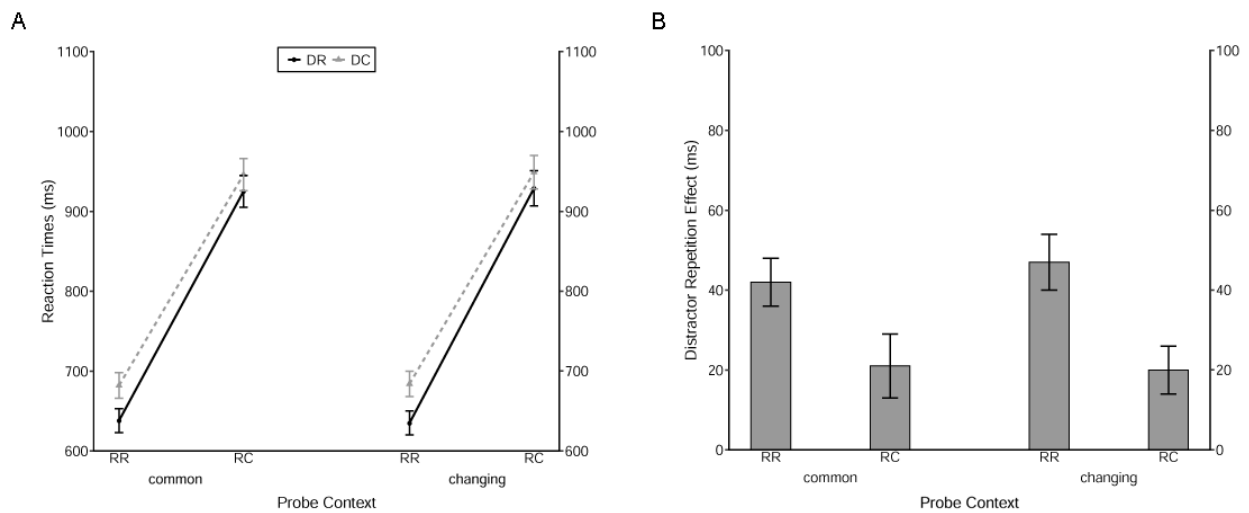
Furthermore, only trials with correct responses in both the prime and the probe were included in the analysis of probe reaction times. In total, approximately 18% trials were excluded from the analysis of probe reaction times.

A 2 (Response Relation: repeated vs. changed) \times 2 (Distractor Relation: repeated vs. changed) \times 2 (Probe Context: common vs. changing) MANOVA on probe reaction times showed significant main effects of Response Relation, $F(1, 57) = 637.98, p < .001, \eta_p^2 = .92$, and of Distractor Relation, $F(1, 57) = 100.17, p < .001, \eta_p^2 = .64$. Reaction times were longer when the response or the distractor was changed than repeated (see Table 3 for mean reaction times and error rates in each 2 \times 2 \times 2 condition, and Figure 7 for an overview of the descriptive findings in reaction times). The main effect of Probe Context was not significant, $F(1, 57) = 0.30, p = .59, \eta_p^2 < .01$. The two-way interaction between Response Relation and Distractor Relation was significant, $F(1, 57) = 14.05, p < .001, \eta_p^2 = .20$, showing a significant general DRB effect (26 ms). However, the three-way interaction of Response Relation, Distractor Relation and Probe Context was not significant, $F(1, 57) = 0.24, p = .63, \eta_p^2 < .001$. Further analyses were conducted to interpret the significant interaction between Response Relation and Distractor Relation. Results showed that the main effect of Distractor Relation was significant when the response was repeated, $F(1, 57) = 74.72, p < .001, \eta_p^2 = .57$, and when the response was changed between the prime and the probe, $F(1, 57) = 23.20, p < .001, \eta_p^2 = .30$, but the size of the effect was larger in the former than

in the latter condition. No other interaction effects were significant, both $F_s < 0.39$, $p_s > .53$.

Figure 7

Descriptive findings in probe reaction times in Experiment 2B



Note. A) Reaction times as a function of Response Relation, Distractor Relation and Probe Context; B) Distractor repetition effect (calculated as the difference between distractor change and distractor repetition trials) as a function of Response Relation and Probe Context. The error bars depict the standard errors of the means.

