



On the Influence of Ignored Stimuli: Generalization and Application of Distractor-Response Binding

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Abstract

In selection tasks where target stimuli are accompanied by distractors, responses to target stimuli, target stimuli and the distractor stimuli can be encoded together as one episode in memory. Subsequent repetition of any aspect of such an episode can lead to the retrieval of the whole episode including the response. Thus, repeating a distractor can retrieve responses given to previous targets; this mechanism was labeled distractor-response binding and has been evidenced in several visual setups. Three experiments of the present thesis implemented a priming paradigm with an identification task to generalize this mechanism to auditory and tactile stimuli as well as to stimulus concepts. In four more experiments the possible effect of distractor-response binding on drivers' reactions was investigated. The same paradigm was implemented using more complex stimuli, foot responses, go/no-go responses, and a dual task setup with head-up and head-down displays. The results indicate that distractor-response binding effects occur with auditory and tactile stimuli and that the process is mediated by a conceptual representation of the distractor stimuli. Distractor-response binding effects also revealed for stimuli, responses, and framework conditions likely to occur in a driving situation. It can be concluded that the effect of distractor-response binding needs to be taken into account for the design of local danger warnings in driver assistance systems.

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Part I.

Introduction and Theoretical Background

Preface

During recent years the technology used in cars has advanced quickly. Nowadays many modern cars are equipped with sensors that measure distances to objects around the car. In turn, a driver backing into a parking space can be informed about how much space is left between car and wall or a driver planning to overtake a leading car can be warned if another car is currently located in the blind spot. In the next future driver assistance systems are likely to use information not only derived from the direct environment of the car but also information that is exchanged between cars and between car and infrastructure (e.g., traffic light circuits).

Imagine for example a driver approaching an intersection. 300 meters before the intersection is reached, the driver assistance system receives the information that braking is likely to become necessary – for example to prevent a rear-end collision – and presents the appropriate warning. The color of this first warning display might be yellow, indicating that this is a pre-warning and prompting the driver to be attentive. An additional symbol of a rear-end collision might inform the driver of the possibly upcoming situation that caused the pre-warning. A moment later, the driver will arrive at the intersection and the driver-assistance system might pick up the information from the leading car that a braking response is indeed necessary. In this case the system presents a red warning display that prompts an immediate braking reaction and presents again the additional information that this response is intended to prevent a rear-end collision.

In such a situation it is crucial which features of the warning have an influence on the actions of the driver. Note that the driver has to carry out completely

different reactions in response to the pre-warning and in response to the actual warning (i.e., being attentive versus pressing the brake). Yet, both reactions are prompted by very similar displays: both times the same icon is presented and only the color around the icon is changed.

It can be argued that the reaction of the driver is triggered solely by the color which differs completely in pre-warning and actual warning. That is, the informational icons can be (and due to the high perceptual load in a driving situation, most likely will be) ignored by the driver. However, recent research presented evidence that also ignored stimuli can influence the swiftness and accuracy of our responses (e.g., Frings & Rothermund, 2011). In particular, even ignored stimuli can retrieve earlier responses and thus facilitate or hamper current responding. That is, ignored stimuli (i.e., ‘distractors’) have been found to play a role in the control of our actions. This mechanism can be assumed to be important in situations similar to the one described above, in which a speeded response is necessary and both relevant and irrelevant information is perceived.

The mentioned mechanism, responsible for influences of ignored stimuli on responses (i.e., distractor-response binding) is first described in detail and I present evidence that the effect replicates both within the auditory and tactile, as well as across modalities. Hence, it becomes clear that the effect is generalizable to a great extent. In a second step, I assess the influence this response-retrieval might have on reactions in everyday situations. Specifically a situation, similar to the one described above, is approached in a laboratory setting. In essence I aim to show that distractors have a significant impact on our behavior in everyday situations such as driving. Eventually, this has important implications, e.g., for the design of human-machine interfaces.

Action Control and The Role of Distractor Processing

As we act and react in our environment, most of the time we do not wonder what happens to the things we ignore. In order to efficiently act in everyday life, we frequently ignore irrelevant stimuli and instead respond to other – relevant – stimuli. Nevertheless, irrelevant stimuli have to be accounted for in our actions as well. One example is the reaching for a certain relevant object: to carry out this action, we have to navigate around irrelevant objects that might be in the way. Similarly, in order to read a certain name on a list, the names above and below that name have to be ignored. Stimuli that are ignored in order to enable adequate responses, have been called distractor stimuli.

There are at least two different possible roles of distractor stimuli in the control of our actions. Top-down controlled perception of our environment includes processes that activate the processing of relevant stimuli on the one hand and actively inhibit the processing of irrelevant or distractor stimuli on the other hand. Thus, in the view of *selective attention*, distractors have a rather passive role of being inhibited. However, this approach of distractor processes is less relevant to this thesis and will only briefly be mentioned later on (see Section 2.1.4, *Selective Attention*; for a review see Styles, 2006).

Of central interest here is the role of distractor processing in automated actions. In a more stimulus driven understanding of perception and action it has been assumed that the retrieval of past episodes, including stimuli and responses, contributes to the automatization of action. That is, a response can be integrated

with a stimulus that is encountered in close temporal proximity of the response and both are stored as one *instance* (Logan, 1988, 1990) or *event file* (Hommel, 1998, 2004) in episodic memory. Another encounter of one part of this memory trace can then retrieve the entire instance.

First, I will give an impression of the relevance of distractor stimuli for automated actions. On that account, binding mechanisms that are responsible for the integration of stimuli and actions are introduced. These mechanisms have first been described in object binding (see Treisman & Gelade, 1980). The process of stimulus-response integrations will then be discussed in detail before the notion of distractor-response binding is introduced and evidence for this account is reviewed. Further, I will consider the role distractor-response bindings can play in human-machine interaction. For that, the Theory of Direct Perception, which can account for perception and action in everyday situations, will briefly be described and two relevant aspects of human-machine interactions will be considered: the presentation of information- or warning displays and performance in dual task situations.

2.1. Automated Actions

A recent view on mechanisms that influence our behavior assumes that also distractors play an important role in action control. Similar to attended stimuli, distractors are suggested to lead to response retrieval and therefore become relevant for the automatization of actions.

According to Logan's (1988, 1990) Instance Theory of Automatization 'performance is automatic when it is based on single-step direct-access retrieval of past solutions from memory' (Logan, 1988, p. 493). If people encounter a new situation, their actions are controlled by a general algorithm. This is sufficient to solve the problem at hand but takes a relatively long time. As people gain experience, the number of episodes in which they solved a problem in a certain way increases and they learn that specific solutions are adequate for certain problems. Each time a familiar situation is encountered, both mechanisms (i.e., the general algorithm and the retrieval of past solutions) start. The mechanism that finishes first accounts for the actual behavior. Eventually, in an automated response, the action that is retrieved from memory is always faster than the general algorithm.

The Instance Theory of Automatization makes three main assumptions. First, *encoding* of a stimulus into memory is obligatory, as an unavoidable consequence

of attention. Second, *retrieval* of stimulus associations from memory is equally obligatory, as an unavoidable consequence of attention. Thus, encoding and retrieval are linked through attention. Third, as an *instance* theory it assumes that each encounter of a stimulus is stored separately in memory. In automatization, the theory accounts for the effect hundreds of exposures to a stimulus have on a response to the stimulus. Yet, the Instance Theory can also account for the effect one or two exposures (e.g. in a training phase) have on the response to a stimulus later on (Logan, 1990). Clearly, automated actions play a role in action control. Let us therefore take a look at one of the processes involved in the automatization of action patterns that is of great interest in the scope of this thesis. This process involves binding of features and responses, and has been investigated largely in research concerning the occurrence of coherent visual perception.

2.1.1. Integrating Object Features: Object Binding

Although we hardly ever realize it, while perceiving our environment in which we act, we constantly need to integrate parts of what we perceive. This becomes clear if we think of invariant object recognition.

Many objects we encounter move in our environment and we ourselves move around the objects as well. Therefore, the sensory pattern of a single object in vision (for the sake of simplicity, perceptions in other modalities are ignored for the moment) can differ infinitely, depending for example on its orientation or distance. Yet, we perceive the same car, whether it is approaching us from the left or moving away from us on the right side. To solve the problem of invariant object recognition many theories of vision assume that the sensory pattern of an object is decomposed into individual features, represented by individual neurons. Thus, an object can be represented by the activation of certain neurons each representing one of the object features; and this happens irrespective of the feature locations in relation to each other (i.e., irrespective of the object location and orientation). Since information about relative position, size, and orientation is lost due to the individual feature representations, binding is a necessary prerequisite to enable this mechanism of invariant object recognition. That is, the individual object feature representations have to be linked to one representation of the entire object. According to Treisman (1996), at least seven different types of binding have to exist. Most approaches aiming to explain binding have focused on two of the seven types: binding of parts and binding of properties. In property binding different properties or features such as color, shape, or location are bound to the

percept of one object. In part binding, object parts have to be segregated from the background and integrated to one object percept. Other forms of binding are range binding, hierarchical binding, conditional binding, temporal binding, and location binding. Given these various forms of binding, an obvious question is how binding takes place. The feature integration theory of attention (Treisman & Gelade, 1980; Treisman, 1993) offers a means to account for binding by assuming *object files*.

Features belonging to the same object usually share the same location. Thus, spatial attention might be one mechanism to enable binding. In fact, it has been shown that visuospatial attention leads to the integration of information belonging to one object (see Treisman & Gelade, 1980; Treisman, 1993). According to the feature integration theory of attention, separate features of objects are registered early, automatically, and in parallel across the visual field. In contrast, entire objects are perceived later on and only after attention has been focused on the objects' location. That is, object features and object locations are initially encoded in separate parallel maps – one feature map and one 'master' location map. Whatever features are attended, become integrated into one *object file* to form an *object token* and are possibly enriched by object related knowledge from long term memory. Stimuli present at different locations are excluded from the object file (Treisman, 1988, 1998). Object files are therefore one possibility that provides representations maintaining the identity and continuity of objects perceived in a particular episode. These temporary representations of objects and events created in perception can be seen as analogous to episodic memory traces.

The initial entry of an object file – and its identifying label – is the location and time. As more features of the object are perceived the object file is updated to include the new information about the object (Kahneman & Treisman, 1984; Treisman, 1992, 1996). That is, smaller changes in the object, such as a change in location, or a change of some feature while the location remains the same, does not require the formation of a new object file. As long as the spatio-temporal coordinates of the object file suggest a plausible continuity of the object, the object location remains the addressing label (e.g., if the location remains the same or if the object is perceived to move from the old to a new location). If such a continuity is not established a new object file is likely to be opened.

For our perception of the world the feature integration theory of attention assumes that we first form representations of the separate features that are present. These are stored separately from their perceived locations. In a second step features and their locations are integrated through focused attention to object

tokens and stored in object files, which can be updated if new information about the objects is perceived. Features and locations might leave temporary traces in the separate maps on which they are represented before binding occurs. Similarly, after binding has occurred object tokens can leave temporary traces which are at least initially accessed through the location in which binding was formed. Object files can also be transferred to visual working memory, thus providing for early explicit recall and recognition. However, this requires continued attention and only three or four bound tokens can be explicitly maintained in visual working memory. In contrast, many more object tokens can be stored as implicit traces of perceptual experiences that influence later re-perceptions (Treisman, 2006).

In a larger time frame, object files can also be stored in episodic long term memory as consciously retrievable traces of particular events. Finally, they can play a role in the formation of learned association in semantic memory between features which have been repeatedly bound in perception (Treisman, 2006). However, for the present purpose, short term bindings are of greater interest.

Treisman (2006) gives an overview of different roles object files can play in human perception. First, object files are the perceptual units into which a scene is parsed. Thus, they become the potential objects of attention. Second, object files represent novel objects for which we have no prior representations. Thus, they can represent unknown objects. Third, object files enable us to represent multiple identical objects (e.g., in a flock of sheep). Fourth, object files constitute a mechanism to bind features to represent objects. Fifth, object files bind successive states of an object over time. And sixth, object files might enable us to consciously see objects. They provide an interface between early vision, top-down knowledge, and conscious experience.

In sum, the notion of object files can explain why the different features we perceive can be identified as separate objects. Another way to approach the mechanisms of object perception, focuses on the level of neural information transmission.

Visual processing seems to be organized within two major cortico-cortical processing pathways both including processing within the primary visual cortex (V1). One of these pathways which has been termed the ventral stream, projects to the inferotemporal cortex. The other (dorsal) pathway projects to the posterior parietal lobule (Mishkin, Ungerleider, & Macko, 1983; Milner & Goodale, 1995). The ventral stream is important for object recognition. Features such as color or form of a stimulus will be processed via this pathway. In contrast, the dorsal

stream is important for spatial perception and visuomotor performance. Examples for features processed via this pathway are stimulus location or motion (e.g., Mishkin et al., 1983; DeYoe & Van Essen, 1988; Treisman, 1996). That is, if we see a red car moving towards us, its color and its form are processed in different neural areas than its location and movement. The question follows how the features that are represented in a distributed fashion become integrated to form the coherent impression of a red car approaching us. Moreover, as soon as more than one object is encountered at the same time, we need a mechanism to separate which of the perceived features belong to one object, and which to another. This question has been termed the *binding problem* (e.g., Colby, 1998; Jeannerod, 1983). The two mechanisms of binding that have been discussed most in recent literature, are integration by convergence and integration by correlation.

The principle of convergence suggests that lower level neurons code for simple features of objects. Projections from these neurons to higher level neurons lead to coding of feature conjunctions at that level. Eventually this may lead to even higher level representations of whole objects (e.g., Barlow, 1972, 2009). Thus, convergence relies on the assumption that at higher levels of stimulus processing, neurons are activated by more and more complex stimulus patterns. The complexity of the pattern to which a neuron responds, might even go as far as the concept of a certain person. In contrast, at the lowest level neurons are activated by single features, such as orientation. For example, a certain neuron may always respond if a stimulus contains a certain orientation, but the same neuron would never respond if the specific orientation is absent. (Barlow, 1972, 2009; Thorpe, 2009). According to Barlow (1972), single neurons in the neural network of the brain can perform the full range of information processing operations. For example they can detect pattern elements, distinguish the depth of objects, and ignore irrelevant causes of variation (Barlow, 1972, 2009).

However, several shortcomings of the notion of convergence have been discussed (see Thorpe, 1995). One example is the considerable variability of object instances and the large number of possible feature combinations, object perception has to account for. If solely convergence mechanisms would account for binding, this would lead to a combinatorial explosion (Hommel & Colzato, 2009). In that sense, we simply do not have enough cells in our brain to solely rely on convergence. An alternative account that solves this problem is the principle of temporal synchronization of neural discharges (e.g. Engel & Singer, 2001).

The term ‘synchronization’ refers to the firing patterns of feature-coding neurons. Here the idea is that rhythmic neuronal discharges in the frequency of the

gamma band (30-80 Hz; also termed 40 Hz-activity) are synchronized and thus provide the necessary spatial and temporal links, integrating the processing of object features in different brain areas (e.g., Engel & Singer, 2001; Eckhorn et al., 1988; Engel, König, Kreiter, Schillen, & Singer, 1992; Gray & Singer, 1989; Tallon-Baudry & Bertrand, 1999).

However, concerns have been raised that the hypothesis of synchronization is also incomplete. Assuming that features encoded in different neural areas are perceived as a unity due to synchronized oscillation of the encoding neurons, the question remains which mechanism decides whether the neurons are oscillating together or not (Barlow, 2009).

Regarding costs and benefits of both principles (convergence and synchronization), it is likely that they both play a role in dealing with binding problems. The advantage of synchronizing is the flexibility of this mechanism. Yet, it is relatively time consuming to bind cooccurring features anew every time they are encountered, especially if certain features are frequently encountered together. In contrast, convergence has the advantage of allowing fast registration of feature combinations which can be of almost unlimited complexity. The disadvantage of this binding principle is that it requires extensive learning and some degree of separability of the integrated feature conjunctions. Thus in terms of processing time, convergence-based integration would be economic and synchronization-based integration wasteful, whereas in terms of structure, convergence-based integration would be wasteful and synchronization-based integration economic (Hommel & Colzato, 2009).

2.1.2. Integration of Action and Relevant Stimuli: Stimulus-Response Binding

With the idea of *object* binding one important element influencing our everyday actions has been introduced. However, of even more interest for action control is the binding of objects or stimuli to *responses*.

Since the 1920s the study of perception and action has largely been conducted separately (Neumann & Prinz, 1990). On the one hand the investigation of perception has been concerned with the registration and identification of the input to the cognitive system. On the other hand and separate from the perception system, action has been viewed as being responsible for producing the appropriate output. Stage theories assume that perception and action are somewhat autonomous pro-

cesses that each have a unique starting time and a unique finishing time (Massaro, 1990). Thus, linear stage theories (e.g., Massaro, 1990; Sanders, 1980, 1998) view actions as responses triggered by stimuli.

Even most textbooks discuss perception and action as two different entities (Hommel, 2005b). However, if we view perception and action as two separate entities that are processed in separate representational systems, we find ourselves confronted with a translation problem: in order to explain how perception can influence behavior (as well as how action can modulate perception) a translation mechanism (first introduced by Welford, 1960) is required that maps the different classes of coding onto each other. Another solution to the translation problem has been proposed by the notion of common coding of perception and action (see Prinz, 1990). The assumption of common coding is that the perception of our environment and our actions are encoded in the same representational system. The difference between percept and act codes can then be interpreted as the distinction between event *representation* and event *effectuation*. Research concerning mirror neurons provides evidence that the representation and the effectuation of action in fact activate partly the same neural systems (for a review see Rizzolatti & Craighero, 2004). For example, the desynchronization of the same EEG rhythm was recorded during active movements and during an observation of others' movements (Cochin, Barthelemy, Roux, & Martineau, 1999). Further, in a study using functional magnetic resonance imaging (fMRI), the mental imagery of a planned finger movement was enhanced, if the same movement was observed (Iacoboni et al., 1999). Common coding can also be seen as the underlying mechanism in what has been termed the *ideomotor principle* (e.g., Greenwald, 1970). The ideomotor principle assumes that actions are represented and triggered through the individuals' goals (i.e., the anticipated action effects; Prinz, 1990; Hommel, 2005b). That is, we only need to think of an action effect and the response happens by itself (James, 1890; cited after Prinz, 1990). Such an experience of continuity between percepts and acts does not come as a surprise if both are encoded by the same representational system, as the principle of common coding proposes.

To enable complex behavior an integration of action features to separate events is crucial. Imagine for example a driver of a car who wants to accelerate and activate the right turn signal at the same time. In order to accelerate, he has to move down his right foot, and in order to set the turn signal, he has to move up his left hand. To allow for these actions, the feature code 'down' has to be integrated with that of the right foot and the code 'up' with that of the left hand. In addition,

to respond in our environment, for example to a changing traffic light, not only action features need to be bound, but features of both perception and action.

Different theories can account for an integration of perception and action features. Some examples are Gibson's theory of direct perception, first proposed for visual perception (Gibson, 1950, 1979), which proposes that the structured light (*optic array*) reaching the eye, already includes information about potential uses of the object responsible for the optic array. Thorndike's principle of temporal belongingness (Thorndike, 1932) assumes that two events (e.g., the perception of a stimulus and a given response) occurring in temporal contiguity are perceived as belonging together. And finally, I already described the instance theory of automatization (Logan, 1988, 1990).

Further to the idea of common coding, another framework has been proposed that can account for linkages between (late) perception and (early) action or action planning. The Theory of Event Coding (TEC) assumes that the underlying principles for the organization of perceptual and action-related information seem to be comparable: elements of action plans may be temporarily bound by similar mechanisms as elements of object representations in perception. Similar to the distributed coding of object perception, action and action planning are represented by patterns of distributed neural codes. Thus, in order to be able to plan and execute an action, the different perception- and action feature codes belonging to the intended action have to be integrated. Following the 'object files' proposed by Treisman and colleagues (Treisman & Gelade, 1980; Kahneman & Treisman, 1984), the result of such bindings have been called *event files* (Hommel, 1998, 2004). These temporarily integrate relevant or salient features of a situation (i.e., both stimuli and responses) and can be reactivated, if part of the situation is repeated. Such an integration of stimuli and responses seems to take place irrespective of the stimulus modality. Several studies have provided evidence for it in visual, auditory, tactile, and crossmodal settings (Hommel, 1998, 2004; Zmigrod & Hommel, 2009; Zmigrod, Spapé, & Hommel, 2009; Zmigrod & Hommel, 2010).

One basic assumption of the TEC is that perception, attention, intention, and action work on the same representational (i.e. common coding) system. Moreover, TEC assumes that perceiving and action planning are functionally equivalent: they both internally represent interactions between external events and the perceiver/actor. Similar to ideomotor theory, the assumption is that actions are cognitively represented by codes of their perceptual consequences, and further that representations of perceived events and of produced actions do not differ (Hommel,

2009). This notion makes sense if we consider that in everyday life, perception of a stimulus can not only trigger an action (stepping back onto the sidewalk when we see a car approaching) but that the perception is only possible due to an action (eye movements up and down the street).

Thus, cognitive codes of stimuli and actions are not codes of a completely different kind, they only represent different events in a particular task. Therefore, both stimulus codes and response codes can always be understood as feature codes of events which can include both perception and action or action planning. Importantly, event- or feature codes, represented in the common coding system, do not refer to proximal effects on the sensory surface or to muscular innervation patterns, but to distal attributes of the perceived event or planned action in the environmental layout. That is, the term ‘distal’ refers to representations of objectively defined people, objects, and events in our environment and not to physical information about them (Hommel, 2009). Due to the reference to distal coding, perception and action planning can be abstracted from domain- and modality-specific coding characteristics and refer to an event’s informational content. Stimulus-response binding has been found with visual, auditory, and tactile stimuli (Hommel, 1998, 2004; Zmigrod & Hommel, 2009; Zmigrod et al., 2009; Zmigrod & Hommel, 2010). However, these studies repeated or changed perceptual features of the stimuli. Therefore the effects can be explained by proximal coding as well as by distal coding. Response retrieval due to the repetition of a stimulus concept without repeating the perceptual features of the stimulus (e.g., by repeating the same stimulus identity in different modalities) would evidence the notion of distal coding.