Analysis of overall probe error rates

Only trials with correct responses in the prime and with probe reaction times longer than 400 ms were included in the analysis of overall error rates, excluding approximately 7% of all trials.

The 2 (Response Relation: repeated vs. changed) \times 2 (Distractor Relation: repeated vs. changed) \times 2 (Probe Context: common vs. changing) MANOVA on probe error rates revealed significant main effect of Response Relation, $F(1, 57) = 76.73, p < .001, \eta_p^2 = .57$. Participants were more error prone when the response was changed than when it was repeated. The main effect of Probe Context was also significant, $F(1, 57) = 4.17, p = .046, \eta_p^2 = .07$, showing higher error rates in the changing context than in the common context condition. None of the other main or interaction effects was significant, all $F_s < 3.56, p_s > .06$.

Discussion

In Experiment 2B, the probe context was manipulated to test the possible influence of contextual similarity between the prime and the probe on the DRB effect. Results showed a general DRB effect, which, however, was not modulated by the probe context manipulation. In other words, when keeping the prime context identical (persisting silence), the probe context (common or changing) did not modulate the DRB effect. These results do not support the notion that the common context is more similar to the persisting silence than the changing context, and that contextual similarity between the prime and the probe accounts for the findings in Experiment 1 and 2A⁵.

⁵ It should be noted that Experiment 2B mainly provides empirical evidence that the DRB effect is not affected by the manipulation of common or changing context in the probe. However, we suppose the four-alternative negative priming paradigm and the DRB paradigm pinpoint the same stimulus-response binding and retrieval processes (see Frings et al., 2020). Therefore, we view Experiment 2B as a valid conceptual control for Experiment 1 as well.

Table 3

Mean probe RTs (ms) and overall probe error rates (%) with SE in parenthesis in Experiment 2B

Prime Context			Response Relation	
			Repetition	Change
Common	Distractor	Repetition	638 (15)	925 (20)
		Relation	0.7 (0.3)	6.2 (0.9)
	Change		682 (16)	946 (20)
			2.0 (0.5)	6.0 (0.9)
Changing	Distractor	Repetition	635 (15)	929 (22)
		Relation	1.0 (0.4)	7.0 (1.0)
	Change		684 (16)	949 (21)
			1.9 (0.5)	7.5 (1.0)

General Discussion

The main purpose of the current study was to investigate the impact of event segmentation on stimulus-response binding, with a focus on the role of auditory context in demarcating the stimulus-response integration window. Using different paradigms, Experiment 1 and 2A revealed conceptually consistent results. In a nutshell, after-effects of binding between the prime distractor stimulus and the response (i.e., the prime-response retrieval effect in Experiment 1, and the DRB effect in Experiment 2A) were larger in the common context as compared with the changing context condition. In Experiment 2B, an alternative account for the

larger after-effects of binding in the common than in the changing context condition was investigated. To test the assumption that a larger contextual similarity between the prime and the probe in the common context condition was the reason for the difference in results, the context in the probe instead of in the prime was manipulated to be either a common context or a changing context. Results showed statistically comparable DRB effects in the common (probe) context and in the changing (probe) context conditions when the prime context was persisting silence, which suggests that the findings in Experiment 1 and 2A cannot be attributed to prime-probe contextual similarity but rather to differences in prime processing (i.e., binding). Together, the findings suggest that sharing a common context strengthens the binding between the prime distractor stimulus and the response, suggesting a binding principle of common context.

Current results are in line with the findings from previous studies that the context can effectively segment events (e.g., DuBrow & Davachi, 2013; DuBrow & Davachi, 2016; Ezzyat & Davachi, 2014; Heusser et al., 2018; Pu et al., 2022). In these studies, a series of items were presented within the same context or in different contexts, and the results showed stronger associations of the items (e.g., by better serial recall performance) in the former than in the latter condition. This influence of the context may be related to its role as a “scaffold” in structuring information (e.g., Burgess et al., 2001; Estes, 1955; Howard & Kahana, 2002; Polyn et al., 2009a). It was proposed that the similarity of the context during the memory encoding procedure is one reason for the *clustering phenomenon*