An event file can be described as a network of bindings that temporarily (up to at least four seconds, see Hommel & Colzato, 2004) link codes of the perceptual event (i.e., stimulus codes), the accompanying action (i.e., response codes), and the task context. The bindings in such a network seem to be binary. That is, the stimulus feature ‘red’ might be integrated with the feature ‘shape’ (e.g., of a car) on the one hand, and with the response ‘stop walking’ on the other hand. However, the two latter features (the ‘shape of a car’ and the ‘stop walking’) might not be integrated with each other (Hommel, 2004).

Of all stimulus features present at a given moment, only some become integrated into the same event file and can trigger an event file retrieval later on. Since I am interested in the contribution such event file retrieval can make to the understanding of action control, it is important to understand which features become part of a given event file and which do not.

Evidence regarding attentional orienting might help to solve this question. Folk, Remington, and Johnston (1992) found exogenous orienting to be partially dependent on task demands. For example, sudden onset color-defined peripheral cues only led to an exogenous shift of attention if the target was defined by sudden onset color as well. That is, the *attentional set* influenced whether a given stimulus could trigger an orienting response. In fact, in line with these findings a given feature is likely to become part of the event file if it signals any response in the entire task context, or if it varies on a dimension that is relevant to the task (Hommel, 2004).

According to their task relevance in perception and action planning, features of event files are weighted. Concerning perception, this weighting selectively prepares the attentional system for the differential processing of relevant and irrelevant stimuli. Thus, in perception a weighting of features can be called an *attentional* process. In action planning on the other hand, feature weighting reflects the actors's intention to initiate a response, and thus can be called an *intentional* process. It is presumed that task relevant features are weighted more strongly than irrelevant features (Hommel, Müsseler, Aschersleben, & Prinz, 2001). As a consequence more strongly weighted ingredients of an event file are more likely to be (re-)activated. Hence, the retrieval of an event file due to a re-encountered feature is influenced by the current task relevance of, and attentional biases for the features included in the event file (Hommel, 2009). Especially relevant for the purpose of this thesis, a stimulus does not have to be necessary or useful for the task at hand, or trigger the reaction in order to have its features bound to a response. If an irrelevant stimulus is perceptually salient it might become part of the event file as well (Hommel, 2004).

The temporal sequence of underlying distal events does not matter; the only prerequisite for the to be integrated stimulus seems to be that it has to appear close in time to the eventual execution of the response (Hommel, 2009). Yet, merely close temporal proximity between a stimulus and the process of action planning does not guarantee an integration. The model suggests that response decisions which lead to success become integrated with the stimulus features which are sufficiently activated around the time of this success, and therefore later in time than action planning (Hommel, 2005a). What exactly counts as a 'success' has not been defined. However, it does not seem to take much: planning an action seems to be sufficient for binding of action features and features of accompanying stimuli (Hommel, 2005a Exp. 4; see also Frings, Bermeitinger, & Gibbons, 2011). In contrast, Mayr, Buchner, and Dentale (2009) found an execution of the prime

response to be a precondition for retrieval due to a repeated prime stimulus. In any case, actually carrying out a planned action largely strengthens an integration of response- and stimulus features.

Obviously one feature code can be part of several events (e.g., the representation of 'left' in setting a turn signal with the left hand and pressing the clutch with the left foot). As a result, the integration of features belonging to one event becomes necessary (see discussion above). This in turn influences perception and action planning at the re-encounter of an integrated feature code. Despite the fact that more than one event file can exist at the same time, a feature that is integrated in one event file is not available to become part of another event file. Thus, for the time the event file exists, if one or more of the feature codes are encountered, the entire event file will be retrieved, including actions or action plans. If all feature codes of the current event match those of the retrieved event file, performance is as good as in cases in which none of the feature codes of the current event match those of an existing event file. However, if only some feature codes overlap (i.e., partial match of current and retrieved event file) performance is hampered (e.g. Hommel, 1998; Hommel et al., 2001; Hommel, 2004). That is, a full match of current and retrieved event file does not facilitate performance; partial match impairs it (Hommel, 2005a). The theory not only suggests that event files (with their responses) are retrieved by a re-encounter of an integrated stimulus. Moreover, actions seem to retrieve event files as well. That is, action effects can influence the perception of stimuli (Wühr & Müsseler, 2001).

Finally, event files are created under the most unlikely circumstances. In fact, the amount of attention directed to the to-be-integrated features does not seem to modulate feature integration effects (Hommel, 2005a). One might therefore speculate that mechanisms assumed by the TEC for relevant stimuli, do also apply to irrelevant or distractor stimuli. However, TEC does not make any assumptions as to whether a task irrelevant or distractor stimulus, integrated merely because of its salience, can retrieve an event file.

A new approach, in particular dealing with distractors in action control, has been introduced with the notion of distractor-response binding. Two theories that lead up to this approach are the Stimulus-Response Retrieval theory, introduced by Rothermund and colleagues (Rothermund, Wentura, & Houwer, 2005), and the Prime-Response Retrieval theory proposed by Mayr and colleagues (Mayr & Buchner, 2006; Mayr et al., 2009).

2.1.3. Integration of Action and Ignored Stimuli: Distractor-Response Binding

The Stimulus-Response Retrieval (SRR) theory generalizes the idea of event files to ignored stimuli and assumes that any stimulus present at the time of the response (i.e., also the distractor) becomes associated with the executed response and can subsequently retrieve this response if encountered again. Importantly, no relevant relation between distractor stimulus and executed response is necessary for a distractor-response integration to occur. The only prerequisite for such binding is that the distractor constitutes a discriminable part of the stimulus situation in close temporal proximity to the response (Rothermund et al., 2005).

A variation of the negative priming paradigm (for reviews see, e.g., Fox, 1995; Neill & Valdes, 1996; Tipper, 2001) has been used to investigate binding of the response to irrelevant features of a stimulus (Rothermund et al., 2005). In the negative priming paradigm the effect of a prime distractor that is repeated as the probe target is analyzed. Typically, such a prime distractor repetition as the probe target leads to longer response times on the probe (i.e., the negative priming effect). Of the mechanisms that have been discussed to account for negative priming, only the distractor inhibition (e.g., Houghton & Tipper, 1994) and the episodic retrieval (Neill, 1997; Neill & Valdes, 1992; Neill, Valdes, & Terry, 1995) account seem to have outlasted theoretical debates (Mayr & Buchner, 2010).

Rothermund et al. (2005) found the negative priming effect to be dependent on a change of the response between prime and probe. The authors used word stimuli and changed the response rules from prime to probe. In their Experiment 1 for example, participants responded to the color of the word on the prime and to the grammatical category of the word on the probe. To both, the prime and the probe displays, participants responded by pressing one of two response keys. Repeating the word from prime to probe only had a facilitative effect, resulting in faster responses if the response had to be repeated from prime to probe. If the response had to be changed, a repetition of the word resulted in slower responses compared with different words presented on prime and probe. That is, negative priming was only found in response change trials, but positive priming (i.e., probe response facilitation due to the repeated presentation of the word) was found if the response had to be repeated.

The SRR theory can also be seen as a variant of episodic retrieval which suggests that a prime distractor that is again presented (as the target) on the probe, serves as a retrieval cue to the prime episode. The retrieved prime episode was originally

suggested to include some sort of ‘do-not-respond’ information, explaining longer response times in ignored repetition trials; i.e., trials in which the prime distractor reappears as the target on the probe (Neill & Valdes, 1992; Neill, 1997).

If no response is required to the prime stimulus, SRR theory becomes indistinguishable from the episodic retrieval account (Neill, 1997; Neill & Valdes, 1992). The episodic retrieval explanation assumes an integration of the distractor with a ‘do not respond’ tag. SRR theory suggests that the ‘response’ to refrain from responding to the prime is integrated with the prime distractor. Thus, both accounts predict the retrieval of ‘do not respond’ on ignored repetition trials (Rothermund et al., 2005).

According to SRR theory, even an internal or hidden response can be associated with a distractor (Rothermund et al., 2005). For example, Frings et al. (2011) measured retrieval of compatible and incompatible motor activations from the prime using the lateralized readiness potential (LRP). Even though participants withheld their response to the prime until after execution of the probe response, the authors found evidence for retrieval of motor activation on the probe. If participants had to respond with the same hand to the prime and the probe, LRP onset occurred significantly earlier if the prime distractor was repeated as the probe target (i.e., in ignored repetition trials) as compared to control trials in which no stimulus was repeated from prime to probe display. In contrast, if participants had to respond with different hands to the prime and the probe, LRP onset tended to occur later in ignored repetition trials as compared to control trials.

With their prime response retrieval account Mayr and Buchner (2006) proposed a model that is very similar to the SRR theory. That is, the authors also provide evidence for integration of the distractor stimulus with the prime response in a negative priming paradigm (see also Mayr et al., 2009; Mayr & Buchner, 2010).

In a typical trial the authors presented their participants with two sounds simultaneously – one to each ear. Participants’ task was to categorize the target sound (i.e., the sound that occurred at the side indicated by a clicking sound before stimulus onset) and ignore the distractor sound. In addition to a typical negative priming effect, the authors found evidence for retrieval of the prime response in the error distribution of the probe responses. The proportion of errors consisting of a prime response repetition was significantly larger if the prime distractor was repeated as the probe target than in control trials, in which no stimulus was repeated from prime to probe (Mayr & Buchner, 2006). That is, the authors present evidence for a binding of the prime distractor with the prime response in the error rates.

In the negative priming paradigm a repetition of the prime distractor on the probe always means a change of the stimulus' role: the stimulus triggering retrieval on the probe is always the *target*. Therefore the evidence mentioned above suggests that a stimulus that is attended can retrieve an event file, even if its role was that of a distractor at the time of the event file creation. Importantly, with the effect of distractor-response binding it has been shown that the probe *distractor* can trigger retrieval as well (e.g., Frings, Rothermund, & Wentura, 2007; Frings, 2011; Frings & Rothermund, 2011; Frings & Moeller, 2010; Giesen & Rothermund, 2011). In other words, even an ignored stimulus is able to retrieve an event file. In order to find evidence supporting this proposition, a new paradigm including distractor-to-distractor repetitions is necessary. Frings et al. (2007) introduced such a paradigm that also includes a selection situation in which a distractor (sharing the S-R mapping with the target) competes with the target for response generation. They argued that the distractor object in such settings becomes part of the whole stimulus-response episode and further that repeating the prime distractor as the distractor on the probe will result in retrieving the whole episode including the response. Hence, this effect of distractor-response binding can be analyzed in prime-probe tasks with targets and distractors presented on every display while also orthogonally varying response repetitions and distractor repetitions. For such tasks, distractor-response binding effects emerge as an interaction of response and distractor relations: repeating a distractor retrieves the last episode containing that stimulus (i.e., the prime episode) which also includes the response to the target that was encountered together with this distractor. Such distractor-to-distractor repetitions should lead to the retrieval of an incompatible response in the case of a response change but to a compatible response in the case of a response repetition. Accordingly, in displays using a flanker configuration of target and distractors (i.e., a central target flanked by two identical distractors, e.g. DFD with F being the target) Frings et al. (2007) observed that distractor repetition effects were modulated by response repetition such that distractor repetitions in the case of response repetition facilitated responses while distractor repetitions in the case of response changes impaired performance. Importantly, this interaction of response relation and distractor relation can only be accounted for by the notion of distractor-response bindings. An account of distractor inhibition would predict the same extent of facilitation due to a repeated distractor both for response repetition and response change trials.

Thus, the typical design to investigate distractor-response binding includes the two factors response relation (repetition vs. change) and distractor relation

(repetition vs. change) resulting in four conditions. In response repetition / distractor repetition (RRDR) trials, the same stimuli are presented as target and distractor on the prime and the probe. In response repetition / distractor change (RRDC) trials the prime target stimulus is repeated as the probe target while the distractor stimulus changes from prime to probe. In response change / distractor repetition (RCDR) trials the probe target stimulus differs from the prime target while the prime distractor is repeated as the probe distractor. Finally, in response change / distractor change (RCDC) trials, no stimulus is repeatedly presented on the prime and the probe.

Resulting from the stimulus-response mapping many studies present the same stimulus configuration on prime and probe in RRDR trials. Yet, the effect does not depend on a complete repetition of the percept. For example Frings et al. (2007, Exp. 2) used a categorization task. Participants pressed the right key, if the target letter was H, J, K, or L and they pressed the left key, if the target letter was S, D, F, or G. Even if the target stimulus identity changed from prime to probe the interaction of response relation and distractor relation was significant. That is, responses were facilitated due to distractor repetition if a response repetition was required, and responses were slightly hampered due to distractor repetition if the response had to be changed from prime to probe.

Recent studies, implementing the paradigm described above, provided evidence for distractor-response binding and identified factors that influence the effect. The time course of distractor-response binding seems to differ from that of bindings between target stimulus features and responses. While Hommel (2004) reports stimulus-response bindings lasting four seconds or longer, distractor-response bindings have been shown to be distinctly more transient. Most studies that found distractor-response binding effects used an interval of 1000 ms or less between the prime response and the probe stimulus onset (e.g., Frings et al., 2007; Frings & Rothermund, 2011; Giesen & Rothermund, 2011; Rothermund et al., 2005). Frings (2011) investigated the time course of distractor-response binding and varied the response-stimulus interval between prime and probe. Distractor-response binding effects revealed with short response-stimulus intervals of 500 ms but not with longer intervals of 2000 ms. This indicates that the binding of responses and distractor stimuli decays relatively quickly: it seems to survive for a period of just over one second.

Early studies investigating distractor-response bindings typically used the same

stimulus set both for targets and distractors. Thus, the same stimulus could be ignored in one trial, and trigger the response in another. It can be argued that with such a design all stimuli that were presented to the participant were response-relevant throughout the experiment. However, it has been shown that even distractors that are response-irrelevant in all trials can become part of an event file and retrieve the response later on. For example Giesen, Frings, and Rothermund (in press) used four different letters as targets. Distractors were either letters from this set (i.e., response-relevant distractors), or different letters (i.e., response-irrelevant distractors of the same class) or digits (i.e., response-irrelevant distractors of a different class). Interestingly, the effect of distractor-response binding revealed both for response-relevant and for response-irrelevant distractors. No difference was found between same class and different class irrelevant distractors. Moreover, distractor-response binding effects in conditions with response-relevant and response-irrelevant distractors were of similar magnitude, indicating that response relevance of the distractor did not modulate distractor-response binding effects.

The cited results give a first impression that the mechanism of distractor-response binding seems to be relatively general. More evidence along these lines was provided by Frings and Moeller (2010). They found that even ignored locations can be integrated with, and subsequently retrieve the response to a different location. Four locations were used as targets and distractors. Participants always responded to one location while ignoring another. Repeating the location of a distractor from the prime to the probe retrieved the response given to the prime target location. That is, just like any other stimulus feature (e.g., color), even spatial distractor information can be bound into an event file and subsequently retrieve the response. In addition, such retrieval due to location repetition does not seem to hinge on stimulus repetition. Frings and Moeller (2010) used the colors red and green to mark target and distractor location. Only directly before prime or probe stimuli onset, participants saw a red or green square indicating the color that would mark the target location on the following display. Thus, target and distractor identity (i.e., color) could change from prime to probe. However, repeating the distractor location on the probe led to retrieval of the prime response, even if the distractor location was marked by different colors on the prime and the probe. This also adds to the evidence indicating that the distractor-response binding effect does not hinge on a complete repetition of the prime display in trials in which both response and distractor are repeated.

It has been shown that even a stimulus which is ignored in order to complete

a task can be bound to and later on retrieve a response to a different (target) stimulus. However, it seems to be highly maladaptive if just any stimulus we perceive was bound to our actions. Instead, the inclusion of distractor information into event files has been shown to be modulated by whether the distractor and target stimuli are perceived as belonging to the same object or as belonging to different objects. Frings and Rothermund (2011) consistently found more evidence for distractor-response binding if target and distractor were perceptually grouped than if the stimuli were not grouped. For example, distractor-response binding effects were significantly larger, if target and distractor letters were presented in a row, resembling a word (e.g., DFD) than if the same stimuli were presented in a vertical column not resembling a word. The authors suggest that for distractor-response binding to occur, distractor processing has to be linked to the same perceptual object that elicits the response.

Such a linkage seems to be possible by at least one other form of grouping as well. Giesen and Rothermund (2011) found the degree of affective match between perceived stimuli to modulate distractor-response bindings. The authors varied the valences of the target (nouns) and distractor (adjectives) stimuli. Participants always decided whether the target referred to a person or to an object. Notably, stimulus valence was not relevant for the task. Distractor-response binding was observed only if target and distractor had the same valence but not if their valences differed. They concluded that detecting an affective mismatch between two stimuli counteracts binding processes and leads to the creation of separate episodes for distractor and target stimuli. In other words, target and distractor seem to be perceived as one group if they have the same valence, whereas stimuli of different valences tend to be perceived separately. Thus, a distractor of the same valence as the target is more likely to get integrated into the same event file as the target response and can subsequently retrieve it (Giesen & Rothermund, 2011).

Distractor-response binding as described above, takes place in relatively short periods of time. A retrieval of a response due to the repeated presentation of a distractor seems to be possible for just over one second after event file creation (Frings, 2011). The role distractor-response binding might play in a longer time frame as we interact with our environment has not yet been thoroughly investigated. However, Frings and Rothermund (2011) point out that the grouping model they propose might be seen as an extension of the temporal principle of belongingness (Thorndike, 1932) on a spatial dimension. The principle of belongingness assumes that associations between stimuli and responses are only formed if the second element of the sequence is perceived to belong with the first. For

such belongingness of entities (e.g., of stimulus and response) the basic condition is temporal contiguity (Postman, 1962). If this principle (restricted to *temporal* belongingness) would apply to temporary associations between distractor stimuli and responses (i.e., distractor-response bindings), a modulation by grouping of target and distractor stimuli would not be expected. Instead, distractors should have been integrated with responses in the experiments cited above, regardless whether they were perceived as belonging to the same or to different objects, as long as they appeared in close temporal proximity to the response – which they always did. In fact, in most experiments the temporal proximity between *distractor and response* was exactly the same as that between *target and response*. Yet, distractor-response binding effects revealed differently depending on the grouping of *distractor and target*. Thus, grouping might be seen as a more general form of belongingness. Apparently distractor-response binding is not only influenced by the *temporal* belongingness of distractor and response, but more generally by a perception of target and distractor stimuli as a unit. Regarding the influence on learning, Frings and Rothermund (2011) suggest that grouping might modulate the acquisition of contingencies between irrelevant stimuli and responses. Then again, if we learned by experience that a given irrelevant stimulus and the target stimulus often cooccur, the two stimuli might be more readily perceived as belonging together and therefore distractor-response binding might be more likely to occur.

In fact, for object tokens similar long-term effects have been found. For example, targets consisting of conjunctions are detected faster if they frequently occur in a particular location than if their location changes randomly. Similarly, detection of a solid blue bar target was faster if the target was also usually vertical (Treisman, 2006). Moreover, object representations have been shown to last over 200 intervening trials and over temporal delays of up to a month (DeSchepper & Treisman, 1996). It can be speculated, that similar effects might hold for traces including action representation (i.e., event files).

2.1.4. Selective Attention

It should be pointed out that of course, other mechanisms play a role in distractor processing besides distractor-response binding. It is widely accepted that one important function of attention is the selection of relevant stimuli. Of the input that can be perceived by the different senses, the attended stimuli are amplified and selectively processed.

Kahneman and Treisman (1984) describe two main interpretations of selective

attention. First, regarding the complexity of the available information, selective attention can be seen to prevent the organism from confusion and overload. Second, regarding the numerous and incompatible response tendencies available in our complex environment, selective attention can be seen to prevent the organism from paralysis and incoherence. In other words, on the one hand attention can be interpreted to ensure the perceptual processing of the currently important sensory messages, on the other hand it can be interpreted to ensure the execution of the currently adequate action (see also Tipper, 1992).

Regardless whether attention is understood to be selective in order to handle the input of, our complex environment or to be able to carry out appropriate actions, the role of distractor stimuli is the same in both cases: irrelevant information has to be controlled in order to prevent an interference with perception of or action toward the currently relevant stimuli.

The term interference control has been used in the same sense as the term inhibition and both have been used in various contexts (Nigg, 2000). On a behavioral level, inhibition can mean an automatic or an intentional suppression of responses which can lead to slowing in a primary response. This is the function most directly associated with active behavioral suppression and executive functioning. In contrast, on a cognitive level inhibition can refer to the suppression of internally represented stimuli that might interfere with operations of the working memory. This kind of inhibition has also been described as the resistance to memory intrusions, which occur due to currently irrelevant information that was previously task relevant. Finally, inhibition can also refer to the suppression of a stimulus that competes with a different stimulus for a response. That is, this kind of inhibition can resolve the interference caused by external, task irrelevant information such as an influence of distractors that are present simultaneously with a target (Friedman & Miyake, 2004; Nigg, 2000). Hence, inhibition in the processing of distractor stimuli, which is of interest here, refers to inhibition of that kind. Such inhibition has also been associated with selective attention and the enhancement of target information processing.

One theory, going a step further and proposing not only enhanced processing of target information but also active suppression of distractor information, is the selective attention model by Houghton and Tipper (1994). This account proposes that not only the encoding of relevant stimuli is amplified, but also that stimuli containing irrelevant information (i.e., distractor stimuli) are only initially activated, and then actively inhibited as to facilitate the processing of other – relevant – information (e.g., Houghton & Tipper, 1994). In particular the theory assumes

that targets and distractors of a stimulus display are encoded and cognitively represented. This representation can then be modulated by both bottom-up, or external and by top-down, or internal sources. The external source of the physically present stimuli has an activating influence on the representation of both target and distractor stimuli. However, internal sources affect the representation codes of distractor and target differently. An attentional system increases activation of target codes on the one hand, and decreases distractor codes on the other hand. If the activating external source (i.e., the distractor stimulus) disappears, the top-down deactivation of the distractor stimulus persists for some time leading to an *inhibitory rebound*. That is, the inhibited stimulus is less accessible for a brief amount of time (see Frings & Wühr, 2007b; Houghton & Tipper, 1994). One construct that has been closely associated with inhibition is negative priming (e.g., Earles et al., 1997; Kane, Hasher, Stoltzfus, Zacks, & Connelly, 1994; but see Friedman & Miyake, 2004). The negative priming effect is investigated with a sequential priming paradigm. It describes a slowing of the reaction time to an object that was ignored on a previous display (for a review see Fox, 1995). Specifically, participants are slower to respond to a target in display n , if the same stimulus was presented as a distractor in display $n-1$ as compared to the case in which the stimulus had not appeared in display $n-1$. One way to explain this effect is the assumption of persisting distractor inhibition. The internal representation of the distractor of display $n-1$ still suffers from inhibition when display n appears, leading to impeded responding to this stimulus.

Generally the inhibition of distractor stimuli is an important account for the influence distractors have on our actions. However for the current thesis this account is of less relevance. As mentioned earlier, a modulation of a distractor repetition effect due to response relation (i.e., the pattern indicating distractor-response bindings) cannot be explained by the inhibition account. Distractor inhibition would instead be expected to have the same effect on performance if the response is repeated from prime to probe as in cases in which the response is changed. In fact, Giesen et al. (in press) present evidence that distractor inhibition and distractor-response binding are two separate processes. In particular, the authors found a smaller effect of distractor inhibition for response irrelevant distractors than for distractors that competed with the target for the response. In contrast, the effect of distractor-response bindings did not differ for response incompatible and response neutral distractors. Hence, distractor inhibition and distractor-response binding can function in parallel and independently of each other.

2.2. Action Control in Human-Machine Interaction

The unity of action and perception is also of central importance in the field of ergonomics. Especially, for the studies of human-machine interaction it is of crucial interest to understand the way our actions are controlled. If factors influencing human responses are taken into account in the design of a user interface, a person working with this machine will have an easier task, which will in turn result in less errors. In contrast, if such factors are ignored in the design of interfaces, slower responses and more frequent errors will be the consequence. With distractor-response binding distractors obviously play a role in action control, facilitating certain responses and hampering others. Therefore, it can be assumed that even typically ignored aspects of user interfaces can influence the users' responses. In turn, various kinds of problems in human-machine interaction might occur due to distractor-response binding. In the scope of this thesis I will only consider some of these. In particular, I will focus on the interaction between drivers and their cars as one sort of human-machine interaction.

One reason why the design of user interfaces is not a trivial matter becomes obvious if we consider human evolution. Mechanisms of perception and action have evolved over a long time. During most of this time humans mainly interacted with natural stimuli, such as a rock in the path that has to be avoided or apples in a tree that can be picked. Consequently, our system for perception and action is well adapted for interactions with *natural* objects. Nowadays, when we interact with *artificial* objects, such as a car, the stimuli (e.g., a display) are not necessarily designed in a way that best conveys relevant information or that easily triggers an appropriate response. Cognitive ergonomics aim to improve the interface of artificial objects in order to facilitate interactions with these objects and to minimize errors in the human-machine interaction.

One factor in human-machine interaction that can be influenced by machine design is the situation awareness of the user (Endsley, 1995). Regarding action control, situation awareness is important because users have to correctly perceive the important aspects of a situation, and to interpret their perception correctly to be able to respond in an adequate way. That is, a driver has to be aware of the traffic situation in general at an intersection in order to adequately respond to a light turning yellow. For example, accelerating is only an option if the road behind the traffic light is free. It has been suggested that automaticity as proposed by Logan (1988) plays a role in situation awareness. That is, direct-access, single-step

retrieval of actions is proposed to benefit situation awareness. Hence, response-retrieval due to a repeated distractor stimulus might modulate situation awareness. On the other hand, situation awareness is suggested to be able to trigger automatic actions (Endsley, 1995).

Yet, the account of situation awareness mainly focuses on conscious decisions and not so much on the control of automatic actions. If the driver has to give a fast response during his approach of the intersection, possibly because the leading car suddenly brakes, processes not accounted for in the theory of situation awareness are likely to influence his reaction.

2.2.1. Direct Perception

The theory of direct perception (Gibson, 1950, 1979) focuses on the relationship of perception and action and is therefore of more relevance for the driving situation described above. This account assumes that action can be influenced by perception in a direct way and with the need of hardly any conscious awareness. That is, Gibson argued that influences of perception on action are possible without complex cognitive processing. Especially if a driver has to respond to a sudden change in the situation such a direct link might largely influence the drivers' reaction.

Gibson regarded his approach as 'ecological' and meant to emphasize that the main function of perception is to allow an interaction of individuals with their environment. One central aspect of the theory therefore is that perception itself requires very little processing capacity. The structured light that reaches the eye (the *optic array*) is proposed to contain all visual information from the environment. For perception, the information provided by the optic array is merely picked up, and this picking up is assumed to be possible with little or no information processing. Thus, it is not necessary to assume retinal, neural, or mental representations or pictures in order for perception to be efficient (Eysenck & Keane, 2010). In fact, Gibson argued that an analysis of the retinal picture would give no insight into perception. Instead, he pointed out the importance of changes in the optic array, which provides feedback to a person moving in their environment. In motion perception, the changes in the pattern of light reaching the observer are called *optic flow*. As we move in our environment, we typically experience everything in the visual field moving away from one point (the *focus of expansion*). This is the point towards which one is heading. If the movement direction is changed, the focus of expansion moves to a different point. Clearly, optic flow becomes especially relevant in traveling situations.

Another range of information that is directly provided by the optic array has been called *affordances*. This concept is of particular interest in the design of ergonomic appliances. Affordances are the potential uses of a given object. For example, a pedal ‘affords’ pressing or releasing and a seat ‘affords’ sitting. In fact, several studies report behavioral (Symes, Ellis, & Tucker, 2005; Tucker & Ellis, 1998; Pappas & Mack, 2008) and neuropsychological (Grèzes & Decety, 2002) evidence for automatic affordances of certain actions due to the perception of an object.

It has been shown that graspable objects, such as a colander, a frying pan, or a hammer can facilitate (i.e., afford) a right or left hand response, depending on the orientation of the object’s handle (e.g., Symes et al., 2005; Grèzes & Decety, 2002; Pappas & Mack, 2008). For example Symes et al. (2005) used photographs of cooking implements and tools. Participants’ task was to decide whether the object could be found in a kitchen or a garage. Each object was either oriented to the left or right. That is, an object oriented to the left was depicted with its handle pointing to the left, and an object oriented to the right was depicted with its handle pointing to the right. The location of each object (on the left or on the right side of the photograph) was varied orthogonally. Besides the typical simon effect, the authors found *orientation* compatible responses (e.g., a keypress with the left hand in response to an object oriented leftwards) to be significantly faster than orientation incompatible responses (e.g., a keypress with the right hand in response to an object oriented leftwards). This can be interpreted as evidence for the existence of affordances. Moreover, the same pattern was found for left and right foot responses, although the stimulus objects presented would typically not be manipulated with the feet. Therefore, affordances seem to be represented in a somewhat abstract manner rather than as a specific motor response (see also Phillips & Ward, 2002). The authors point out that this property of affordances fits well with the Theory of Event Coding (see above). In fact, the idea of affordances is not far from a single step direct retrieval of a response due to the current perception. In contrast to retrieval models however, direct perception does not necessarily require any sort of memory trace for this automatic action control. Instead, the theory does not make any assumptions as to how an optic array comes to contain certain affordances.

However, Gibson (1979) points out that affordances of the same object differ for different animals. For example a water surface affords support for a water bug but not for a person. Similarly, a surface of a certain height might afford sitting to one person but not to another. A surface affording sitting is typically knee high, which

is different for persons of different height. The height of a surface that affords sitting for a small child is considerably lower than that of a surface that affords sitting to an adult. Considering that the child might grow up to a considerable height, it is obvious that the affordances a person perceives of the same object can change over time. Hence, affordances are not invariable to a given person. In fact, affordances of the same object can also change with the current condition of the same person. It has been pointed out that the same orange might afford throwing to a person who is angry, but eating to the same person, if he is hungry (Eysenck & Keane, 2010). Processes like distractor-response bindings might be involved in determining affordances of a percept. The facilitation of an action due to the retrieval of a past response might contribute to the afforded actions in a certain situation. Further, it might even be the first step in ‘learning’ affordances of a certain situation.

It is easily conceivable that accounting for affordances in the design of household appliances will make the interaction with those easier. Likewise, an interaction with a machine (such as a car) will be easier, if the displays provide adequate affordances. In fact, the theory of direct perception has influenced research concerning display design. For example Eriksson et al. (2008) proposed to use ‘virtual’ optic flow in head-up displays in order to prevent spatial disorientation in pilots. If a display is used as a warning and thus directly prompts a response, affordances of the presented images become important for display design as well. For example a warning display prompting a braking response should rather afford stepping on the center pedal than turning the steering wheel. Suppose for example that the driver, arriving at an intersection and seeing the traffic light change to yellow, intends to accelerate in order to pass the light before it turns red. However, the car in front might suddenly stop. If his driver assistance system presents a warning display that affords braking, his braking response might still be fast enough to prevent a rear end collision with the suddenly stopping car.

2.2.2. Visual Warnings in Human-Machine Interaction

Regarding drivers’ response times to warning signals in general, it has been shown that early collision warnings can significantly reduce the number of collisions as well as collision severity, both for distracted and undistracted drivers (e.g., Lee, McGehee, Brown, & Reyes, 2002). It obviously enhances drivers’ performance to present warnings in critical situations. In fact, advanced driver assistance systems that include warning functions, have become increasingly popular in recent years.

Yet, a driver does not attend all aspects of a warning display. Thus, response retrieval due to attended and ignored stimuli can influence the swiftness and accuracy of responses. In other words, both stimulus-response and distractor-response bindings are likely to influence drivers' reactions to warning displays.

Mainly two different classes of visually presented warning displays have been discussed for driver assistance systems. *Head-up displays* are images projected onto a transparent screen (i.e., onto the windshield). This leads to superimposed displayed images on the visual information of the environment outside the vehicle, which is assumed to reduce scanning of the environment during driving. Head-up displays are collimated to appear at optical infinity in order to be perceived at the same distance as the world outside the vehicle. Typically, driving performance in a system using head-up displays is compared to performance with displays being presented in the console of the car (*head-down displays*). In fact, compared to head-down displays, head-up displays seem to have a positive effect on driving performance. For example, Sojourner and Antin (1990) compared head-up display and dashboard-mounted digital speedometers in a simulated environment and found that participants being presented with information via head-up displays responded significantly faster to salient cues than participants presented with information via head-down displays.

Although head-up displays have in general been received rather favorably (e.g., Goesch, 1990; Liu & Wen, 2004; Liu, 2003), some aspects are still problematic. For example, it has been pointed out that optic clutter can result from head-up displays being overimposed on the relevant scenery, leading to perceptual problems. In turn, such optic clutter can impair performance (e.g. Fischer, Haines, & Price, 1980; Foyle, McCann, Sanford, & Schwirzke, 1993; Oppitek, 1973). In addition, visual accommodation might still be more problematic with head-up displays than with head-down displays. Edgar (2007) discusses potential accommodation problems with 'virtual image displays' (i.e., head-up displays and helmet-mounted displays). For example, it has been suggested that a virtual collimated display leads to poorer accommodation than a real display (e.g., a head-down displays; Iavecchia, Iavecchia, & Roscoe, 1978; Randle, Roscoe, & Petitt, 1980). In turn, Roscoe (1987) expressed concern about the use of head-up displays. In sum, evidence regarding performance with head-up displays has been mixed. Therefore, in the design of driver assistance systems it should be carefully considered whether a given information is better presented via head-up display or via head-down display, to ensure that the manner of warning presentation does not impede fast and accurate responding. This consideration is even more important,

since we have to assume that responding to warning displays is not the only task a driver completes. For example, while approaching an intersection a driver will steer the car, scan the street and sidewalks, and possibly change the radio station at the same time.

2.2.3. Dual Task Performance

People interacting with machines typically complete more than one task simultaneously. For example the driver of a car always has to steer the car while he reacts to traffic lights or warning displays presented by the driver assistance system. Obviously, dual task performance is an important factor that has to be considered in human-machine interaction. Even more so because performance of two tasks completed at the same time is typically degraded, compared to performance in the same tasks completed separately. Three influential explanations of this effect are capacity sharing, bottlenecks, and cross talk.

Capacity sharing assumes that people have a given amount of processing capacity which they share among tasks. That is, the more tasks are processed at the same time the less capacity is available for each task. And also, the more capacity is needed for one task, the less capacity can be distributed to the processing of other tasks. Different varieties of capacity sharing assume either a single mental resource of processing capacity (e.g., Kahneman, 1973), or multiple resources (e.g., Wickens, 1980). Yet, independently of the number of resources, a limited processing capacity is assumed to be the cause of degraded performance in dual task situations (Pashler, 1994).

With the account of bottlenecks it has been assumed that parallel processing is impossible for certain processes. If a mental operation requires such a processing mechanism this mechanism has to be entirely dedicated to that operation. While the operation is going on, the same mechanism cannot be used in a different mental operation, creating a bottleneck. As with capacity sharing, bottlenecks can be an explanation for dual task interference both if one single mental resource is assumed (i.e., one bottleneck is in effect) and also if multiple resources exist (i.e., multiple bottlenecks restrict processing).

Cross talk models suggest that dual task interference is dependent on the content of the processed information, rather than on the operations that have to be carried out. Typically, processing of two tasks in parallel is assumed to be more difficult if they involve similar information (e.g., similar perceptual input or similar required responses; Pashler, 1994).

Dual task performance has been studied in a variety of different paradigms. For example, in probe reaction time tasks, participants decide whether two successively presented letters were identical or not, while an additional (auditory) stimulus is presented on half of the trials and at different points in the decision process. Depending on the response time to the additional stimulus, it can be inferred how much processing capacity is left unoccupied by the primary task. Concurrent memory load effects demonstrate that performance in a task can be hampered if we are holding on to a moderate amount of memory. In contrast, producing a motor response without uncertainty, for example finger tapping, does not interfere with speeded tasks that require different response modalities (Pashler, 1994). Only other motor responses or rhythmic requirements might be hampered (Klapp, 1979; Klapp et al., 1985). Further, between unspeeded perceptual judgment tasks (e.g., letter identification) and speeded tasks (e.g., detection response to a tone) interference seems to be rather small (e.g., Blake & Fox, 1969).

Finally, one widely known procedure is the Psychology Refractory Period (PRP) procedure. This procedure has effectively been used to investigate the time course of mental operations as they unfold over short periods of time (Pashler, 1994). Typically two stimuli (S1 and S2) are presented with a stimulus onset asynchrony (SOA) between 0 and 1000 ms. Participants complete two discrete tasks: task 1 in response to S1 resulting in response time 1, and task 2 in response to S2 resulting in response time 2. Typically, response times in task 2 are strongly affected by SOA, with longer response times as the SOA decreases. In contrast, response times to S1 are unaffected by SOA duration (Logan & Delheimer, 2001). This effect has been found with two manual responses, but also with tasks that use very different kinds of responses such as eye-movement, vocal, or foot responses (Pashler, Carrier, & Hoffman, 1993; Pashler, 1990; Osman & Moore, 1993; Pashler & Christian, 1994). It has also been observed for different stimulus modalities (e.g. Bertelson, 1967; Brebner, 1977; Osman & Moore, 1993) and even across modalities (Creamer, 1963; Borger, 1963). This is of special relevance for driving situations, in which different modalities are used increasingly to deliver information to the driver.

One reason for dual task slowing is assumed to be the fact that response selection cannot be carried out for more than one task simultaneously. Another reason is that tasks are prepared less efficiently if other tasks have to be prepared at the same time. Pashler (1994) concludes that PRP effects can mainly be explained by bottleneck theories and a limited ability to prepare multiple task mappings at the same time. In addition Aschersleben and Müsseler (2008) assume that sensory,

cognitive, and motoric processes on a central level can also be interfered in a dual task situation.

PRP procedure has been effective to give insight into which specific mechanisms can function in parallel and which cannot. However, the tasks that need to be completed in a driving situation do not necessarily all require the driver to choose and respond to two stimuli as rapidly as possible. Instead, a dual task situation in driving most likely includes *continuous* dual task performance. One of the first studies using continuous dual tasks, required participants to copy unrelated words at dictation and simultaneously read and understand short stories (Hirst, Spelke, Reaves, Caharack, & Neisser, 1980). Since then, continuous tasks have also been implemented as visual and/or manual tracking, comprehending prose, answering questions, and shadowing speech. Performance measures in such tasks are generally aggregated over periods of seconds or minutes (Pashler, 1994). Indeed, studies intending to study performance in human-machine interaction, often use relatively abstract continuous tasks to simulate driving requirements. For example, Ho, Tan, and Spence (2006) investigated the potential use of spatially predictive warning signals in facilitating drivers' responses to certain driving events. The authors used a rapid serial visual presentation (RSVP) task to simulate the continuous and uniformly highly attention demanding driving task. Participants' second task was to identify the color of numberplates of cars that were either visible through the windscreen or via the back mirror. The authors found an attentional cueing effect for auditory warning signals in this dual task driving-like situation: color identification was faster if the numberplate appeared in a previously cued location as compared to if it appeared in an uncued location. Other studies have implemented the continuous task requirements of driving by using for example a serial recall task (e.g., Vilimek & Hempel, 2005), a tracking task via the computer mouse (e.g., Isler & Starkey, 2010), a pursuit tracking task via a joystick (e.g., Strayer & Johnston, 2001), a driving simulator (e.g., Caird, Chisholm, & Lockhart, 2008), or even real driving (e.g., Brookhuis, de Vries, & de Waard, 1991). Although changes in priority of two concurrent continuous tasks lead to a relatively smooth trade of function, which might be interpreted as a graded capacity allocation, it is likely that the same processes function in the processing of continuous dual tasks as have been found with the PRP procedure. A central process might simply distribute the time during which each task has access to a bottleneck mechanism, required by both continuous tasks (Pashler, 1994). Regarding speeded responses to warning displays in a driving situation, it is important to understand whether mechanisms influencing response time and ac-

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curacy (e.g., distractor-response binding) can be affected by bottleneck constraints in a dual task setup.

In sum, the way perception influences action is of special interest in the design of interfaces for human-machine interaction. Any direct link between the perceived interface and a response by the user will influence the swiftness and the precision of an interaction. Driving is a context in which a person interacts closely with a machine and in which correct and fast responses are crucial. Due to the high velocities in traffic, a slight delay of a correct response can largely influence the seriousness of a possible crash, and an incorrect reaction can have even more serious consequences if the responding person is traveling at a high speed. Therefore, factors influencing response times and response accuracy are of major importance in the design of driver assistance systems.

Objective of the Thesis

From the cited evidence regarding distractor-response binding it becomes clear, that until now all studies suggesting binding of distractor and response features were conducted in the visual modality. In contrast, *stimulus*-response bindings have been shown to reveal in different (visual, auditory, and tactile) modalities as well as across modalities. However, some effects particularly regarding distractor influence differ across different modalities (e.g., Frings, Amendt, & Spence, 2011; Spence, 2010; Spence, Pavani, & Driver, 2004). For example in a negative priming task, repetitions of previously ignored stimuli as target stimuli led to stronger performance costs when the stimuli were tactile as compared to visual – even when differences in the processing difficulty between tactile and visual stimuli were controlled for (Frings et al., 2011). Furthermore, Soto-Faraco et al. (2002) found that visual distractors lead to stronger interference in spatial attention tasks as compared to tactile distractors. Especially regarding an application of distractor-response bindings in the driving context, it is important to investigate whether similar differences hold for distractor-response bindings, or whether these lead to similar effects on responding in the different modalities. Because the visual modality suffers from an overload in some driving situations, signals alerting the driver have increasingly been given in auditory or tactile modalities. If distractor-response binding effects can be found in audition, in the tactile modality, and especially if the effects also hold across modalities, the effect might be of relevance for the design of driver assistance systems, also if signal modality varies.

In addition, regarding fundamental research, it is also of great theoretical interest to investigate whether distractor-response binding effects influence responses in

other or across modalities. Regarding past research, the effect of distractor-response binding seems to be very stable and relatively general (revealing for different letter- and word-configurations, location stimuli, etc.). However, one crucial step to investigate the general applicability of distractor-response binding is to test whether the effect holds in different modalities. In fact, distractor-response binding effects across modalities might indicate that distractor-response binding also operates on a distal and not only a proximal level. Therefore, the first series of experiments in this thesis is dedicated to a generalization of distractor-response binding effects.

In a first step, I aim to generalize distractor-response binding effects to the auditory modality. In Chapter 4 two experiments are presented implementing the same design as in (Frings et al., 2007) with artificial sounds serving as stimuli. Along the lines of Frings and Rothermund (2011) target and distractor sounds in Experiment 1 are either presented in a grouped fashion (i.e., both stimuli are presented to both ears, resulting in the perception of one central sound source) or in a non-grouped fashion (i.e., one stimulus to each ear, resulting in the perception of two different sound sources). Thus, with Experiment 1 it can be investigated whether distractor-response bindings are possible in audition. More specifically, the comparison of the grouped and non-grouped condition indicates whether similar effects of grouping on distractor-response binding exist in audition as have been observed in vision (e.g., Frings & Rothermund, 2011).

To further generalize the effect of distractor-response binding, in Experiment 2 (Chapter 5) tactile rhythms are used as stimuli. The design is the same as in the previous experiments and the tactile target and distractor stimuli are presented to the two hands via two skin transducers. The question of grouping is especially interesting in the tactile modality, because different frames of reference are possible. For an external frame of reference, hand- and arm posture are irrelevant regarding the grouping of tactile stimuli, but this is not the case if a somatotopic frame of reference is assumed.

As a third effort to generalize the distractor-response binding effect, in Experiment 3 (Chapter 6) both visual and auditory stimuli are used as targets and distractors. One stimulus is always presented in the visual modality (a line drawing of an animal), and the other stimulus is always presented in the auditory modality (the sound of an animal). Whether the distractor is presented auditory or visually varies and the distractor modality can change between prime and probe. That is for example, the same distractor can be presented visually on the prime and auditory on the probe. An indication of particular importance of

Experiment 3 therefore concerns the level of cognitive representation on which distractor-response bindings take place.