(Bousfield, 1953) of free recall (i.e., in the testing phase, certain items tend to cluster in recall sequences, which reveals strong connections of these items in the memory system). For example, the *lag recency effect* (i.e., temporally closer items are more likely to be reproduced successively) was discussed to result from the fact that items being close to one another are more likely to share a similar context than items being farther apart (the *temporal context model*, Howard & Kahana, 2002). Empirical evidence further shows that the more similar the contexts, the more likely the items presented within the contexts were later clustered during recall (e.g., Heusser et al., 2018; Polyn et al., 2009b), which indicates that these items were more strongly associated in memory (Polyn et al., 2009a). This “scaffold” role of context may contribute to its ability in event segmentation, in the way that it helps to structure information into cohesive temporal units, which are perceived and remembered as events. Transferring this role of context into stimulus-response binding, it is possible that sharing a common context binds the perceptual and response features more strongly together into an episode (i.e., the event file), thereby leading to a larger binding effect in the common than in the changing context condition. This is exactly what we observed in the current study, in terms of a larger prime-response retrieval effect and a larger DRB effect in the common context than in the changing context condition.

Moreover, given that both effects (i.e., the prime-response retrieval effect and the DRB effect in Experiment 1 and 2A, respectively) were not significant in the changing context condition, the current results are consistent with the

hypothesis that working memory is updated at event boundaries (Zacks et al., 2007). According to the event segmentation theory, the event model is updated when prediction errors accumulated, which results in the perception of an event boundary. Assuming that only the latest event model is stored in working memory (Radvansky & Zacks, 2014), the active memory for the current, observed unit of experience is flushed at event boundaries. The hypothesis is corroborated by empirical evidence that items occurring directly at or shortly after event boundaries were more easily remembered (e.g., Heusser et al., 2018; Swallow et al., 2009), which is considered as a consequence of “enhanced processing” due to active memory flush (Kurby & Zacks, 2008; Swallow et al., 2009). If working memory was updated at the event boundary cued by context change, then the stimulus presented preceding the event boundary might not be stored together with the response made after the event boundary. Hence, repetition of the stimulus was less likely to retrieve the response and as a result, binding effects were not observed in the changing context condition. The update of working memory, which presumably impairs binding, as well as the potential reinforcement of binding by the common context, may both underlie the current results pattern showing larger prime-response retrieval effects and DRB effects in the common context than in the changing context condition. It will be relevant for prospective studies to further distinguish between these processes and to further specify the influence of event segmentation on stimulus-response binding.

Current findings also suggest that an “event file” may bear some resemblance with an “event” as described in event segmentation theory. Zacks and Tversky (2001, p 3) define an event as “a segment of time at a given location that is conceived by an observer to have a beginning and an end”. Although the definition of an event file does not incorporate the subjective perception of a beginning and an end (Frings et al., 2020; Hommel, 2004), an event file seems to (partly) fit the definition of an event. If considering an event file as an episode which starts with the presentation of stimuli and ends with the execution of a response, an event file may be structurally similar to an event, but on a very short time scale (see Zacks, 2020 for a similar perspective). The current findings support this notion of structural similarity, as the present results indicate that an event file may be further segmented by external context into separated perceptual features and responses. External context has been proven as an effective segmentation factor of events as well (e.g., Heusser et al., 2018; Pu et al., 2022). Taken together, although there are some differences between event files and events (e.g., subjective perception, temporal scale), they seem to be closely related.

The commonalities between an event file and an event also suggest that the two rather independent fields – event segmentation and stimulus-response binding and retrieval – are approaching each other. This indication is even more pronounced with the development of the broader concept of *event cognition* (Radvansky & Zacks, 2014, 2017). As compared with event segmentation, which mainly focuses on the perception and memory aspect, event cognition focuses on

event perception and its interaction with memory, language and action control (Zacks, 2020). The observed influence of event segmentation on stimulus-response binding in the current study can be viewed as evidence for the interaction between event perception and action control, which suggests that paradigms within the BRAC framework can be effective tools to investigate event cognition. It should be noted that the current study only focused on the temporal segmentation of events by context, while several segmentation factors other than external context have been proposed and tested in previous studies in the field of event segmentation, such as spatial location and causal relationship (for a review, see Zacks, 2020). It would be fruitful and interesting for future studies to investigate the role of other segmentation factors in stimulus-response binding and retrieval. Several modulating factors have been found in the field of stimulus-response binding and retrieval (e.g., Gestalt principles, Frings & Rothermund, 2011; Frings & Rothermund, 2017). Whether and how these factors influence event segmentation may also be interesting to investigate in future studies.