After presenting the evidence for the general applicability of distractor-response binding, I will turn to a more specific applicability of distractor-response binding in everyday situations. Particularly, a situation is approached in which the driver of a car might frequently find himself. Due to the increasing use of driver assistance systems, a person is likely to occasionally respond to various warnings of such a system while driving. In contrast to the context in Experiments 1 through 3, in such a situation, people respond to more complex stimuli, and the responses requested are not necessarily keypresses on a computer keyboard. In fact, some responses in a driving situation might even be to withhold a certain reaction. Possibly the most obvious difference is the number of tasks a driver has attend to at once. While participants in all past experiments investigating distractor-response bindings had only one task (i.e., to identify and respond to the target stimulus), the driver of a car typically attends to at least two tasks at once (e.g., scanning the road and responding to a warning signal).

Thus, the second series of experiments aimed to approach the requirements of a driving situation as sketched above. Experiment 4 (Chapter 7) investigates whether relatively complex distractors that are more likely to be encountered while driving a car, can become part of distractor-response bindings. The stimuli used in Experiment 4, resemble warning displays of an advanced driver assistance system that is currently being developed at the German Research Center for Artificial Intelligence (DFKI) for the project simTD (<http://www.simtd.de/>).

In Experiments 5 and 6 I investigate whether distractor-response bindings occur with responses that are more likely to be required while driving a car. That is, whether a response given with a foot can become integrated with a distractor. The same stimuli as in Experiment 4 are used, and participants respond by pressing one of two foot pedals (Experiment 5), or by either pressing one foot pedal or restraining a pedal press (Experiment 6).

With the final Experiment, I intend to investigate whether distractor-response binding effects can be found in dual task situations (Experiments 7a and 7b, Chapter 9). Participants complete a continuous tracking task while responding to occasionally appearing warning displays. Two different manners of display presentation are compared: the setup either resembles a head-up display or a head-down display arrangement. A difference in distractor-response binding effects due to the form of warning display presentation (head-up display vs. head-down display) is particularly interesting, because the previously customary head-down

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displays are increasingly being exchanged for head-up displays in advanced driver assistance systems.

Implications that the present results might have for the understanding of the general effect of distractor-response binding will be discussed in the last part of this thesis, along with implications the results might have for the design of advanced driver assistance systems.

Part II.

Experiments Series 1: Generalization of Distractor-Response Binding

Auditory Findings

4.1. Relevance

Our first step toward generalizing the effect of distractor-response binding concerns the auditory modality. If a stimulus is repeatedly encountered, the repetition usually affects the behavior as shown in the behavioral response to the repeated stimulus. As introduced in the Theoretical Background, Section 2.1, *Automated Actions*, the instance theory of automatization is an important account that explains effects of stimulus repetition (Logan, 1988). It describes the acquisition of automaticity as based on a single-step, direct-access retrieval of past solutions from memory; that is, upon encountering a stimulus a second time, the stimulus will retrieve the last episode containing this very stimulus from memory. In Section 2.1.2, *Integration of Action and Relevant Stimuli: Stimulus-Response Binding* it was described that based on Logan's (1988, 1990) instance theory, the theory of event coding assumes that stimulus-response episodes are stored as 'event files' in memory (Hommel, 1998, 2004; Hommel et al., 2001). Subsequently, if any part of an event file is repeated, the entire event file – including the response – will be retrieved. Thus, if a stimulus is repeated a second time while the response is also repeated, performance will be enhanced due to the fact that the retrieved response will be compatible to the currently demanded response. Besides the previously cited evidence for the integration of visual stimuli and responses, several recent studies provided evidence for an integration of auditory stimuli and responses as

well (e.g., Mondor, Hurlburt, & Thorne, 2003; Mondor & Leboe, 2008; Zmigrod & Hommel, 2009).

Yet, most stimuli are not encountered in isolation. Instead they will often be accompanied by task-irrelevant stimuli and/or context information (see Section 2.1.3, *Integration of Action and Ignored Stimuli: Distractor-Response Binding*). Stimulus-response-retrieval (SRR) theory (Rothermund et al., 2005; see also Mayr & Buchner, 2006) expanded the basic idea of event file creation (see Hommel et al., 2001 for a framework theory on event coding) to selection situations in which targets are accompanied by distractors competing with the targets for response generation. In fact, SRR theory assumes that targets and accompanying distractors are encoded together with the response into a single event file, and furthermore that each stimulus of this episode (i.e., also the distractor stimulus) will retrieve the complete episode including the response that was given to the target. We already described that such ‘distractor-response bindings’ are evidenced by an interaction of response relation and distractor relation. That is, in a design with two subsequent stimulus displays (i.e., a prime display and a probe display) with orthogonally varied response and distractor repetitions, the repetition of the prime distractor as the probe distractor delays responding if the probe response is incompatible to the prime response. On the other hand, repetition of the distractor facilitates responding if prime and probe responses are compatible. Accordingly, in displays using a flanker configuration of target and distractors (i.e., a central target flanked by two identical distractors, e.g. DFD with F being the target), Frings et al. (2007) observed that distractor repetition effects were modulated by the response relation between prime and probe, such that distractor repetitions in the case of response repetition facilitated responses while distractor repetitions in the case of response changes interfered with performance in the probe.

Interestingly, in accordance with SRR theory, Mayr and colleagues obtained evidence for prime response retrieval with auditory stimuli (Mayr & Buchner, 2006; Mayr et al., 2009; Mayr, Buchner, Möller, & Hauke, 2011; Mayr, Möller, & Buchner, 2011), that is, repeating an irrelevant auditory stimulus also led to a retrieval of the previous response. Note that for our purpose the term ‘distractor’ is used in the same sense it has been used in visual experiments, i.e. a distractor describes a sound that is mapped to a response and thus competes with the target sound for response execution. Importantly, the target sound must be selected against the distractor sound by a feature which is not correlated with the task (for example, in the experiment reported below, the sound pitch defined which of two stimuli is the target and which one is the distractor albeit participants’ task was

to identify the target sound irrespective of its pitch). In contrast, in perception studies in audition the term 'distractor' does not denote a specific stimulus that is irrelevant for identifying the correct response, but sometimes is used to denote an unspecific disturbing noise in the background that hampers performance and can, for example, mask the perception of the target (see Frings & Spence, 2010, for discussing differences between visual, auditory, and tactile 'distractors'). In the present experiment, however, whenever we use the term 'distractor', we denote a distinct auditory stimulus that affects performance not because of its unspecific intensity but because it is associated to a specific response.

Taken together, so far the evidence suggests that irrelevant sounds are bound to responses as are distractor objects in vision. Yet, there are obvious differences between auditory and visual perception that are relevant for the processing of irrelevant information. For example, sounds cannot be filtered out as easily as visual stimuli (e.g., by closing the eyes or focusing the eyes on a different location). Since we have not as many options to protect ourselves from irrelevant auditory input as we do in vision, the control of auditory distractor-response bindings might even be of greater importance than the control of visual distractor-response bindings. Just imagine a context in which people respond to auditory stimuli (say in human-machine interfaces) – how can our cognitive system prevent that simultaneously heard but irrelevant sounds influence the currently executed response?

Distractor-Response Bindings and Their Constraints

The present experiment aimed to investigate, under which circumstances auditory task-irrelevant stimuli become integrated with the response. Recent studies, using visual stimuli, indicated that the interaction of response relation and distractor relation can be modulated by grouping of targets and distractors. In particular, Frings and Rothermund (2011) observed that distractor-response bindings were stronger if the target and the distractor gave the impression of belonging to the same object as compared to situations in which distractor and target were clearly separable. Giesen and Rothermund (2011) varied the valences of the target and distractor stimuli. Distractor-response bindings were observed only if target and distractor had the same valence but not if their valences differed. The authors concluded that detecting an affective mismatch between two stimuli counteracts

binding processes and leads to the creation of separate episodes for distractor and target stimuli. Taken together, these findings suggest that visual distractor-response bindings are modulated by perceptual or affective grouping of targets and distractors (see Theoretical Background, Section 2.1.3, *Integration of Action and Ignored Stimuli: Distractor-Response Binding*).

In the present experiment we transferred the idea of perceptual grouping to the auditory domain. Specifically, we investigated whether bindings between auditory distractors and responses are moderated by the grouping information of auditory target and distractor stimuli. Target-distractor grouping was supposed to facilitate distractor-response bindings, whereas the non-grouping of target and distractor was supposed to diminish the emergence of distractor-response bindings.

Target and distractor were always presented simultaneously. One sound was presented in high and the other in low pitch – the sounds could easily be transformed in pitch without alteration of their identity. Selection criterion was stimulus pitch, that is, participants identified the target stimulus by selecting the sound in one frequency and ignoring the sound in the other frequency. An arrow cue before each sound pair presentation indicated whether target pitch was high or low. In the grouped condition, target and distractor stimuli were always presented to the left and right ear simultaneously, giving the impression of a centrally presented sound-pair. In contrast, in the non-grouped condition, target and distractor stimuli were always presented to different ears and thus appeared to originate from two different locations.

If the stimulus configuration affects the integration of auditory distractors into event files then an interaction of response repetition with distractor repetition that indicates a retrieval of distractor-response bindings should be stronger in the grouped condition than in the non-grouped condition. In the grouped condition, we expected response times to be shorter for repeated distractors than for changed distractors if the response had to be repeated, whereas if responses had to be changed, this advantage should be reduced or even turn into a disadvantage. In the non-grouped condition, we expected a weaker interaction of distractor relation and response relation due to a reduced likelihood that distractors are integrated with target responses.

4.2. Experiment 1

4.2.1. Method

Participants. A total of sixty students (38 women) from Saarland University took part in the experiment. Their median age was 24 years with a range from 18 to 29 years. Thirty participants were assigned to the grouped condition, and another thirty participants were assigned to the non-grouped condition. Gender distribution was equal in both samples. The data of one participant had to be replaced, because of missing data in one experimental block. All participants were paid 8 € for participation. None of the participants reported any hearing impairment.

Design. Within both grouping conditions, the design essentially comprised two within-subjects factors, namely response relation (repetition vs. change) and distractor relation (repetition vs. change). In addition, the pitch of the prime and probe targets (high versus low) was varied orthogonally to all other factors. In the non-grouped condition, presentation ear of the prime and the probe targets (left versus right ear) was also varied orthogonally to all other factors.

Materials. The experiment was conducted using the E-prime software (version 1.1). Instructions, the cue, and the fixation marker were shown in white on black background on a standard CRT screen. The stimuli in both grouping conditions were four digitized artificial sounds, which could be presented either in high or in low pitch. All sounds were synthesized with a sampling rate of 1411 kBit/s, using the software Audacity. Frequencies of low pitched sounds ranged from 200 to 600 Hz, whereas frequencies of high pitched sounds ranged from 1000 to 3000 Hz. Sound 1 was an alternation of two 30 ms continuously presented sinusoids (500 Hz and 300 Hz for low, 2500 Hz and 1500 Hz for high pitched sounds). Sound 2 was an alternation of 10 ms square-wave bursts (400 Hz for low, 2000 Hz for high pitched sounds) and 10 ms silences. Sound 3 consisted of five 60 ms continuously presented sinusoids (200, 300, 400, 500, and 600 Hz for low, 1000, 1500, 2000, 2500, and 3000 Hz for high pitched sounds). Sound 4 alternated 20 ms square-wave sound periods and 20 ms silences. The 20 ms sound periods alternated in frequencies and always consisted of two 10 ms square waves without silences. For the low pitched sound, the first 20 ms included the frequencies 500 and 600 Hz (2500 and 3000 Hz for the high pitched sound) and the second sound period included the frequencies 200 and 300 Hz (1000 and 1500 Hz for the high pitched sound). All sounds were 300 ms long and were presented

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over headphones (Terratec Headset Master 5.1 USB). Sounds were presented to the participants at an intensity of approximately 65 dB SPL.

Procedure. Participants were tested individually in soundproof chambers. Instructions were given on the screen and summarized by the experimenter. The experimenter placed middle and index fingers of the participants' hands on the keys D, F, J, and K of a standard computer keyboard. Their task was always to identify the target sound by pressing a key with the corresponding finger. Distractor sounds had to be ignored. Participants were instructed to react as quickly and as correctly as possible. Sound 1 corresponded to the left middle finger, sound 2 to the left index finger, sound 3 corresponded to the right index finger, and sound 4 to the right middle finger. Participants always heard one target and one distractor sound simultaneously - one in high and one in low pitch. A white arrow on black background, pointing upwards or downwards was presented for 300 ms before stimuli onset, indicating the pitch in which the target would be presented in the following sound pair. For example, if the arrow pointed upwards, the participant was supposed to identify the sound presented in high pitch and to ignore the sound presented in low pitch. In the grouped condition, the target and distractor sounds were presented to both ears. In the non-grouped condition, the target was presented to one ear and the distractor was presented to the other ear. A single trial (prime – probe sequence) consisted of the following sequence of events (cf. Figure 4.1): after the participant started the trial by pressing the space bar, the arrow-cue, pointing up or down appeared in the middle of the screen for 300 ms, indicating the pitch of the target for the following sound pair. The arrow was followed by a plus sign. Participants were instructed to fixate this sign throughout the trial. After a silent period of 200 ms the prime sound pair was presented for 300 ms. Participants reacted to the prime target. Five-hundred ms after the response to the prime, an arrow-cue replaced the plus sign for 300 ms, indicating the pitch of the probe target. After another 200 ms, the probe stimuli were presented for 300 ms. After the response to the probe target, the plus sign was replaced by an asterisk which signaled to the participant that the next trial could be started.

Target pitch was always the same on the prime and the probe, and the distractor was always presented in the other pitch (e.g., if targets were high, distractors were low). In response repetition trials (RR) the same sound-type was presented as the target on the prime and the probe, respectively. In response change trials (RC) the target varied between prime and probe. That is, two different sound-types were presented as targets on the prime and the probe. Orthogonally to the response

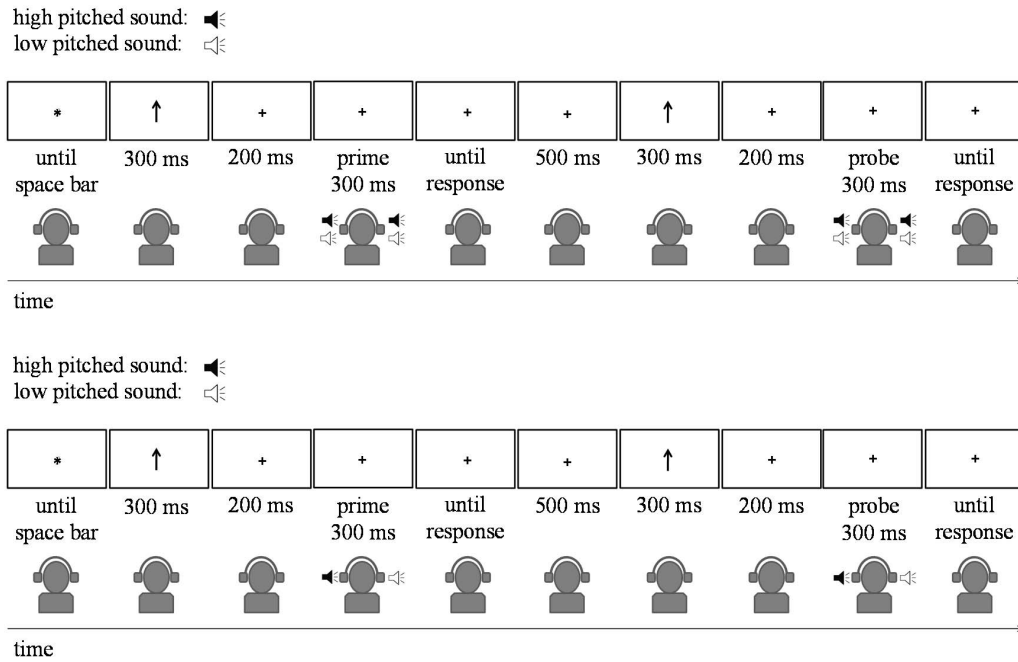


Figure 4.1.: Sequence of events in the grouped condition (upper panel) and in the non-grouped condition (lower panel) in Experiment 1. Target and distractor sounds were presented for 300 ms on both prime and probe. An arrow presented before each prime or probe display indicated the target pitch for the next sound pair. High pitched sounds (targets in the example) are represented by black loudspeaker symbols while low pitched sounds (distractors in the example) are represented by white loudspeaker symbols. On each prime and each probe, participants reacted to the identity of the target by pressing the corresponding key. In the grouped condition, targets and distractors were always presented simultaneously to both ears (leading to the perception of a centrally presented sound) whereas in the non-grouped condition the target and the distractor were always presented to different ears.

relation, the distractor relation was varied. In distractor repetition trials (DR) the to-be-ignored sound-type was the same on the prime and the probe whereas in distractor change trials (DC), different sound-types were presented as distractor on the prime and the probe. In turn, four different conditions were conducted: in RRDR trials, the prime target and the prime distractor were repeated on the probe. In RRDC trials, the prime target was repeated as the probe target while the distractor changed from prime to probe. In RCDR trials, the probe target differed from the prime target while the prime distractor was repeated as the probe distractor. Finally, in RCDC trials, no stimulus-type was repeated from the prime to the probe.

In both grouping conditions, targets were presented in high pitch in half of the prime-probe sequences and in low pitch in the other half. The selection criterion (i.e. target pitch) was varied blockwise within participants as to avoid influences on binding due to task switches (Pösse, Waszak, & Hommel, 2006), and block sequence was counterbalanced across participants. Each of the sound-types was presented equally often as the probe target in high and in low pitch in both grouping conditions and equally often to the right and to the left ear in the non-grouped condition.

Each participant worked through two experimental blocks. In one block participants responded to the high pitched sound and in the other block they responded to the low pitched sound. In the grouped condition, each experimental block consisted of 96 prime-probe sequences. The four trial types (RRDR, RRDC, RCDR, and RCDC) were realized in 24 trials in each block, and varied orthogonally to sound-type and sound-pitch of the probe target. In the non-grouped condition, each experimental block consisted of 128 prime-probe sequences. The four trial types were realized in 32 trials in each block, and varied orthogonally to sound-type, sound-pitch and presentation-side of the probe target and to presentation-side of the prime target. In each prime and each probe, different sound-types were presented as target and distractor. After defining the probe target sound, in each trial the remaining three stimuli were randomly assigned to the roles of probe distractor, prime target, and prime distractor. For each trial sequence, stimuli were then changed in accordance with the particular condition; for example, in a RRDC trial, the prime target identity was then changed to the probe target identity. Before the experimental blocks started, participants worked through a practice phase in which they were first familiarized with all sounds and their mapping to the middle and index fingers. Then participants practiced the mapping of individually presented sounds in 48 trials. In 48 further trials participants learned to distinguish

one of two simultaneously presented sounds. Finally they practiced this task until they reached a criterion of 25 out of 32 correctly answered prime-probe sequences. The learning phase before the experiment had on average a duration of 20 to 25 minutes.

4.2.2. Results

Only trials with correct answers to the prime and the probe were considered. Reaction times that were more than 1.5 interquartile ranges above the third quartile of the RT distribution of the whole sample in each grouping condition (Tukey, 1977), and those that were shorter than 200 ms were excluded from the analysis. Due to these constraints, in the grouped condition 23.1 % of all trials were discarded (probe error rate was 7.4 %, prime error rate was 11.6 %), in the non-grouped condition 21.3 % of all trials were discarded (probe error rate was 7.0 %, prime error rate was 11.5 %). Mean RTs and error rates for probe displays are depicted in Table 4.1.

In a mixed model repeated-measures ANOVA with grouping (grouped versus non-grouped) \times 2 (distractor relation: repeated versus non-repeated) \times response relation (repeated versus non-repeated) both main effects of response relation and distractor relation were significant, $F(1, 58) = 539, p < .001, \eta_p^2 = .90$, for response relation, and $F(1, 58) = 184, p < .001, \eta_p^2 = .76$, for distractor relation. Reactions to repeated targets (grouped condition: $M = 922$ ms, $SD = 190$ ms; non-grouped condition: $M = 910$ ms, $SD = 146$ ms) were faster than reactions to changed targets (grouped condition: $M = 1283$ ms, $SD = 200$ ms; non-grouped condition: $M = 1276$ ms, $SD = 149$ ms), and reactions to sound pairs with repeated distractors (grouped condition: $M = 1022$ ms, $SD = 178$ ms; non-grouped condition: $M = 1045$ ms, $SD = 133$ ms) were faster than reactions to sound pairs with changed distractors (grouped condition: $M = 1183$ ms, $SD = 200$ ms; non-grouped condition: $M = 1140$ ms, $SD = 144$ ms). The effect of distractor repetition was significant for both response repetition and response change trials, $t_{RR}(29) = 11.77, p < .001$ and $t_{RC}(29) = 2.36, p = .025$ in the grouped condition and $t_{RR}(29) = 8.00, p < .001$ and $t_{RC}(29) = 2.44, p = .021$ in the non-grouped condition. The interaction of distractor relation and grouping, $F(1, 58) = 12.23, p = .001, \eta_p^2 = .17$, was significant, as well as the interaction of response relation and distractor relation, $F(1, 58) = 67.27, p < .001, \eta_p^2 = .54$, indicating distractor-response binding effects. In fact, separate analyses, re-

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Table 4.1.: Mean reaction times (in ms) and mean error rates (in percentage) as a function of response and distractor relation and experiment, Experiment 1; standard deviations in parentheses

	<i>Response Relation</i>	
	<i>Response Repetition (RR)</i>	<i>Response Change (RC)</i>
<i>(grouped sounds)</i>		
Distractor Change (DC)	1058 (229)	1308 (203)
	5.6 (3.8)	12.6 (6.3)
Distractor Repetition (DR)	787 (166)	1257 (214)
	1.0 (1.9)	10.6 (6.0)
Priming Effect ^a	271 [23]	51 [21]
	4.6 [0.7]	2.0 [1.0]
<i>(non-grouped sounds)</i>		
Distractor Change (DC)	988 (162)	1293 (156)
	5.9 (4.7)	10.5 (5.1)
Distractor Repetition (DR)	833 (147)	1258 (152)
	1.6 (1.6)	10.1 (5.3)
Priming Effect ^a	155 [19]	35 [15]
	4.3 [0.8]	0.4 [0.8]

Note. ^a Priming Effect is computed as the difference between Distractor Change minus Distractor Repetition, standard error of the mean in squared brackets.

vealed a significant effect of distractor-response binding in both grouping conditions, $F(1, 29) = 39.56, p < .001, \eta_p^2 = .58$, for the grouped condition and $F(1, 29) = 29.27, p = .001, \eta_p^2 = .50$ for the non-grouped condition, respectively. Importantly, the three-way interaction of grouping, distractor relation, and response relation was also significant, $F(1, 58) = 6.06, p = .017, \eta_p^2 = .10$, indicating a significantly stronger interaction of response relation and distractor relation in the grouped condition with target and distractor presented to both ears simultaneously (cf. Figure 4.2, left panel) than in the non-grouped condition with target and distractor presented to the ears separately (cf. Figure 4.2, right panel).

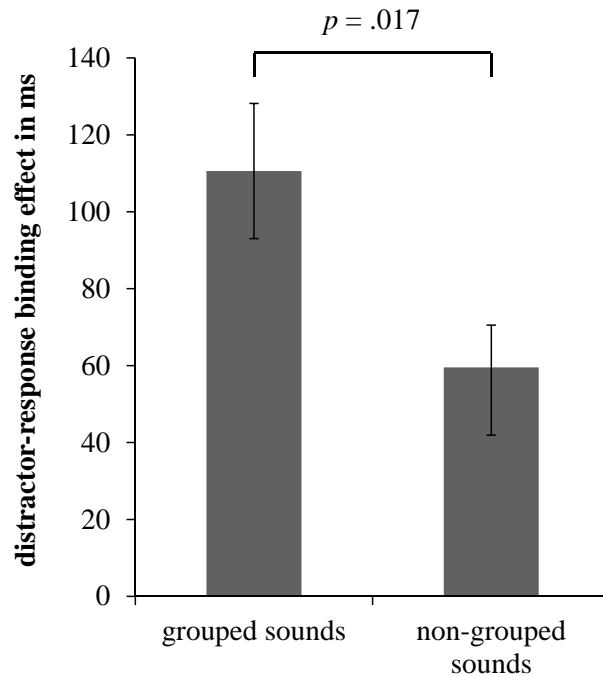


Figure 4.2.: Distractor-response binding effects (i.e., the interaction of response and distractor relation) for reaction times as a function of grouping condition (grouped sound presentation versus non-grouped sound presentation) in Experiment 1. Distractor-response binding effects are computed as the difference between the distractor repetition effects in response repetition and response change trials. Error bars indicate the standard error of the mean.

The same ANOVA on error rates revealed similar results. Both main effects of response relation and distractor relation were significant, $F(1, 58) = 164.38, p < .001, \eta_p^2 = .74$, for response relation, and $F(1, 58) = 36.54, p < .001, \eta_p^2 = .39$, for distractor relation. The interaction of response relation and distractor relation was significant as well, $F(1, 58) = 17.90, p < .001, \eta_p^2 = .24$. However, the three-way interaction of grouping, distractor relation, and response relation was not significant, $F(1, 58) = 1.79, p = .187, \eta_p^2 = .03$. Separate analyses of the grouped and non-grouped conditions revealed identical patterns.

4.2.3. Discussion

The purpose of the present experiment was to investigate whether distractor-response bindings are possible with auditory distractor stimuli, and whether the grouping of targets and distractors has a modulating effect on auditory distractor-response bindings. Several studies provided evidence that task irrelevant stimuli can be bound to responses (e.g. Frings et al., 2007; Frings, 2011; Frings & Moeller, 2010; Giesen & Rothermund, 2011; Mayr & Buchner, 2006; Mayr et al., 2009; Rothermund et al., 2005). However, it would be maladaptive for the cognitive system to integrate every perceived irrelevant stimulus with the actually executed response. Thus, it makes sense to assume mechanisms that control whether a distractor will be integrated into an event file or not. The aim of the present experiments was to investigate such control mechanisms for the auditory modality. The results reported here show that distractor-response bindings in the auditory modality can be regulated by grouping of targets and distractors. This finding parallels results from the visual modality (Frings & Rothermund, 2011; Giesen & Rothermund, 2011), and hence yields evidence for conceptually similar processes underlying distractor-response bindings in vision and audition.

In the grouped condition we used a setup in which target and distractor sounds were presented to both ears simultaneously. In contrast, in the non-grouped condition target and distractor sounds were presented to separate ears. With both settings, we found evidence for auditory distractor-response binding in the reaction times. However, a comparison of the two grouping conditions revealed a significantly stronger effect of distractor-response bindings if target and distractor stimuli were both presented to the left and right ear simultaneously compared with the effect for target and distractor stimuli presented separately to the ears.

It can be argued that in our experiment the grouping-modulation was conducted by presenting target and distractor in the same or at different locations. If target

and distractor were presented to the left and right ear simultaneously, participants had the impression of both sounds originating from one location within the head. If target and distractor were presented to separate ears, the impression was that of two sounds originating from different locations. Van Dam and Hommel (2010) have suggested that for binding of features only location matters whereas Frings and Rothermund (2011) argued that location is only a special case (namely the principle of proximity) of a more general binding principle. We cannot decide with the present data whether in audition location is just a special case or whether only location influences binding.

Further, it must be acknowledged that the grouped and the non-grouped conditions differed with respect to the predictability of the target. In particular, in the grouped condition, the perceived location of the target is always predictable and the participant does not need spatial attention shifts to locate the target, whereas in the non-grouped condition, the location of the target is unpredictable and attention shifts to left and right are necessary to find the target. As a result, one might wonder whether this difference can explain differences in the binding of distractors and responses. However, if spatial attention shifts did have a strong influence here, the processing efficiency (in terms of average RT and error rates) between the grouped and non-grouped condition should differ in that the non-grouped condition should have elicited a lower processing efficiency (i.e., higher reaction times and error rates). Yet, in our study the processing efficiency was comparable in both conditions (reaction times were even slightly higher in the grouped presentation condition).

In conclusion, we were able to generalize the effect of distractor-response binding to the auditory modality. Moreover, our experiments support the notion that grouping information plays an important role for binding processes in the auditory domain. An automatic integration of irrelevant auditory information into event files seems more likely if this information is grouped than if the information is non-grouped. Apparently, grouping seems to serve as a cue that shields processes of behavioral automatization against an influence of irrelevant stimuli.

Tactile Findings

5.1. Relevance

We discussed evidence for distractor-response binding effects with visual stimuli (see e.g., Frings & Rothermund, 2011; see Section 2.1.3, *Integration of Action and Ignored Stimuli: Distractor-Response Binding* of the Theoretical Background), and presented results indicating distractor-response bindings in the auditory modality. Together, this evidence suggests a relatively wide applicability of the mechanism. In turn, it seems worthwhile to analyze whether distractor-response binding can be observed in touch as well (for the journal article on these data see Moeller & Frings, 2011). More specifically to tactile distractor-response binding, this phenomenon could have clear implications for human action in everyday life. For example, current in-car-warning systems increasingly use tactile stimuli to trigger reactions by the driver (e.g., a vibration of the steering wheel alerting the driver to an imminent lane departure). Yet, given that in next generation interfaces for mobile phones, touch screens, MP3 players etc., vibro-tactile stimulation will often be used, it becomes likely that another tactile stimulus (i.e. a distractor stimulus; for example the vibrating cell phone of the driver) occurs at the same time as the steering wheel vibrates. If tactile distractors can be bound to responses, an ignored cell phone vibration could then be integrated with the response to the tactile warning of the driver assistance system and retrieve the same response later on, even if it is not appropriate for the situation. Especially in a driving situation, fast and accurate responses are crucial and we need to understand the binding

between tactile (distractor-) stimuli and responses as the re-encountering of the tactile distractor might retrieve the former response. Yet, generally speaking, as feedback from tactile interfaces will very probably increase in the years to come, it is in general worthwhile to understand the processes that might be involved when the cognitive system faces two tactile stimuli simultaneously. Therefore, the aim of the present experiment is to investigate whether distractor-response bindings can be obtained within the tactile modality.

On the one hand, it seems very plausible that tactile distractors can be bound to target-responses. First, evidence for distractor-response binding effects exist both in vision (e.g., Frings et al., 2007), and in audition (see chapter 4, *Auditory Findings*). Thus, one may speculate that distractor-response bindings reflect modality-independent binding processes. Second, various studies found binding of target and response features in the visual (e.g., Hommel, 1998, 2004), the auditory (e.g. Mondor et al., 2003; Mondor & Leboe, 2008; Zmigrod & Hommel, 2010), and the tactile modality (Zmigrod et al., 2009). In addition, some recent studies suggest that there is a common cortical representation of visual and tactual objects in the nervous system (e.g., James, James, Humphrey, & Goodale, 2006). Thus, if visual objects are bound together with response features and additionally if visual and tactile objects share a common representation, why should we not assume that tactile distractor features can be bound to response features as well?

However, on the other hand, the perception of tactile stimuli differs from visual and auditory stimuli in several aspects. First, the perception of tactile stimuli requires an integration of spatial somatosensory information over time which is reflected in the involvement of the inferior parietal cortex (Saetti, De Renzi, & Comper, 1999). Second, somatosensory stimuli are typically perceived haptically, which includes exploratory finger movements. And third location is coded by the location of the stimulus in external space, as well as by the perceived location of the stimulated body site. Even more important for the investigation of tactile versus visual distractor-response bindings are differences in the cortical organization of the somatosensory and visual system concerning the processing of perception and action (for a review, see Dijkerman & de Haan, 2007). Several studies support the existence of separate ‘what’ and ‘where’ pathways in the visual systems (e.g. Mishkin et al., 1983; DeYoe & Van Essen, 1988; Treisman, 1996). A notion, which was further dissociated as ‘what’ and ‘how’ pathways (Goodale & Milner, 1992; Milner & Goodale, 1995; but see Franz, Fahle, Bülthoff, & Gegenfurtner, 2001). In particular, two separate but interacting cortical streams have been proposed for the processing of action and perception in the visual system: the dorsal

stream is involved in the visual guidance of immediate goal directed movements, whereas the ventral stream is primarily associated with visual perception and recognition (Milner & Goodale, 1995). In contrast, in the tactile modality, action- and perception related pathways are less distinct. The tactile dorsal pathway projects from the anterior parietal cortex (APC), to the posterior parietal cortex (PPC), either directly, or via the secondary somatosensory cortex (SII). The tactile ventral pathway includes projections from the APC, via the SII to the posterior insula and the PPC. Thus, for the somatosensory system, several cortical areas are involved in perception as well as in action-related processes (Dijkerman & de Haan, 2007). This is not surprising, because most somatosensory perception of objects occurs haptically, and therefore is a process that involves action. Further to the findings reported by Dijkerman and de Haan, Drewing and Schneider (2007) in fact suggest that the somatosensory system should not be divided into two structural streams (e.g., dorsal vs. ventral) but merely into functional streams of ‘how’ and ‘what’; however, it should be noted that the dissociation into ‘what’ and ‘how’ pathways is controversially discussed not only for touch (e.g., Drewing & Schneider, 2007).

Yet, concerning feature-bindings, one can assume that the features of a distractor might be integrated into an event file more readily, if object codes of the distractor and the response codes are less distinct. In particular, if the representation of the distractor and the response to the target partially include the same cortical regions, a repetition of the distractor would partially activate cognitive codes of the accompanying response. Consequently, effects of distractor-response bindings might be influenced by the extent to which perception and action related cortical pathways overlap. Regarding the possible differences in cortical representations of perception and action between vision and the somatosensory system, it seems possible that the tactile modality differs from the visual in terms of distractor-response bindings. One might argue that tactile distractor-response binding effects have the potential to emerge even under conditions in which visual binding effects diminish.

Additionally, several studies have found behavioral evidence for modality-specific processing of distractor stimuli (e.g., Frings et al., 2011; Spence, 2010; Spence et al., 2004). For example, in spatial attention tasks visual distractors lead to stronger interference as compared to tactile distractors (Soto-Faraco et al., 2002). Furthermore, in identification tasks, the effects of visual and tactile distractors seem to differ as well. Sometimes vision seems to dominate touch and as a result, tactile distractors are then irrelevant (e.g., Rock & Harris, 1967;

Pettypiece, Goodale, & Culham, 2010) whereas sometimes the effects of tactile distractors can even be stronger than the effects of visual distractors (Frings et al., 2011). In fact, in a negative priming task (for a review see e.g., Fox, 1995), repetitions of previously ignored stimuli as target stimuli led to stronger performance costs when the stimuli were tactile as compared to visual – even when stimulus factors (i.e. differences in the processing difficulty between tactile and visual stimuli) were controlled for.

To investigate, whether tactile distractor-response bindings can be obtained, we transferred the visual task in which we usually observe distractor-response bindings to the tactile modality. We implemented a tactile selection paradigm (cf. Frings, Bader, & Spence, 2008; see also Frings et al., 2011) with two orthogonally varied factors, namely response relation (repetition vs. change) and distractor relation (repetition vs. change). Four different tactile rhythms were used as stimuli. On each prime and each probe two different rhythms, one target rhythm and one distractor rhythm, were presented simultaneously to the participants' left and right hand. The selection criterion was stimulus location (right vs. left). Tactile distractor-response bindings would be indicated by an interaction of response relation and distractor relation, that is, repeating a tactile distractor should enhance response repetition effects when the response repeats from the prime to the probe whereas repeating a tactile distractor should decrease performance when the response changes between the prime and the probe.

5.2. Experiment 2

5.2.1. Methods

Participants. Eighteen students (15 women) from Saarland University participated in the experiment; they were paid 8 € for participation. None of the participants reported any visual, auditory, or somatosensory perceptual impairment. The data of one participant were discarded due to extreme error frequencies (27.08 % probe errors, as compared with a mean probe error rate of 8.49 % in the remaining sample). The median age of the remaining sample was 22 years with a range from 19 to 27 years.

Design. Essentially, the design comprised two within-subjects factors, namely response relation (repetition vs. change) and distractor relation (repetition vs. change).

Materials. The experiment was conducted using the E-prime software (E-prime 1.1). Instructions and the fixation mark were presented in white on black background on a 17-in. standard cathode-ray tube screen (refresh rate was 75 Hz). Vibrotactile stimuli were presented via two skin transducers (Model VBW32, Audiological Engineering Corp.) to the left and right hand (see 5.1). The transient response of each transducer was measured at 5 ms (attack and decay). The amplitude range extended to 50 dB above the sensory threshold. The sound files used to generate the vibrotactile stimuli were amplified by a Sony hi-fi system before being presented via the transducers. Each transducer had a mass of 6.5 g (including the Velcro strap used to fasten it to the participant's hand) and was $2.54 \times 1.85 \times 1.06$ cm in size. A white or blue colored square with a visual angle of 0.8° was presented at the CRT screen to cue the target position. A white square indicated that the target would be presented on the right hand and a blue square indicated that the target would be presented on the left hand. The straps on the subjects' hands holding the skin transducers in place were colored accordingly (i.e., a white strap on the right and a blue strap on the left hand). The stimuli were four different vibrotactile rhythms which were used in a previous study and are known to be easily identifiable by participants (e.g., Frings et al., 2011). All rhythms were presented repeatedly until participants responded. Rhythm 1 consisted of a single long vibration (340 ms) followed by three short vibrations (decreasing in intensity over 180 ms each). There were two pauses of 60 ms each, one after the long vibration and the other after the last of the three short vibrations. The whole sequence lasted 1000 ms. Rhythm 2 was comprised of four vibrations of equal length (192 ms each), with each vibration being followed by a 58 ms empty interval. Rhythm 3 was composed of one short vibration (110 ms) followed by an 890 ms pause. Rhythm 4 consisted of a continuous vibration presented until participants responded. All vibrations had a frequency of 250 Hz¹.

Procedure. The experiment was conducted on a standard computer in a light-

¹Note that an interesting feature of our experiment was that we used quite complex tactile patterns as stimuli whereas in most published experiments on tactile processing short pulses were used as stimuli (e.g., Soto-Faraco, Ronald, & Spence, 2004). Our stimuli develop over time and could be identified not earlier than about 500 ms after stimulus onset. However, participants needed on average about 1250 ms for identifying these patterns even when they were presented without distractors in a learning phase before the experiment. Note, that the average RTs in our experiment are hence much higher as compared to the RTs in studies using simpler stimuli. Yet, the tactile patterns used here might tap tactile processing as it happens in real life, as most tactile information in real life is generally more complex than a brief pulse (e.g. a specific vibration of a cell phone).

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dimmed room. Instructions were given on the screen and summarized by the experimenter. White noise was presented to the participants over headphones throughout the experiment, to mask all possible sounds generated by the transducers. Participants were instructed to place the middle and index fingers of both hands on the keys D, F, J, and K of the computer keyboard. Each of the four rhythms was mapped to one particular finger. On every prime and every probe, one rhythm was presented as the target to one hand and a different rhythm was presented as the distractor to the other hand. Roughly following the procedure used by Frings and colleagues (2008), a colored square was presented in the center of the screen simultaneously to the rhythms, indicating whether the target was presented on the left or on the right hand. If the square was white participants identified the rhythm on the right hand, if the square was blue participants reacted to the rhythm on the left hand. Rhythms were presented until participants' response. Participant's task was to identify the target rhythm by pressing the corresponding key as quickly and correctly as possible. Distractor rhythms had to be ignored. A single prime-probe sequence included the following events (cf. Figure 5.1): the participant started the sequence by pressing the space bar and a white plus sign appeared as a fixation mark for 1000 ms. Then a white or blue

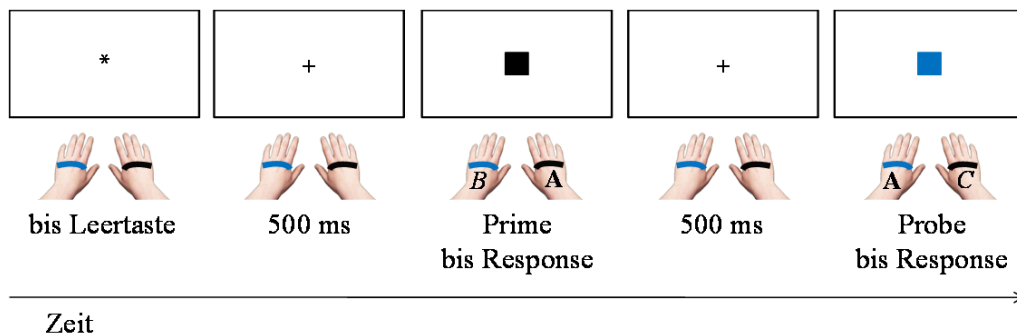


Figure 5.1.: Sequence of events in one trial in Experiment 2. A visual cue presented simultaneously with each prime and probe indicated the hand on which the target was delivered. Participants reacted to the identity of the target rhythm by pressing the corresponding key. The letters A, B, and C depict different vibrotactile rhythms (bold letters indicate the target rhythm whereas italic letters indicate the distractor rhythm). White is depicted in black and black is depicted in white. Stimuli are not drawn to scale.

colored square, indicating the target side, appeared in the center of the screen. Simultaneously target and distractor rhythms were presented to the left and the right hand until participants reacted to the prime target rhythm by pressing the corresponding key. After the response to the prime, the fixation mark appeared for 1000 ms, followed by a colored square indicating the target side for the probe. Simultaneously, the probe rhythms were presented until participants reacted to the probe target rhythm. Finally an asterisk appeared in the middle of the screen, signaling to the participant that the next trial could be started.

In response repetition trials (RR) the same rhythm was presented as the target on the prime and the probe, respectively. In response change trials (RC) the target rhythm varied between prime and probe. Orthogonally to the response relation, the distractor relation was varied. In distractor repetition trials (DR) the rhythm presented as the distractor was the same on the prime and the probe whereas in distractor change trials (DC), different rhythms were presented as distractor on the prime and the probe. In turn, four different conditions were conducted: in RRDR trials, the prime target and the prime distractor were repeated on the probe. In RRDC trials, the prime target rhythm was again presented as the probe target while the distractor rhythm changed from prime to probe. In RCDR trials, the probe target differed from the prime target while the prime distractor was repeated as the probe distractor. Finally, in RCDC trials, no rhythm was repeatedly presented on prime and probe.

Target rhythms were presented to the right hand in half of the trials and to the left hand in the other half. This holds true for primes and probes. With the orthogonal variation of response repetition, distractor repetition, side of the probe target, and side of the prime target, 16 different combinations resulted. In addition, we varied target identity orthogonal to these factors, i.e., every one of these 16 combinations was conducted equally often with each rhythm as the probe target. For each particular trial, the roles of the prime target, the prime distractor, and the probe distractor were randomly assigned to the three remaining rhythms. If the trial type demanded it, the prime stimuli were then changed as to realize the particular condition for this trial. For example, in a RRDC trial, the prime target rhythm was changed to the probe target rhythm. Participants worked through 192 trials which were presented in random order. The four trial types (RRDR, RRDC, RCDR, and RCDC) were realized in 48 trials each.

Before the experimental trials participants worked through four learning and practice phases, gradually introducing the experimental task. During the first two phases, a photograph of two hands was shown on the CRT screen, indicating the

correct response finger. First, only one rhythm was presented to one hand and participants identified the rhythm. Simultaneously, a colored square indicating the stimulated hand, was presented in the middle of the screen. The first phase consisted of eight prime-probe sequences. Before the second phase started, participants were instructed to determine the correct response without the help of the photograph. Everything else remained the same as in the first phase. The second phase included 16 prime-probe sequences. During the third part of the practice no photograph indicating the correct response was shown. Each of the four rhythms had to be correctly identified for four consecutive times before the last practice phase could be started. In the last phase, the distractor stimulus was introduced. Participants received one rhythm on each hand and identified the rhythm that was presented to the hand indicated by the colored square while ignoring the other rhythm. This last phase consisted of 48 prime-probe sequences. During all practice phases, feedback was presented after each response. On average, participants finished practice within 20 to 25 minutes.