To sum up, using both the negative priming paradigm as well as the DRB paradigm, the current study shows that sharing a common context, as compared with being separated by different contexts, leads to a stronger binding between the stimulus and the response, suggesting a binding principle of common context.

Declarations

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Data availability

After acceptance of the manuscript, the data and programming code for data analysis of all experiments will be available on <https://www.psycharchives.org/>.

During the reviewing process, the data and programming code for data analysis are available upon request. None of the experiments were preregistered. This work is part of the doctoral dissertation by Ruyi Qiu.

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Chapter 5: General Discussion

5.1 Summary and Interpretation

The current thesis was aimed to specify the role of context in S-R binding and retrieval. Intrigued by previous studies (which are introduced in Section 1.2 in Chapter 1), the context was considered either as an element that can be integrated into an S-R episode, or as an event segmentation factor that can impact the binding between the distractor stimulus and the response into an S-R episode. In order to test these roles of the context in S-R binding and retrieval, three studies were conducted, findings of these studies are briefly summarized in the following.

Study One and Two: The Role of Context as an Element in S-R episodes

Study One and Two investigated the role of context as an element which can enter into different binding structures (binary vs. configural) in an S-R episode. Study One focused on the saliency property of the context. Across three experiments, the context saliency was manipulated by systematically changing the loudness and the emotional valence of the contextual stimulus. Results reveal consistent evidence that saliency determines the integration of the context in an S-R episode. Specifically, when the context saliency is low and presumably lower than the saliency threshold of integration (Hommel, 2004), the context is not integrated into an S-R episode. When the context saliency is above such an integration threshold but not high enough for the context to be bound in a binary fashion with the response, the context enters into a configural binding with the prime distractor stimulus and the prime response, as observed by Mayr et al. (2018). Finally, when

the context saliency is sufficiently high, the context is bound directly with the response in a binary fashion into an S-R episode. Taken together, these findings suggest that apart from the saliency threshold that determines whether a stimulus can be integrated into an S-R episode or not (Hommel, 2004), there might be a second saliency threshold which determines the specific binding structure (binary vs. configural) of the stimulus in an S-R episode.

In Study Two, the inter-trial variability of the contextual stimulus was manipulated to investigate the integration of the context into an S-R episode. Participants were either assigned into the low-variability group (in which two out of the eight selected sine tones were used as the context) or into the high-variability group (in which all of the eight sine tones were used as the context). Results showed a pattern of configural binding among the context, the prime distractor stimulus and the response in the low-variability group. In the high-variability group, however, a binary binding between the context itself and the response was observed. These results indicate that simply increasing the inter-trial variability of the context can lead it to be bound directly with the response in the binary fashion.

Given that the more frequently changing stimulus may be perceived as more novel and less predictable, and thus, presumably more salient (e.g., Alink & Blank, 2021; Ernst et al., 2020), the results of Study Two seem to fit the aforementioned assumption of the second saliency threshold which determines specific binding structures. In the low-variability group, each participant only

experienced two context tones, which were as loud as the target and distractor sound pair. In this sense, the low-variability group can be considered as comparable to the moderate-saliency condition in Experiment 1 of Study One. This means that the context of low-variability may not be salient enough to cross the second saliency threshold (Qiu et al., 2022), but is salient enough to cross the first saliency threshold (Hommel, 2004). Therefore, the context of low-variability should enter into a configural binding together with the prime distractor stimulus and the response, as observed in the moderate-saliency condition in Experiment 1 of Study One. In the high-variability group, however, the increased inter-trial variability may result in a higher saliency level of the context, which is above the second saliency threshold, thereby leading to a binary binding between the context and the response. This is exactly what was observed in Study Two. Furthermore, the results of both Study One and Two reveal that the binding structure involving the context changes as a function of a property of the contextual stimulus, indicating a transformation process from a configural binding to a binary binding.

Taken together, Study One and Two show that saliency and inter-trial variability determine the integration of the contextual stimulus into an S-R episode, which helps to specify the role of context as an element in S-R binding and retrieval.