5.2.2. Results

Only trials with correct answers to the prime and the probe were considered. Reaction times that were more than 1.5 interquartile ranges above the third quartile of the individual RT distribution of each participant (Tukey, 1977) and those that were shorter than 200 ms were excluded from the analysis. Due to these constraints, 21.05 % of all trials were discarded (probe error rate was 8.49 %, prime error rate was 9.68 %). Mean RTs and error rates for probe displays are depicted in Table 5.1.

In a 2 (response relation: repetition vs. change) \times 2 (distractor relation: repetition vs. change) ANOVA with Pillai's trace as the criterion, the main effect of distractor relation was significant, $F(1, 16) = 15.56, p = .001, \eta_p^2 = .49$. Reactions were faster if the distractor was repeated from prime to probe (1882 ms) than if the distractor differed on prime and probe (1998 ms). The main effect of response relation did not reach significance, $F(1, 16) < 1, \eta_p^2 = .05$. Importantly, the interaction of response relation and distractor relation was also significant, $F(1, 16) = 5.75, p = .029, \eta_p^2 = .26$, indicating that distractor-response bindings occurred (see Figure 5.2, left panel).

The same ANOVA on the error rates yielded an analogous pattern. The main effect of distractor relation reached significance, $F(1, 16) = 25.97, p < .001, \eta_p^2 = .62$, indicating more errors for trials with distractor change than for trials with

Table 5.1.: Mean reaction times (in ms) and mean error rates (in percentage) as a function of response relation and distractor relation (repeated versus changed). Experiment 2.

<i>Distractor Relation</i>	<i>Response Relation</i>	
	<i>Response Repetition (RR)</i>	<i>Response Change (RC)</i>
Distractor Change (DC)	2013(11.4)	1982(11.0)
Distractor Repetition (DR)	1844(3.8)	1919(7.7)
Priming Effect ^a	+169[44](+7.6[1.0])	+63[28](+3.3[1.4])

Note. ^a Priming Effect is computed as the difference between Distractor Change minus Distractor Repetition, standard error of the mean in squared brackets.

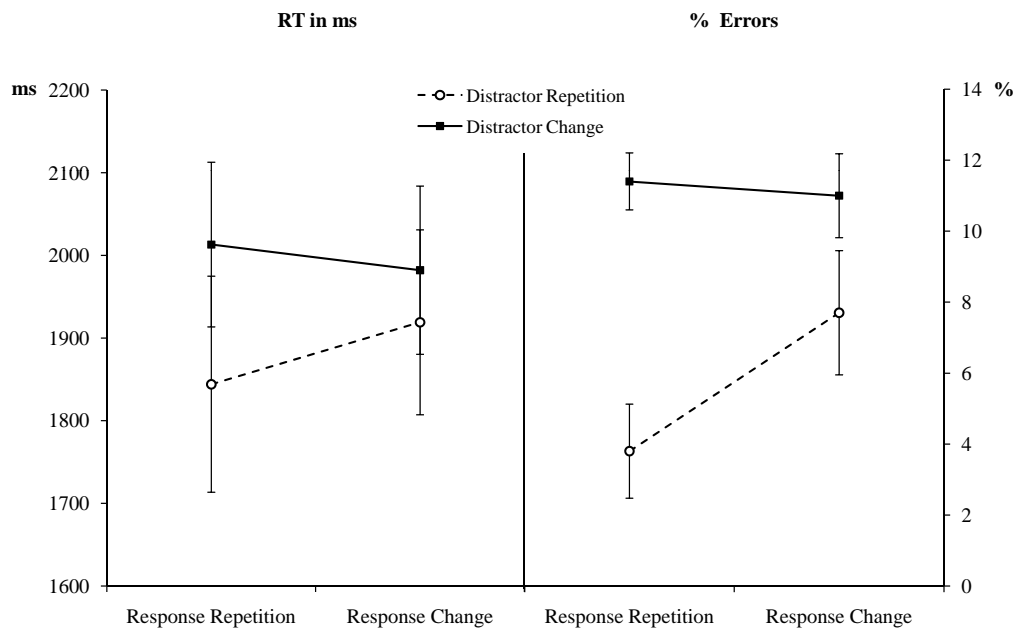


Figure 5.2.: Mean response times (left panel) and mean percent errors (right panel) as a function of response relation (repeated vs. changed) and distractor relation in Experiment 2. Error bars depict standard error of the mean.

distractor repetition. The interaction of response relation and distractor relation reached significance as well, $F(1, 16) = 13.57, p = .002, \eta_p^2 = .46$, again indicating distractor-response bindings (see Figure 5.2, right panel). Participants made fewer errors if the distractor was repeated than if the distractor was changed. This difference was significantly larger for trials with response repetition than for trials with response change. The main effect of response relation was not significant, $F(1, 16) = 2.25, p = .153, \eta_p^2 = .12$.

To further corroborate the robustness of tactile distractor-response binding effects, we ran two control analyses. First, in most visual experiments, the target was always presented in the same location on the prime and the probe whereas in our experiment the probe target stimulus was presented to the same hand as on the prime only in half of the prime-probe sequences. In the other half, the prime and the probe target were presented to different hands. Depending on whether or not the target presentation side changed between prime and probe, a larger or smaller effect of distractor-response bindings might have revealed. To determine whether the relation of target presentation side influenced distractor-response bindings, a 2 (response relation) $\times 2$ (distractor relation) $\times 2$ (target presentation side relation: target location changed versus target location repeated) ANOVA with Pillai's trace as the criterion was conducted. The main effect of target presentation side relation was significant, $F(1, 16) = 85.33, p < .001, \eta_p^2 = .84$, indicating that response times were significantly faster if prime and probe targets were presented to the same hand (1783 ms) as compared to trials in which prime and probe targets were presented to different hands (2096 ms). However, the interaction of response relation and distractor relation (i.e., the effect of distractor-response bindings) was not significantly modulated by the relation of target presentation side between prime and probe, $F(1, 16) = 1.30, p = .271, \eta_p^2 = .08$. However, the main effect of distractor relation (i.e., distractor inhibition effect: an average benefit when the distractor repeats from the prime to the probe) was marginally modulated by target presentation side relation, $F(1, 16) = 4.04, p = .06, \eta_p^2 = .20$: if the distractor was presented to the same hand on the prime and the probe (i.e., target presentation side repeated), response times were significantly faster for distractor repetition than for distractor change trials, $t(16) = 4.16, p = .001$, whereas if the distractor was presented to different hands on the prime and the probe (i.e., target presentation side changed), response times for distractor repetition and for distractor change trials did not differ, $t(16) = 1.44, p = .170$.

Past research found evidence for spatial compatibility effects, i.e. Simon effects, within the tactile modality (e.g., Frings, et al., 2008; Hasbroucq & Guiard,

1992). In the present study participants perceived the stimuli at their right and left hands while they also reacted with either their right or their left hand. As a consequence, the compatibility of presentation- and response hand could have had an influence on our results. To determine whether compatibility of presentation side and response side influenced distractor-response bindings, we conducted a 2 (response relation) \times 2 (distractor relation) \times 2 (presentation side/ response side compatibility: compatible versus incompatible) ANOVA with Pillai's trace as the criterion. The main effect of compatibility was marginally significant, $F(1, 16) = 4.27, p = .055, \eta_p^2 = .21$, indicating faster responses if the presentation hand of the probe target was compatible with the response hand (1904 ms) than in trials with incompatible presentation and response hands (1967 ms). However, the compatibility of presentation- and response hand did not significantly moderate the effect of distractor-response bindings, $F(1, 16) < 1, \eta_p^2 = .03$.

5.2.3. Discussion

In the present chapter, we investigated whether tactile distractors can be bound to, and subsequently retrieve, responses to tactile target stimuli. In a prime-probe paradigm with orthogonally varying response and distractor relation, the interaction of response relation and distractor relation was significant, indicating a larger advantage in response times and error rates due to distractor repetition if the same response was required than if the response had to be changed. Note that participants were instructed to ignore distractor stimuli; nevertheless we found clear evidence for distractor-response bindings both in probe reaction times and in probe errors (cf. Figure 5.2). This result supports the idea that even an actively ignored tactile stimulus can be integrated with and subsequently retrieve, the response given to a simultaneously presented relevant stimulus (Rothermund et al., 2005). In addition, our findings corroborate that distractor-binding is a process that works in all three modalities tested, as now evidence for distractor-response binding has been yielded in vision, audition, and touch. That is, the differences in the neural processing of perception and action in the somatosensory as compared to the visual system did not modulate distractor-response bindings. In contrast, regarding the present results one might speculate that the modality does not play a role for distractor-response bindings at all. Particularly, the effect size of $\eta_p^2 = .26$ which we found with tactile stimuli is comparable to the effects sizes of visual and auditory distractor-response binding effects in experiments in our laboratory using the same design and roughly the same number of trials

and participants (mean effect of $\eta_p^2 = .29$; Frings & Moeller, 2010; Frings, 2011; Frings & Rothermund, 2011, chapter 4, *Auditory Findings*, this thesis). This might be an indication that binding functions in a similar way in the different modalities, regardless of differences in the cortical processing of action and perception. It might also indicate that distractor-response bindings involve the integration of conceptual distractor features with the response, rather than perceptual features (see Frings et al., 2011; Spapé & Hommel, 2008). To test this assumption, we conducted Experiment 3 (see the next chapter).

We should also discuss our findings with respect to previous studies on tactile response competition (e.g., Evans & Craig, 1992, 1992). In fact, two levels of interference from a tactile distractor have been discussed. First, the interference caused by the distractor because the stimulus is physically different from the target and thus interferes with the identification of the target on a perceptual level (due to masking). Second, it has been suggested that both target and distractor stimuli are processed up to the representation of the response. Consequently, participants have two response representations available - the one of the target and the one of the distractor. The interference of the distractor is at least in part due to the incipient response activation of the distractor, which interferes with the response activation of the target (i.e., response competition). In the task we used in the present study, the distractor always interfered with the target at the level of response competition and at a perceptual level. Thus, response competition and masking have influenced all conditions to an equal amount and cannot explain our main finding of distractor-response binding.

In conclusion, our findings provide evidence for binding of distractor-features and response-features when stimuli are delivered to the tactile modality. Given that similar effect sizes occurred in tactile, visual, and auditory modality, a general principle for the binding of distractor-features seems likely. The next question that remains is on which representational level distractor-response bindings are mediated.

Crossmodal Findings: Conceptual Distractor-Response Binding

6.1. Relevance

With the evidence for distractor-response bindings in visual, auditory, and tactile modalities in the discussion of the last chapter we speculated that distractor-response binding might involve the integration of conceptual distractor features with the response, rather than perceptual features (see also Frings et al., 2011; Spapé & Hommel, 2008). The current experiment was designed to further test this hypothesis.

Previous studies concerned with the retrieval of stimulus-response episodes typically repeated perceptual features (or the stimuli themselves) from one display to another to analyze whether repeated elements from a previous episode will retrieve the previous response. The same holds true for studies showing the binding of responses (to targets) and distractor stimuli (i.e., distractor-response bindings). As a result, the binding of features and responses might completely be explained due to direct links between perception and action (Hommel et al., 2001).

In the present experiment however, we analyzed whether a conceptual representation of irrelevant stimulus elements also allows for the retrieval of event files. Specifically, we wanted to test whether distractor-response bindings occur even if only the conceptual distractor-features are repeated from the prime to the probe

while the perceptual distractor-features are changed. If we still observe distractor-response binding effects under such circumstances, that would imply that episodic retrieval can operate on the level of conceptual distractor representations.

A look at the literature on ‘object files’ (cf. Kahneman & Treisman, 1984; Kahneman, Treisman, & Gibbs, 1992) suggests that such conceptual binding is possible. In particular, Gordon and Irwin (1996, 2000; see also Henderson, 1994) showed that repetition of a concept from prime to probe (e.g. the word FISH on the prime display, the picture of a fish on the probe display) lead to object-specific facilitation effects. In turn, it was argued that the representation of stimuli in object files consist not only of perceptual features but also of identity or conceptual features. In the same vein, research on crossmodal congruency showed that hearing the irrelevant sound of a dog will facilitate identifying the picture of a dog (Chen & Spence, 2010; see also Laurienti, Kraft, Maldjian, Burdette, & Wallace, 2004). This finding suggests that irrelevant stimuli presented in a different modality than the target are processed up to a conceptual level and can then facilitate responding to the target. Taken together, it seems possible that distractor stimuli are represented also on a conceptual level and hence the conceptual features of distractors can be bound to the features of a response. Repetition of the distractor concept will then lead to the retrieval of the response encoded with the distractor.

In order to investigate conceptual distractor-response bindings, we randomly switched the modality (sounds versus pictures) of target and distractor stimuli on a trial-by-trial basis in a sequential priming paradigm. As discussed earlier, in such a paradigm, distractor-response binding effects are reflected in an interaction of distractor repetition effects with response relation (Frings et al., 2007; Rothermund et al., 2005). Repeating the distractor from the prime to the probe should facilitate responding in the case of a response repetition (RR) between the prime and probe, because the retrieved prime response is compatible to the to-be-executed probe response. In the case of a response change (RC) between a prime and a probe display, a distractor repetition should impede responding to the probe target because the retrieved prime response is then incompatible to the to-be-executed probe response. Of crucial interest for the present experiment is the question whether a retrieval of distractor-response episodes is restricted to those cases in which an identical perceptual representation of the distractor is repeated on the probe or whether the episodic retrieval of prime responses also occurs if the distractor is repeated only conceptually (i.e. presented in a different modality on the prime and probe trials).

6.2. Experiment 3

6.2.1. Methods

Participants. Thirtynine students (29 women) from Saarland University participated in the experiment; they were paid 6 € for participation. The median age was 22 years with a range from 18 to 37 years. The data of three participants were replaced; one of them had an average reaction time that was an outlier when compared to the RT distribution of the sample (Tukey, 1977). The data of two further participants were excluded due to their extreme probe error rate (>14 %). None of the participants reported any hearing impairment. All had normal or corrected to normal vision.

Design. Essentially, the design comprised three within-subjects factors, namely response relation (repetition vs. change), distractor relation (repetition vs. change), and distractor modality relation (repetition vs. switch).

Materials. The experiment was conducted using the E-prime software (version 1.1). Instructions, fixation marker, and visual stimuli were shown in white on black background on a standard CRT screen. The auditory stimuli were four digitized animal sounds easily identifiable as lamb, frog, chicken, and singing bird. The sounds had a duration of 300 ms and were presented via headphones (Terratec Headset Master 5.1 USB). The software Audacity was used to adapt the sounds for presentation. All auditory stimuli were 300 ms long and had the same intensity, which was a priori judged as subjectively comfortable by two different raters. The visual stimuli were four white line drawings on black background of the same animals (lamb, frog, chicken, and singing bird). They were 4.5 cm to 7.4 cm wide and had a vertical extension of 5.3 cm to 7.0 cm. The viewing distance to the screen was about 60 cm.

Procedure. Participants were tested individually in soundproof chambers. Instructions were given on the screen and summarized by the experimenter. Participants were instructed to place the middle and index fingers of both hands on the keys D, F, J, and K of the computer keyboard. The key D corresponded to the sound and picture of the lamb, F corresponded to frog, J to chicken, and K to singing bird. On each prime and each probe presentation, one picture and one sound (one as the target and the other as the distractor) were simultaneously presented over the headphones and the screen. Before stimulus onset, a cue-word ('picture' or 'sound') appeared in the center of the screen for 300 ms. This cue indicated in which modality the target would be presented in the following

6. CROSSMODAL FINDINGS: CONCEPTUAL DISTRACTOR-RESPONSE BINDING

picture-sound pair. Participants had to ignore the distractor and had to identify the target by pressing the corresponding key. That is, either participants had to attend to the picture and ignore the sound or they were supposed to attend to the sound and ignore the picture. For example, if the word ‘picture’ appeared followed by a picture of a bird simultaneously presented with the sound of a frog, participants were supposed to press the key K for singing bird and ignore the frog sound. Participants were instructed to react as quickly and as correctly as possible. A single prime-probe sequence included the following events (cf. Figure 6.1): After the participant had started the sequence by pressing the space bar, the word, cueing the modality in which the target would be presented, appeared in the middle of the screen for 300 ms. A plus sign then appeared for 200 ms

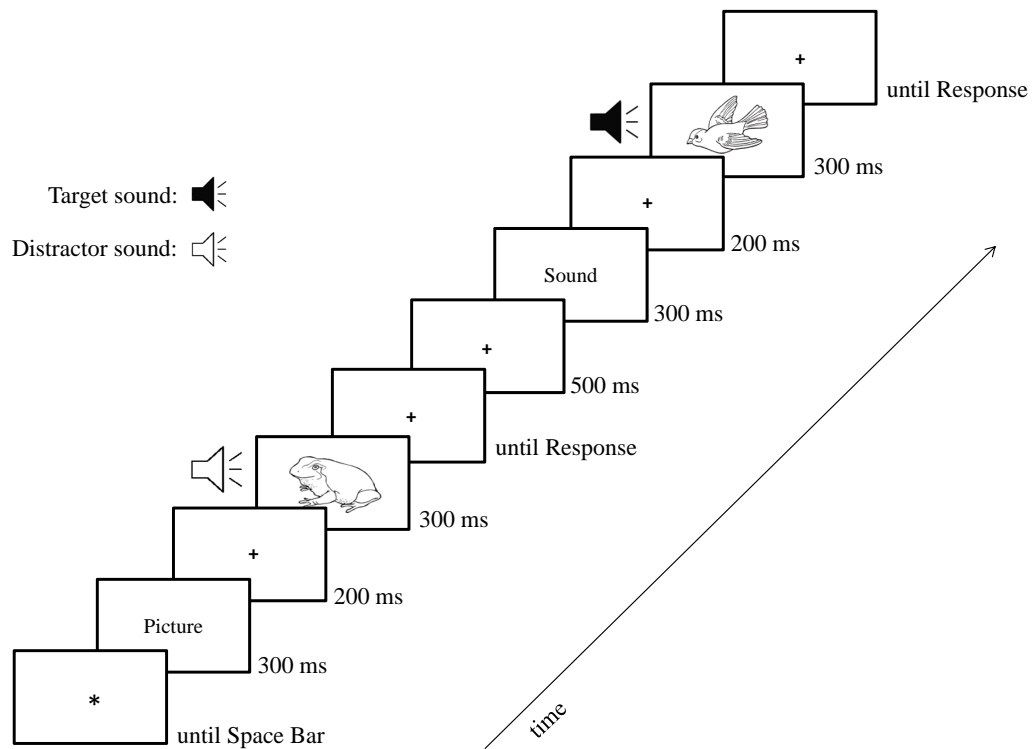


Figure 6.1.: Sequence of events in Experiment 3. The example depicts a prime-probe sequence with a visual prime target and an auditory probe target. Stimuli are not drawn to scale.

in the middle of the screen as a fixation marker. Participants were instructed

to look at this point throughout the experiment. Then the prime stimuli, one picture and one sound, were presented. Participants reacted to the prime target by pressing the corresponding key. After the response to the prime, the fixation marker reappeared for 500 ms, before another cue (the word 'picture' or 'sound') indicated in which modality the probe target would appear (300 ms). After further 200 ms during which the fixation marker was shown, the probe stimuli were presented. After the response to the probe, an asterisk appeared in the middle of the screen, signaling that the next trial could be started. In response repetition trials (RR) the same animal was presented as the target in the prime and the probe, respectively. In response change trials (RC) the target animal varied between prime and probe. Orthogonally to the response relation, the distractor relation was varied. In distractor repetition trials (DR) the animal presented as the distractor was the same on the prime and the probe whereas in distractor change trials (DC) different animals were presented as distractors on the prime and the probe. In turn, four different conditions were conducted: in RRDR trials, the same animals were presented as target and distractor on the prime and the probe. In RRDC trials the prime target was repeated as the probe target animal while the distractor animal changed from prime to probe. In RCDR trials, the probe target animal differed from the prime target animal while the prime distractor animal was repeated as the probe distractor. Finally, in RCDC trials, no animal was repeatedly presented on prime and probe. Modality repetition or switch between prime and probe was varied orthogonal to response and distractor relation and varied randomly from trial to trial. Furthermore, distractors were presented as a picture in half of the trials and as a sound in the other half. The target was always presented in the other modality, respectively. All stimuli were presented equally often as visual or auditory targets. Each animal was presented equally often as the probe target. In each trial, the remaining three animals were randomly assigned to the roles of probe distractor, prime target and prime distractor. According to the current trial type, stimuli were then changed to realize the particular condition; for example, in a RRDC trial, the prime target identity was changed to the probe target identity. An experimental session consisted of two practice blocks with 32 prime-probe sequences each, and an experimental block with 192 prime-probe sequences. The four trial types (RRDR, RRDC, RCDR, and RCDC) were realized in 48 trials each.

Table 6.1.: Mean reaction times (in ms) and mean error rates (in percentage) as a function of response and distractor relation and distractor modality repetition, Experiment 3.

	<i>Response Relation</i>	
	<i>Response Repetition (RR)</i>	<i>Response Change (RC)</i>
<i>Distractor modality repetition</i>		
Distractor Change (DC)	659 (2.2)	813 (6.3)
Distractor Repetition (DR)	587 (1.7)	825 (5.1)
Priming Effect ^a	72 [14]	−12 [17]
<i>Distractor modality change</i>		
Distractor Change (DC)	903 (9.0)	846 (6.4)
Distractor Repetition (DR)	845 (6.0)	873 (7.1)
Priming Effect ^a	58 [30]	−27 [20]

Note. ^a Priming Effect is computed as the difference between Distractor Change minus Distractor Repetition, standard error of the mean in squared brackets.

6.2.2. Results

Only trials with correct answers to the prime and the probe were considered. For each participant, four individual RT distributions were calculated, one for each condition of response and distractor repetition. Reaction times that were more than 1.5 interquartile ranges above the third quartile of the respective RT distribution (Tukey, 1977), and those below 200 ms were excluded from the analysis. Due to these constraints, 15.5 % of all trials were discarded (probe error rate was 5.5 %, prime error rate was 6.4 %). Mean RTs and error rates for probe displays are depicted in Table 6.1.

A 2 (response relation: repetition vs. change) \times 2 (distractor relation: repetition vs. change) \times 2 (distractor modality on prime and probe: repetition vs. change) ANOVA was conducted. All main effects reached significance, $F(1, 35) = 34.40, p < .001, \eta_p^2 = .50$, for response relation, $F(1, 35) = 7.73, p = .009, \eta_p^2 = .18$, for distractor relation, and $F(1, 35) = 111.23, p < .001, \eta_p^2 = .76$, for distractor modality relation. Reactions to repeated targets (740 ms) were faster than reactions to changed targets (839 ms) and reactions to picture-sound pairs

with repeated distractors (778 ms) were faster than reactions to picture-sound pairs with changed distractors (801 ms). Reactions were also faster if the target modality was repeated from prime to probe (721 ms) than if participants had to react to targets presented in different modalities on prime and probe (867 ms). Importantly, the interaction of response relation and distractor relation was significant, $F(1, 35) = 7.43, p = .010, \eta_p^2 = .18$, indicating that repeating the distractor facilitated responding on the probe in case of response repetition sequences, $F(1, 35) = 12.09, p = .001, \eta_p^2 = .26$, but not if a different response had to be given on the probe, $F(1, 35) = 1.47, p = .233, \eta_p^2 = .04$. The three-way interaction was not significant, $F < 1$, showing that repeating or switching the modality of the distractor from prime to probe did not influence the interaction of response relation and distractor relation. In two separate ANOVAs, the response relation \times distractor relation interaction reached significance for modality repetitions on prime and probe, $F(1, 35) = 8.71, p = .006, \eta_p^2 = .20$, and most importantly also for modality switches on prime and probe, $F(1, 35) = 4.31, p = .045, \eta_p^2 = .11$ (cf. Figure 6.2, left panel).

The same ANOVA on error rates revealed significant main effects for response relation, $F(1, 35) = 9.33, p = .004, \eta_p^2 = .21$, and for target modality relation, $F(1, 35) = 30.59, p < .001, \eta_p^2 = .47$; indicating fewer errors both for response repetition sequences and for sequences in which the modality of target and distractor was repeated. The interaction of target modality relation and response relation was significant, $F(1, 35) = 16.03, p < .001, \eta_p^2 = .31$, showing that participants made exceptionally few errors in response repetition conditions in which the prime and probe targets were presented in the same modality. In addition, the three-way interaction, $F(1, 35) = 4.65, p = .038, \eta_p^2 = .12$, was significant. Yet, note that this interaction was of the ordinal type, that is, the response repetition \times distractor repetition interaction was significant if the modality changed between prime and probe, $F(1, 35) = 4.62, p = .039, \eta_p^2 = .12$, (cf. Figure 6.2, right panel) but not if the distractor modality was the same on prime and probe, $F(1, 35) < 1$.

6.2.3. Discussion

With the current findings we replicated the standard effect of distractor-response bindings. Repeating the prime distractor on the probe facilitated responding for response repetition sequences, but not if a different response had to be executed in the probe (e.g., Frings et al., 2007; Rothermund et al., 2005). This finding

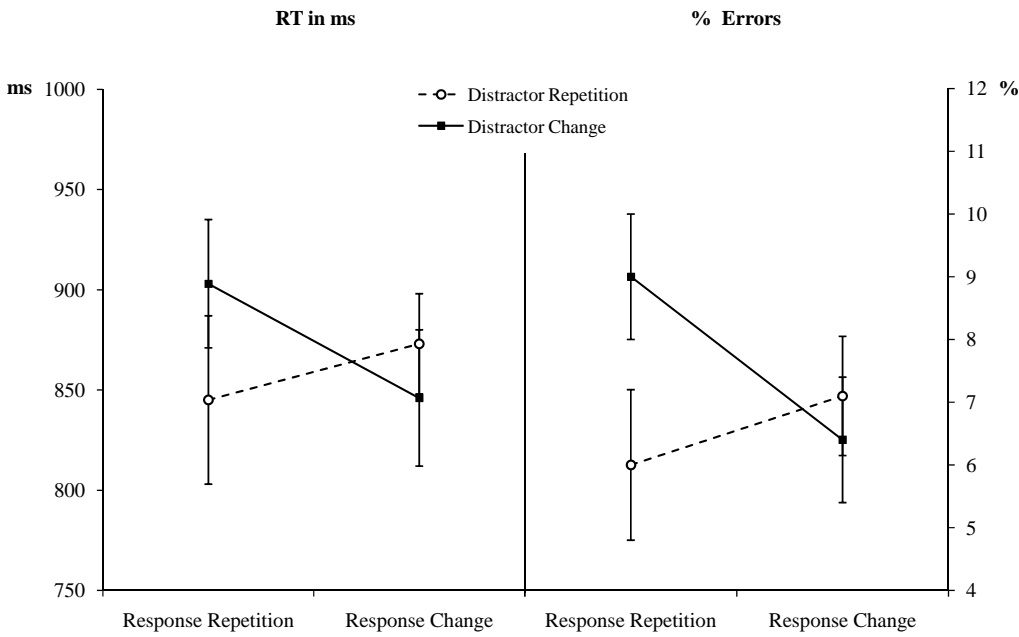


Figure 6.2.: Reaction times and error rates as a function of response repetition and distractor repetition only for trials with distractor modality switch from the prime to the probe in Experiment 3. Error bars depict the standard error of the mean.

emerged although the distractor stimuli were always presented in a different sensory modality than the targets, replicating previous findings reported by Zmigrod et al. (2009). That is, any stimulus that is perceived to occur together with the target stimulus close in time to the response can be integrated with the response and retrieve it later on, regardless of a modality match between target and distractor stimulus. Importantly, this episodic retrieval effect also emerged if the repeated distractor stimulus was presented in different modalities on the prime and the probe, indicating a conceptually mediated retrieval of event files.

The most important finding of Experiment 3 concerns the level of representation on which binding took place. In fact, in previous studies the binding of stimulus-response episodes referred to the integration of perceptual features with the target response. Here we observed that even if a repeated distractor switched the modality (e.g., the picture of a chicken on the prime, then the sound of a chicken on the probe) it will retrieve the last stimulus-response episode including the response to the target. In fact, we found evidence for distractor-response binding effects in the response times and the error data (cf. Figure 6.2). Thereby, our data suggest some kind of conceptually mediated response retrieval for distractor stimuli. This finding has some important indications. First, distractor stimuli on the prime must have been processed up to a conceptual level of representation. As outlined in the introduction to the present experiment, this assumption is plausible (Chen & Spence, 2010; Gordon & Irwin, 2000). This processing had to take place before an integration of the distractor with the response to the target. Second, the probe distractor must have been processed up to a conceptual level as well, and this conceptual representation of the probe distractor must have retrieved the response given to the prime target. Third, since participants were clearly instructed to ignore the distractor stimuli, the processing of distractor stimuli up to a conceptual representation must have functioned automatically.

Yet, it should be noted that in the task used here, participants were instructed to process the stimuli up to a conceptual level and in addition, distractors and targets were drawn from the same set of stimuli. Thus, it remains open to future research to analyze whether conceptual distractor-features are bound to responses when the distractor stimuli are completely irrelevant to the task.

In sum, the data of the Experiments 1, 2, and 3 underline the generality of the distractor-response binding mechanism. Effects of distractor-response binding have now been shown for the visual, the auditory, the tactile, and even across modalities. One can therefore speculate that distractor-response binding is a centrally controlled mechanism. These findings are also of great importance regarding

everyday actions. Most objects we encounter can be perceived via different modalities. If we look down a street, we can both see and hear an approaching car. In addition, multimodal perception is also relevant in human-machine interaction. For example, driver assistance systems of modern cars increasingly present warnings in various modalities. We will next turn to this special case of human-machine interaction and investigate whether distractor-response bindings might influence reactions to warnings given by a driver assistance system.

Part III.

Experiments Series 2: Application of Distractor-Response Binding

Stimulus Side

7.1. Relevance

Until now we reviewed evidence that distractor-response binding is a very stable and generalizable effect. It can influence responses to visual, auditory, and tactile stimuli, and it also holds for distractor locations and even across modalities. Given the stability of the effect it is highly probable that real life distractors are frequently integrated with our real life responses. However, all cited studies used rather artificial stimuli that are hardly ever encountered in other than laboratory contexts. In the following we aim to approach a real life situation to test whether distractor-response binding effects hold as well for rather complex stimuli.

In the Theoretical Background (2.2, *Action Control in Human-Machine Interaction*) we discussed human-machine interaction as one real life situation in which distractor-response binding effect might be highly relevant. Especially in the interaction with a car, timely and correct responses can be crucial. In addition, the task of a driver in road traffic is rather demanding. A driver monitors the road and sidewalks, steers the car, responds to traffic signs or changing traffic, monitors the instruments of the car, checks the rear mirrors and possibly talks to a passenger. To facilitate fast and correct reactions by the driver, increasingly more technology has been developed to assist drivers with their different tasks. Additionally, research has been aiming to improve drivers' perception and responding by optimizing information presentation of displays (e.g., Eriksson et al., 2008).

Resulting from this development, various warning signals can prompt the driver

about critical events immediately surrounding the car. Drivers can be informed for example, whether their car is changing lanes, whether the distance to the car ahead is sufficient, or whether another car is located within the blind spot. Moreover, with car-to-car communication even information concerning situations that have yet to be approached can be presented to a driver. That is, the car we are driving might receive messages about potential dangers ahead, from another car that is traveling some distance in front of us. For example, if the car ahead arrives at the end of a traffic jam, it sends a message to the following cars, warning of this danger.

Currently, the project ‘simTD’ (Safe and Intelligent Mobility – Testfield Germany; <http://www.simtd.de/>), which started in 2008, is dedicated to investigate so called ‘car-to-X communication’ and its possible applications in mobility. That is, information is not only to be transmitted between cars in order to assist drivers, but also between car and infrastructure. Examples of infrastructure are traffic light circuits or road maps providing information like traffic light changes or the right of way at an upcoming junction. As part of this project, an advanced driver assistance system is being designed by the German Research Center for Artificial Intelligence (DFKI) that implements visual warning displays. On the one hand, these displays are supposed to prompt the driver as to which response is required: as long as the critical situation is being approached, the display color remains the same. As soon as the situation changes to being critical, the display color also changes to prompt a braking response. On the other hand, the displays include pictographic information about the approached situation. Figure 7.1 shows displays, similar to those developed in the project simTD. The examples include both warning specification and color codes. The same displays were used in Experiment 4 through 7.

For example, if a person is driving toward an intersection, the system might receive the information that the driver will have to yield the right of way, and present an according symbol 300 m in advance, along with the color indicating to the driver to be attentive. A moment later, the car reaches the intersection and the driver might actually have to brake. In that case, the pictographic information presented by the system is the same as in the first warning. Yet, the color now prompts a braking response. Since the driver responds to the color change, the pictographic information might be ignored and thus resemble a distractor stimulus. If distractor-response bindings can occur with such complex stimuli, the repeated presentation of the symbol might retrieve the response from the first warning and hamper a different (i.e., the braking) response. Evidence indicating



Figure 7.1.: Examples for color coded warning displays. The same displays were used as stimuli in Experiments 4 through 7.

distractor-response binding effects for as complex stimuli as warning displays, would therefore be a first indication that this mechanism should be considered in the design of driver assistance systems.

To investigate whether distractor-response bindings are possible with relatively complex stimuli resembling local danger warnings, the paradigm applied in Experiments 1 through 3 was implemented with a new sort of stimuli (see figure 7.1). Participants always responded to rectangular displays that resembled local danger warnings. More specifically, they responded with a left or right keypress to the color at the sides, and ignored the icons in the middle of these displays. That is, in addition to being relatively complex, the distractor stimuli in Experiment 4 were always of a different stimulus class than the targets and were thus always response irrelevant. The two factors response relation (repetition vs. change) and distractor relation (repetition vs. change) were varied orthogonally. Four different symbols that can be encountered on traffic signs were used as distractors to investigate whether distractor-response bindings are possible with this kind of stimuli.

7.2. Experiment 4

7.2.1. Method

Participants. Thirty students (24 women) from Saarland University participated in the experiment; they were paid 4 € for participation. The median age was 23 years with a range from 19 to 37 years. None of the participants reported any impairment in color vision.

Design. Essentially, the design comprised two within-subjects factors, namely response relation (repetition vs. change) and distractor relation (repetition vs. change).

Materials. The experiment was conducted using the E-prime software (version 1.1). Instructions and the fixation marker were shown in white on black background on a standard cathode-ray tube screen (refresh rate was 75 Hz). The viewing distance was approximately 60 cm. The stimuli were rectangular displays with a horizontal visual angle of 7.4° and a vertical visual angle of 4.8°. Four different icons could be presented in the center of the displays: warning triangle, traffic jam warning, crash warning, or snow warning. The sides of the displays could be presented in red or in blue, resulting in eight different stimuli.

Procedure. Participants were tested individually in soundproof chambers. Instructions were given on the screen and summarized by the experimenter. Participants were instructed to place the index fingers of both hands on the keys D and K of the computer keyboard. Half of the participants responded to the blue stimuli by pressing the key D and to the red stimuli by pressing the key K, while the other half received the opposite mapping. Participants' task was to identify the color of the warning display by pressing the corresponding key as quickly and correctly as possible. The icons in the center of the displays served as distractors and had to be ignored. A single prime-probe sequence included the following events (cf. Figure 7.2): the participant started the sequence by pressing the space bar and a plus sign appeared in the center of the screen as a fixation marker.

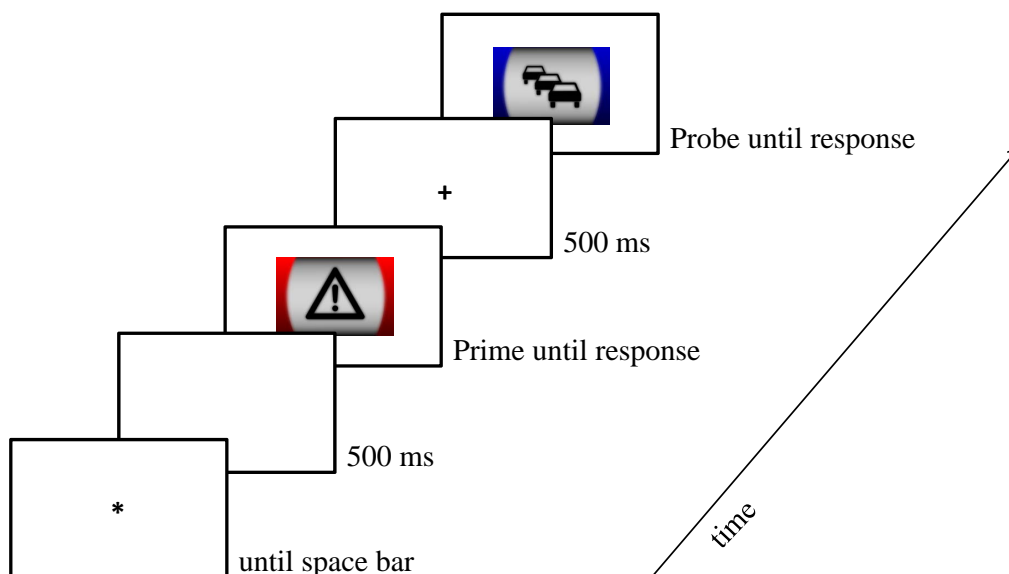


Figure 7.2.: Sequence of events in Experiment 4 and 5. Participants reacted to the color of the display sides by pressing a corresponding key. Stimuli are not drawn to scale.

After 500 ms the plus sign was exchanged for the prime warning display, which remained on the screen until the participant responded by pressing the key corresponding to the color. In case of an incorrect response, feedback appeared, reminding the participant to react as quickly as possible without making errors. Then the fixation marker reappeared for 500 ms followed by the probe warning

display. Participants reacted to the probe color by pressing the according key. As on the prime, if the response was incorrect, feedback was presented, reminding the participant to react as quickly as possible without making errors. Finally an asterisk appeared in the center of the screen, signaling to the subject that the next trial could be started.

In response repetition trials (RR) the stimulus had the same color on the prime and the probe, respectively. In response change trials (RC) the stimulus color varied between prime and probe. Orthogonally to the response relation, the distractor relation was varied. In distractor repetition trials (DR) the icon presented in the center of the display was the same on the prime and the probe whereas in distractor change trials (DC), different icons were presented as the distractor on the prime and the probe. With the orthogonal variation of response repetition and distractor repetition, 4 different conditions resulted: in RRDR trials, the prime color and the prime icon were repeated on the probe. In RRDC trials, the prime color was again presented on the probe while the icon changed from prime to probe. In RCDR trials, the probe color differed from the prime color while the prime icon was repeated as the probe distractor. Finally, in RCDC trials, neither color nor icon of the prime was again presented on the probe. The two different target colors and four different distractor icons combined to eight possible stimuli. Each of the eight stimuli was presented ten times as the probe stimulus in every one of the 4 conditions (RRDR, RRDC, RCDR, RCDC). Prime target color was assigned according to the randomly chosen condition. The distractor icon was then randomly assigned with the constraint that prime and probe icons had to have the same identity in distractor repetition trials and different identities in distractor change trials. Due to this procedure, 320 trials resulted. During the experimental block, every subject saw all of the 320 trials in a random order. An experimental session consisted of a practice block with 32 prime-probe sequences and one experimental block. The four trial types (RRDR, RRDC, RCDR, and RCDC) were realized in 80 trials each.

7.2.2. Results

Only trials with correct answers to the prime and the probe were considered. Reaction times that were more than 1.5 interquartile ranges above the third quartile of the RT distribution of the whole sample (Tukey, 1977), and those that were shorter than 200 ms were excluded from the analysis. Due to these constraints, 10.40 % of all trials were discarded (probe error rate was 2.76 %, prime error rate

Table 7.1.: Mean reaction times (in ms) and mean error rates (in percentage) as a function of response relation and distractor relation, Experiment 4.

	<i>Response Relation</i>	
	<i>Response Repetition (RR)</i>	<i>Response Change (RC)</i>
<i>Distractor Relation</i>		
Distractor Change (DC)	389 (2.4)	428 (3.0)
Distractor Repetition (DR)	376 (1.5)	433 (4.2)
Priming Effect ^a	+13 [2]	−5 [3]

Note. ^a Priming Effect is computed as the difference between Distractor Change minus Distractor Repetition, standard error of the mean in squared brackets.

was 4.10 %). Mean RTs and error rates for probe displays are depicted in Table 7.1.

In a 2 (response relation: repetition vs. change) \times 2 (distractor relation: repetition vs. change) ANOVA with Pillai's trace as the criterion, both main effects were significant, $F(1, 29) = 54.46, p < .001, \eta_p^2 = .65$, for response relation and $F(1, 26) = 7.87, p = .009, \eta_p^2 = .21$, for distractor relation, respectively. Responses to repeated stimulus color (386 ms) were faster than responses to changed stimulus color (430 ms) and responses to displays with repeated icons (405 ms) were faster than responses to displays with changed icons (411 ms). Importantly, the interaction of response relation and distractor relation was also significant, $F(1, 29) = 19.91, p < .001, \eta_p^2 = .41$, indicating that a repetition of the distractor led to quicker response times if the response had to be repeated from prime to probe, $t_{RR}(29) = 5.91, p < .001$, but slightly delayed response times if the response was changed from prime to probe, $t_{RC}(29) = -1.75, p = .045$ (one tailed).

A ANOVA on error rates, using the same design, revealed mainly along the same lines. A significant main effect of response relation was found, $F(1, 29) = 14.06, p = .001, \eta_p^2 = .33$, indicating less errors with response repetition than with response change. The main effect of distractor relation did not reach significance, $F(1, 29) < 1$. Importantly, the interaction of response relation and distractor relation was again significant, $F(1, 29) = 12.38, p = .001, \eta_p^2 = .30$, indicating effects of distractor-response bindings in the error rates as well.

7.2.3. Discussion

The results of Experiment 4 clearly show that even relatively complex distractor stimuli (i.e., icons) can be integrated with, and subsequently retrieve a response. A repeated presentation of a distractor icon led to faster response times if the response had to be repeated. In contrast, response times in trials with repeated distractors were slightly slower, if the response had to be changed from prime to probe.

This result is the first evidence that distractor-response bindings might be important for the design of displays that are used in driver assistance systems: regarding the integration of rather complex displays into distractor-response bindings, it seems to be possible that distractor-response bindings influence reaction times to local danger warnings. However, distractor-response bindings are likely to influence responses of drivers only if they are possible between relatively complex stimuli and responses that are likely to be required while driving a car. That is, in a next step we investigated whether more natural reactions that are likely to occur in response to a local danger warning, can become integrated with and be retrieved by a repeated presentation of a distractor stimulus.

Response Side

8.1. Relevance

In Experiment 4 participants responded to the targets by pressing two different keys on a standard keyboard with their index fingers. Yet, in everyday situations we obviously carry out responses with other effectors as well. Specifically while driving a car, we often have to react by pressing a pedal with one of our feet. Furthermore, in a driving context a driver assistance system will possibly give advance warnings that prompt the driver to be attentive, but also to withhold a braking response for the moment. For example, if a driver approaches an intersection at which he will encounter a YIELD sign, the system introduced earlier will give a pre-warning about 300 m before the intersection is reached. At this point the driver still has to restrain from braking (e.g., to avoid a rear-end collision with the driver of the following car, who will not expect the car ahead to brake at this point in time). At this point distractor-response binding might occur, integrating the response restraint, the color, and the icon of the pre-warning. If the driver actually has to give way at the intersection, the assistance system will then present the same warning (i.e., icon), this time prompting a braking response, indicated by the color of the display. That is, in the described scenario the response changes from a response restraint to a foot pedal press, while the possibly ignored icon is repeated. If distractor-response binding did occur at the pre-warning, a slow or incorrect response at the intersection might result.

In order to investigate whether distractor-response bindings might be relevant

in such a situation, it is first important to test whether foot responses can become integrated with and be retrieved by distractor stimuli. Therefore, in Experiment 5 we implemented the same design as in Experiment 4 and used pedal presses with the left and right foot as responses. Further, the effect of distractor-response bindings becomes even more relevant for reactions to local danger warnings, if a non-response can become integrated with a distractor as well. Thus, Experiment 6 was a replication of Experiment 5 in which we exchanged one of the foot responses with a response restraintment. That is, responses in Experiment 6 were to either press a foot pedal or to withhold the response.