Study Three: The Role of Context as an Event Segmentation Factor

In Study Three, the influence of event segmentation by context on S-R binding was investigated by manipulating the prime context as a common context or a changing context, whereas no context tones were displayed in the probe (i.e., the probe context was persisting silence). As expected, results showed larger after-effects of binding (i.e., a larger prime-response retrieval effect in Experiment 1, and a larger DRB effect in Experiment 2A) in the common context than in the changing context condition. An alternative account of contextual similarity of these findings was tested in Experiment 2B, in which the common and the changing context was manipulated in the probe instead of in the prime. Results showed comparable DRB effects in the common (probe) context and the changing (probe) context conditions, which indicates that the contextual similarity between a common context and the persisting silence may not significantly differ from that between a changing context and the persisting silence. Therefore, contextual similarity cannot account for the findings from Experiment 1 and 2A. Together, the findings in Study Three indicate that sharing a common context, as compared with being separated by different contexts, can strengthen the binding between a stimulus and the response, which supports the notion of a binding principle of common context.

5.2 Remaining Questions and Implications for Future Research

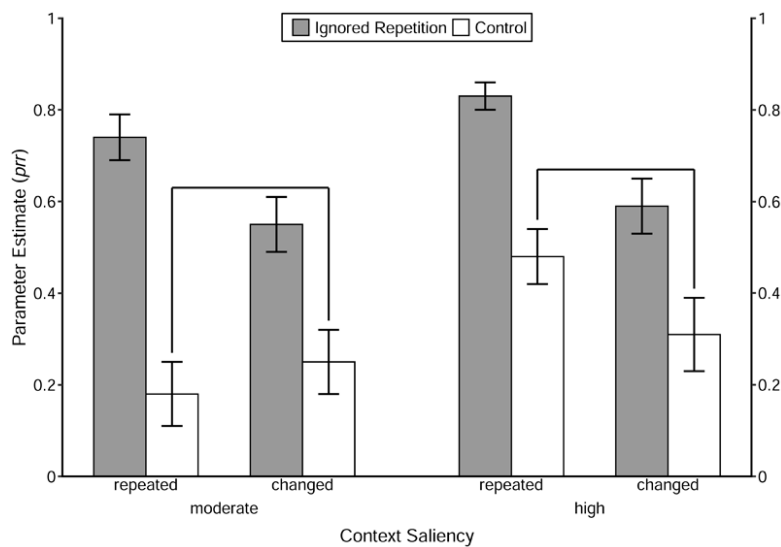
The findings from the three studies lead to some questions that may be interesting to address in future research. The most straightforward one is what exactly is the so-called configural binding. The result pattern of a configural binding is a significantly larger prime-response retrieval effect induced by the repetition of the prime distractor stimulus in the context repetition than in the context change condition (i.e., a significant contextual modulation of the binding between the prime distractor stimulus and the response). This is similar to what was found about the so-called occasion setter in the learning literature (for reviews, see Bonardi et al., 2017; Bouton, 2010), that is, an additional stimulus which can modulate the association between the conditional stimulus (CS) and the response (e.g., a contextual stimulus). Several accounts were proposed to explain the modulation of an occasion setter. On the one hand, the occasion setter may exert a *hierarchical* control over the association between the CS and the response, which is referred to as the *hierarchical theory* (e.g., Holland, 1983). On the other hand, the occasion setter and the other stimuli (e.g., the CS) may form a combination which is subject to associative learning (i.e., the so-called *configural theory*, e.g., Rescorla, 1973). The latter is similar to the possible structure of a configural binding proposed in Study One and Two, that is, the context and the prime distractor form a compound, and the compound is bound with the response into an S-R episode. However, taking the hierarchical theory in the learning literature into consideration, it may also be the case that the context exerts a

hierarchical control over the binding between the prime distractor stimulus and the response. Moreover, the pattern of a configural binding may simply indicate a relatively weak integration of the context with the response, which is not strong enough to show the pattern of a binary binding between the context and the response. These possible structures of a configural binding cannot be distinguished based on the results of Study One and Two.

The next question that remains to be answered is about the transformation between different binding structures. As mentioned earlier, in both Study One and Two, a change of the binding structure according to the change of a property of the contextual stimulus was observed, indicating a transformation process from a configural binding into a binary binding. Following the assumption of the saliency threshold of integration proposed by Hommel (2004), a second saliency threshold was assumed to guide the transformation between the binding structures. However, whether the transformation is an abrupt one or a gradual one is not yet clear. Given the result patterns of the configural binding in Experiment 1 of Study One (see Figure 5.1), it seems that the tendency to directly retrieve the previously executed prime response by repeating the context itself is increasing with the increase of the loudness of the contextual stimulus. Presumably, with even louder contextual stimuli, the pattern of a binary binding might be observed. Based on this observation, it may be the case that the transformation from a configural binding into a binary binding is a gradual one.

Figure 5.1

Probability estimates for the model parameters representing the probability of prime-response retrieval (prr) as a function of trial type and context relation in the moderate-saliency condition and the high-saliency condition in Experiment 1 of Study One



Note. The lines connecting the bars of the control conditions indicate comparisons for testing a binary binding between the context and the prime response. Specifically, a binary binding between the context and the prime response is indicated by a significantly larger probability of retrieving the prime response when the context per se is repeated, as compared with the condition when the context is changed. In Experiment 1 of Study one, the context saliency was manipulated by changing the loudness of the contextual stimulus. In both the moderate-saliency and the high-saliency conditions, results of model analysis showed that the context was involved in a configural binding with the prime

distractor stimulus and the response. However, there was a clear tendency of a binary binding between the context and the prime response in the high-saliency condition.

Furthermore, in the learning literature, the contextual stimulus was found to modulate the association between the CS and the behavior, and at the same time, to be associated with the behavior (e.g., Bouton, 1984; Bouton & King, 1986). Transferring this finding into S-R binding and retrieval, the contextual stimulus may be simultaneously involved in a configural binding with the prime distractor stimulus and the response, and in a binary binding with the response. However, neither in Study One nor in Study Two, there was any evidence of the context entering into these binding structures simultaneously. It may be the case that the employed manipulations of the saliency property and the inter-trial variability property were not appropriate to observe patterns of context being involved in both a binary and a configural binding at the same time. Thus, it is still undecided whether the context can be involved in both a configural binding and a binary binding, which should be tested in future studies, possibly by manipulating the saliency or other properties of the contextual stimulus in a stepwise fashion. Findings from these studies may help to specify the transformation process from a configural binding into a binary binding as well.

Finally, in Study Three, the results indicate that an effective event segmentation factor (i.e., the context) may structure the event file and the event (e.g., Heusser et al., 2018; Pu et al., 2022) in a similar way, which suggests some commonalities between S-R episodes and events. The commonalities between S-R episodes and events implicate that the two rather independent research fields (i.e., S-R binding and retrieval, event segmentation) are approaching each other. It would be fruitful for prospective studies to further investigate the resemblance between S-R episodes and events. For example, an essential feature of events is the so-called *hierarchical structure* (Zacks et al., 2007). In a nutshell, a larger event can be segmented into smaller events, and smaller events can be grouped together into a larger event (Zacks, 2020). It may be interesting to examine whether such a hierarchical structure also exists for S-R episodes, and how it influences binding and retrieval. For example, future studies may investigate whether a sequence of prime and probe can be perceived as a larger “event” which is comprised of a prime episode and a probe episode. Given that belonging to the same event strengthens associations (Pu et al., 2022), improved retrieval of the prime information in the probe may be observed when the sequence of prime and probe is perceived as one “event”, as compared with the condition when the prime and the probe are separated by an event boundary.

5.3 Conclusion

To sum up, the results in the three studies showed that as an element, the context can enter into different binding structures of an S-R episode, which is determined

by the saliency property or the inter-trial variability property of the contextual stimulus. The findings confirm the binding principle of saliency (Hommel, 2004), and extend the saliency principle by suggesting a second saliency threshold that determines the specific binding structures (i.e., binary vs. configural) of an S-R episode. As an event segmentation factor, the context can demarcate the integration window of an S-R episode, which influences the binding between a stimulus and the response. The findings extend the list of binding principles of S-R episodes by suggesting a new principle of sharing a common context. Together, the current thesis specifies the different roles the context plays in S-R binding and retrieval, thereby shedding some light on how contextual information influences human behavior.

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Declaration of Own Contributions

My thesis includes three research articles with a total of seven experiments. For each article, the authors who were involved in designing the experiments, implementing the experiments, analyzing the data, and writing the manuscripts are listed below. The predominant part of the work of each article was done by the first author.

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