8.2. Experiment 5

8.2.1. Methods

Participants. Twenty nine students (23 women) from Saarland University participated in the experiment; they were paid 5 € for participation. The median age was 22 years with a range from 19 to 30 years. None of the participants reported any impairment in color vision.

Design. Essentially, the design comprised two within-subjects factors, namely response relation (repetition vs. change) and distractor relation (repetition vs. change).

Materials and Procedure. Stimuli and procedure were the same as in Experiment 4 with the following exceptions. The sides of the four different stimuli could be presented in red, yellow, green, or blue, resulting in sixteen different stimuli. Participants were tested individually. Two foot pedals (Psychology Software Tools, Inc.) were placed in a comfortable position on the floor in front of the participants. The foot pedals were connected to the computer via a serial response box (PST, Inc.), providing a zero ms debounce period. Participants' task was to identify the color category of the warning display by pressing the corresponding foot pedal as quickly as possible without making errors. Half of the participants responded to the blue and the green stimuli by pressing the left pedal and to the red and the yellow stimuli by pressing the right pedal, while the other half received the opposite mapping. As before, the icons in the center of the displays served as distractors and had to be ignored. A single prime-probe sequence included the following events (cf. Figure 7.2): participants started the sequence by pressing the space bar and a plus sign appeared in the center of the screen as a fixation marker.

After 500 ms the plus sign was exchanged for the prime warning display, which remained on the screen until the participant responded by pressing the foot pedal corresponding to the color. In case of an incorrect response, feedback appeared, reminding the participant to respond as quickly as possible without making errors. Then the fixation marker reappeared for 500 ms followed by the probe warning display. Participants responded to the probe color by pressing the according foot pedal. As on the prime, if the response was incorrect, feedback was presented, reminding the participant to respond as quickly as possible without making errors. Finally an asterisk appeared in the center of the screen, signaling to the subject that the next trial could be started.

In response repetition trials (RR) the prime and probe stimuli were of the same color category (blue/green or red/yellow respectively) and thus, the required response was the same on the prime and the probe. In response change trials (RC) the category of the stimulus color varied between prime and probe; accordingly, the required response on the probe differed from that on the prime. Orthogonally to the response relation, the distractor relation was varied. In distractor repetition trials (DR) the icon presented in the center of the display was the same on the prime and the probe whereas in distractor change trials (DC), different icons were presented as the distractor on the prime and the probe. In turn, four different conditions were conducted: in RRDR trials, the prime color category and the prime icon were repeated on the probe. In RRDC trials, the prime color category was again presented on the probe while the icon changed from prime to probe. In RCDR trials, the probe color category differed from the prime color category while the prime icon was repeated as the probe distractor. Finally, in RCDC trials, prime and probe color were of different categories and the icon changed from prime to probe.

The four different target colors and four different distractor icons combined to sixteen possible stimuli. Every one of the four conditions (RRDR, RRDC, RCDR, RCDC) was presented six times with each of the sixteen stimuli on the probe. Due to this procedure, 384 trials resulted. Response repetition could either mean a repetition of the same color (e.g. prime: red – probe: red) or a repetition of the same color category, without a repetition of the same color (e.g. prime: yellow – probe: red). For half of the trials a required response repetition was indicated by the same color on the prime and the probe and for the other half, a required response repetition was indicated by different colors from the same color category on the prime and the probe. During the experimental block, every subject saw all of the 384 trials in a random order. An experimental session consisted of a

practice block with 32 prime-probe sequences and one experimental block. The four trial types (RRDR, RRDC, RCDR, and RCDC) were realized in 96 trials each.

8.2.2. Results

According to the same criteria as in Experiment 4, 9.28 % of all trials were discarded (probe error rate was 3.18 %, prime error rate was 2.57 %). Mean RTs and error rates for probe displays are depicted in Table 8.1.

Table 8.1.: Mean reaction times (in ms) and mean error rates (in percentage) as a function of response relation and distractor relation, Experiment 5.

	<i>Response Relation</i>	
	<i>Response Repetition (RR)</i>	<i>Response Change (RC)</i>
<i>Distractor Relation</i>		
Distractor Change (DC)	538 (3.5)	593 (2.7)
Distractor Repetition (DR)	531 (2.6)	601 (4.0)
Priming Effect ^a	+7 [4]	−8 [3]

Note. ^a Priming Effect is computed as the difference between Distractor Change minus Distractor Repetition, standard error of the mean in squared brackets.

In a 2 (response relation: repetition vs. change) \times 2 (distractor relation: repetition vs. change) ANOVA with Pillai's trace as the criterion, the main effect of response relation reached significance, $F(1, 28) = 90.52, p < .001, \eta_p^2 = .76$. Response repetitions (534 ms) led to faster response times on the probe than response changes (597 ms). The main effect of distractor relation was not significant. Importantly, the interaction of response relation and distractor relation was also significant, $F(1, 28) = 8.83, p = .006, \eta_p^2 = .24$, indicating that a repetition of the distractor lead to marginally faster response times if the response had to be repeated from prime to probe, $t_{RR}(28) = 1.60, p = .06$ (one tailed), but to delayed response times if the response had to be changed from prime to probe, $t_{RC}(28) = -3.23, p = .003$.

The same ANOVA on error rates revealed no significant main effects. However, the interaction of response relation and distractor relation was again significant, $F(1, 28) = 9.02, p = .006, \eta_p^2 = .24$, indicating less errors for repeated distractors

if the response had to be repeated, but more errors for repeated distractors if the response had to be changed from prime to probe.

8.2.3. Discussion

We found a clear effect of distractor-response bindings for foot responses both in response times and in error rates in Experiment 5. This is an indication that a foot response can become integrated with a simultaneously presented distractor stimulus and further, that a foot response can also be retrieved by a subsequent presentation of the same distractor stimulus. These results can be interpreted as a first indication that more natural responses, required in a driving situation might also be influenced by distractor-response binding effects.

8.3. Experiment 6

The responses required in Experiment 5 (i.e., foot responses with the two feet) had a close resemblance to responses that are frequently required while driving: pressing a pedal with one of the feet is oftentimes the adequate response to a local danger warning. However, a warning may sometimes notify the driver that a response has to be restrained for the moment. Thus, the sixth Experiment was designed to investigate if distractor-response bindings still reveal if the response set includes retention of the response (i.e., the response ‘not to press the foot pedal’).

Two paradigms that are frequently used to investigate response inhibition are the go/no-go paradigm and the stop-signal paradigm (Verbruggen & Logan, 2008a). In both paradigms participants see a series of different stimuli to which they either respond or withhold a response. In the go/no-go paradigm (Donders, 1969), participants are instructed to respond if one stimulus (i.e., the go-stimulus) is presented, and to withhold their response if another stimulus (i.e., the no-go-stimulus) is presented. Typically, instructions about the mapping of stimuli to go and no-go responses, respectively, are given at the beginning of the experimental session and remain the same throughout the session. Thus, stimulus-no-go mapping is typically consistent and a stimulus can become associated with the stop-response. In contrast, in the stop signal paradigm (Lappin & Eriksen, 1966; Logan & Cowan, 1984; for a review see, Verbruggen & Logan, 2008b), participants perform a go task, responding to each presented stimulus. This is typically a response selection

task, such as responding to the identity of a target. Occasionally a stop signal is presented, prompting participants to withhold their response to the following target. The stop-signal can be presented at a variable delay before target presentation, shorter delays leading to a more difficult task of stopping the response (Verbruggen & Logan, 2009, 2008a). Thus, an important difference between the stop-signal and the go/no-go paradigm is that stopping can be required at the presentation of different stimuli in the stop-signal paradigm, but is usually required at the presentation of only one specific stimulus in the go/no-go paradigm (Verbruggen & Logan, 2008a). In addition, participants in a stop-signal paradigm always prepare a certain response at presentation of a regular stimulus and are about to carry it out when the stop signal is presented. Thus, the response process is almost complete when the participants have to hold it back and oftentimes they do not succeed in stopping. In contrast, in a go/no-go paradigm ideally no response is prepared at presentation of the no-go stimulus.

Mostly if a pre-warning is shown, the driver will not have initiated the braking response and thus does not need to inhibit or ‘stop’ it. Moreover, the required reaction of the driver on such occasions is not to respond yet. That is, the color of a pre-warning display always indicates the no-go response. This situation is better resembled by the go/no-go paradigm than by the stop-signal paradigm. We therefore used a go/no-go paradigm to test whether withholding a response can also become a part of distractor-response bindings.

In Experiment 6, participants did no longer respond with their different feet but completed a go/no-go task with their right foot, responding to one stimulus category and withholding a response to another stimulus category.

8.3.1. Methods

Participants. Sixty students (39 women) from Saarland University participated in the experiment; they were paid 5 € for participation. The median age was 23 years with a range from 17 to 29 years. None of the participants reported impairment in color vision. The data of one participant were discarded due to an outlier error rate (21.56 %) with respect to the error rate of the sample (6.6 %; Tukey, 1977).

Design. Essentially, the design comprised two within-subjects factors, namely response relation (repetition vs. change) and distractor relation (repetition vs. change).

Materials and Procedure. Materials and procedure were the same as in Experi-

ment 5 with the following exceptions. One foot pedal was placed in a comfortable position on the floor in front of the participants. Participants were instructed to place their right foot above the response pedal. Their task was to identify the color of the warning display and, if appropriate, to press the foot pedal as quickly as possible. Half of the participants responded to the blue and the green stimuli by pressing the pedal and restrained from reacting in response to the red and the yellow stimuli, while the other half received the opposite mapping. As before, the icons in the center of the displays served as distractors and had to be ignored. A single prime-probe sequence included the following events (cf. Figure 8.1): participants started the sequence by pressing the space bar and a plus sign appeared in the center of the screen as a fixation marker.

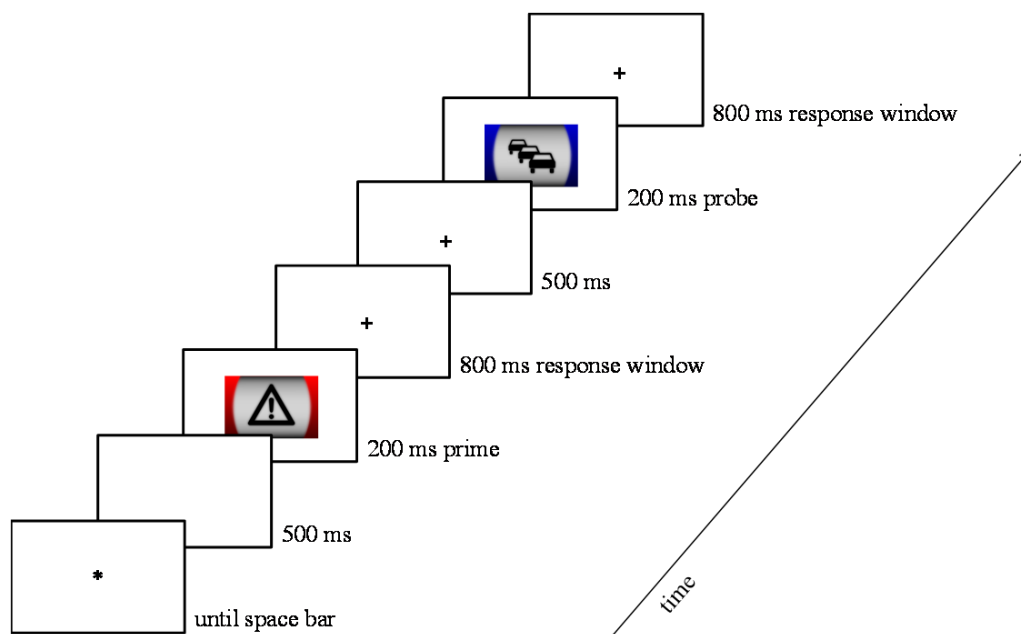


Figure 8.1.: Sequence of events in Experiment 6. Participants responded to the color category of the display sides by pressing a corresponding foot pedal or withholding a pedal press. Stimuli are not drawn to scale.

After 500 ms the plus sign was exchanged for the prime warning display, which remained on the screen for 200 ms. The participant had to respond within 1000 ms after prime onset. Depending on the color, the correct response was to press the foot pedal or not to respond within this time window. In case of an incorrect

response, feedback appeared, reminding the participant to react as quickly and correctly as possible. Then the fixation marker reappeared for 500 ms followed by the probe warning display, which was presented for 200 ms. Participants responded to the probe color within 1000 ms after probe onset by pressing the foot pedal or restraining a reaction. As on the prime, if the response was incorrect, feedback was presented, reminding the participant to respond as quickly and correctly as possible. Finally an asterisk appeared in the center of the screen, signaling to the subject that the next trial could be started.

The four possible conditions were again RRDR (response repetition and distractor repetition), RRDC (response repetition and distractor change), RCDR (response change and distractor repetition), and RCDC (response change and distractor change). Response repetition either meant restraining a foot pedal press to both the prime and the probe display (i.e., no-go prime and no-go probe), or pressing the foot pedal in response to both the prime and the probe display (i.e., go prime and go probe). Response change either meant to press the foot pedal in response to the probe display after restraining a pedal press in response to the prime display (i.e., no-go prime and go probe), or to restrain a pedal press in response to the probe display after pressing the foot pedal in response to the prime display (i.e., go prime and no-go probe).

Every participant worked through 384 randomly presented trials during the experimental block. The four trial types (RRDR, RRDC, RCDR, and RCDC) were realized in 96 trials each. An experimental session consisted of a practice block with 32 prime-probe sequences and one experimental block.

8.3.2. Results

Only trials with correct answers to the prime and the probe were considered. Reaction times that were more than 1.5 interquartile ranges above the third quartile of the response time distribution of the sample (Tukey, 1977), and those that were shorter than 200 ms were excluded from the analysis. Due to these constraints, 5.86 % of all trials were discarded (probe error rate was 2.53 %, prime error rate was 1.49 %). Mean RTs and error rates for probe displays are depicted in Table 8.2.

Go probes. In a 2 (response relation: repetition vs. change) \times 2 (distractor relation: repetition vs. change) ANOVA on RTs with Pillai's trace as the criterion, the main effect of response relation was significant, $F(1, 58) = 94.32, p < .001, \eta_p^2 = .62$, whereas the main effect of distractor relation failed to reach signifi-

Table 8.2.: Mean reaction times (in ms; only for go probes) and mean error rates (in percentage) as a function of response relation and distractor relation, Experiment 6.

	<i>Response Relation</i>	
	<i>Response Repetition (RR)</i>	<i>Response Change (RC)</i>
<i>go probes</i>		
Distractor Change (DC)	386 (0.6)	418 (0.6)
Distractor Repetition (DR)	382 (0.7)	419 (0.5)
Priming Effect ^a	+4 [2]	−1 [2]
<i>no-go probes</i>		
Distractor Change (DC)	2.2	3.4
Distractor Repetition (DR)	2.2	4.6
Priming Effect ^a	0 [0.3]	−1.2 [0.5]

Note. ^a Priming Effect is computed as the difference between Distractor Change minus Distractor Repetition, standard error of the mean in squared brackets.

cance, $F(1, 58) = 2.12, p = .151, \eta_p^2 = .04$. Reaction times for repeated responses (384 ms) were faster than reaction times for changed responses (419 ms). Importantly, the interaction of response relation and distractor relation was also significant, $F(1, 58) = 4.62, p = .036, \eta_p^2 = .07$, indicating that a repetition of the distractor lead to faster response times only if the response had to be repeated from prime to probe (i.e., a foot pedal press was required both in response to the prime and in response to the probe, $t_{RR}[58] = 2.82, p = .007$), but not if the response had to be changed (i.e. the foot pedal press had to be restrained on the prime but carried out on the probe, $t_{RC}[58] = -0.64, p = .522$). A ANOVA on error rates, using the same design revealed no significant results, all $F_s < 1$.

No-go probes. In a 2 (response relation: repetition vs. change) \times 2 (distractor relation: repetition vs. change) ANOVA on error rates with Pillai's trace as the criterion, the main effect of response relation was significant, $F(1, 58) = 19.91, p < .001, \eta_p^2 = .26$, and the main effect of distractor relation was marginally significant, $F(1, 58) = 4.36, p = .041, \eta_p^2 = .07$. Error rates for repeated responses (2.2 %; i.e., a foot pedal press had to be restrained both in response to the prime and in response to the probe) were smaller than error rates for changed responses

(4.0 %; i.e., a foot pedal press had to be restrained on the probe after it had been required in response to the prime) and error rates for reactions to displays with repeated distractors (3.4 %) were higher than error rates for reactions to displays with changed distractors (2.8 %). Importantly, the interaction of response relation and distractor relation was also significant, $F(1, 58) = 4.825, p = .032, \eta_p^2 = .08$, indicating that distractor repetition lead to more errors, only if the response had to be changed (i.e. the foot pedal press had to be carried out on the prime but restrained on the probe, $t_{RC}[58] = -2.50, p = .015$), but not if the response had to be repeated (i.e. the foot pedal press had to be restrained both on the prime and on the probe, $t_{RR}[58] = -0.24, p = .811$).

8.3.3. Discussion

The results of Experiment 6 reveal that even if one of the responses is exchanged for retention of responding, the effect of distractor-response binding can be found. It should be noted that probe response times might indicate that no event file was created if no response was required on the prime. On response change trials, on which participants did not respond on the prime and then responded on the probe, responses were equally fast for distractor changes and distractor repetitions. However, since the interaction of response relation and distractor relation was significant, it is also possible that both an integration of ‘response’ and distractor and a distractor inhibition took place on no-go primes. In that case, the fact that no difference between distractor change and distractor repetition trials was found for response change trials might be due to both effects working in parallel (Giesen et al., in press). If the distractor is repeated, distractor inhibition would facilitate responding while the retrieval of the prime ‘response’ would hamper responding as compared to trials in which the distractor changed from prime to probe. Yet, error percentages on no-go probes were the same for distractor change and distractor repetition if the response was repeated. This indicates no facilitation due to a repeated distractor if the response had to be restrained both on the prime and the probe. In contrast, distractor repetition impeded response restraintment on the probe if a response was executed on the prime. That is, it is likely that the reaction to withhold a response was not integrated with the distractor stimulus. Nonetheless, for the driver assistance system we described earlier, the current results are exceedingly relevant, at any rate. An ignored part of a presented display can become integrated with a response and a subsequent presentation of the same distractor retrieves that response even in situations in which no response at all is

required. For example, this might lead to incorrect braking responses in situations in which no such response is expected by a following driver. In turn a rear-end collision might result. Lee et al. (2002) mentions that rear-end collisions account for 28 % of all crashes. With such a high percentage, design options should be implemented that might help prevent rear-end collision and all factors contributing to even more rear-end collisions should be avoided. The present results indicate that distractor-response binding might be one factor that has to be taken into account.

Participants always responded to the category of the stimulus color, pressing one foot pedal in response to one category of colors (e.g., blue and green stimuli) and the other foot pedal in response to the other color category (e.g., red and yellow stimuli) in Experiment 5, or pressed a foot pedal to one and withheld a response to the other category in Experiment 6. Thus in the current experiments, target color could change independently of a response change. Therefore the results also provide additional evidence that distractor-response bindings do not hinge on a complete repetition of the stimulus display.

In sum the current results might be specifically relevant for the design of driver assistance systems. Together the results of Experiments 4 through 6 indicate that distractor-response bindings are likely to influence response times of drivers. On the one hand more complex distractor stimuli, which occur in everyday life (i.e., icons frequently encountered in car displays), can be integrated with a response and on a subsequent presentation facilitate the same response. On the other hand, responses more frequently required in a driving task, and carried out by different effectors than the fingers (i.e., foot pedal presses), can be integrated with distractor stimuli and are then facilitated by a repeated presentation of the same distractor. Therefore, it seems possible that effects of distractor-response binding can influence reaction times of drivers. Yet, in a realistic driving situation, one has to complete more than one task at once. That is, it can only be assumed that distractor-response binding effects influence drivers responses, if they also hold for dual task situations.

Driving Context: Dual Task

9.1. Relevance

Most people would agree that they can complete more than one task at once. For example, many of us have driven a car and had a conversation at the same time. Yet, as soon as one of the tasks becomes more demanding, performance in the other task diminishes: as we approach a busy junction, we probably pause our conversation until we have passed the demanding traffic situation. Three influential explanations why dual task performance is problematic are capacity sharing, bottlenecks, and cross talk (see Theoretical Background 2.2.3, *Dual Task Performance*). Dual task performance has typically been studied with a speeded response task completed simultaneously with a second task, that can assume various forms. Examples are a second speeded response task, letter matching, concurrent memory tasks, continuous motor responses, perceptual judgment tasks and continuous tracking tasks.

Experiments 4 through 6 provide evidence that distractor-response bindings are likely to influence performance in natural situations, such as driving. However, to determine whether distractor-response bindings can in fact influence drivers' reaction times or error rates, it is important to investigate, whether distractor-response bindings can also reveal in a dual task situation. It can be argued that driving is a continuous task including (among other requirements) continuous scanning of the environment. Thus, for a first approximation of a task with similar demands as driving, we used a continuous tracking task. If the car is equipped with a driver

assistance system, another requirement while driving is to adequately respond to occasional warnings. This requirement can be resembled by a speeded response, such as in Experiments 4 through 6. Therefore, in Experiment 7, participants completed two tasks simultaneously. A continuous tracking task resembled continuous driving requirements while speeded responses to the same displays as used in Experiment 4 through 6 simulated responses to local danger warnings. Mainly two different modes of display presentation have been discussed in the literature: head-up displays (HUD) and head-down displays (HDD) (see Theoretical Background 2.2.2, *Visual Warnings in Human-Machine Interaction*). Head-up displays are increasingly used in current driver assistance systems. In fact, some studies found that head-up displays have a positive influence on driver performance (e.g., Sojourner & Antin, 1990). Yet, other research indicates that optic clutter or visual accommodation might be problematic with head-up displays, and further that head-down displays might prevent certain driving errors (see Edgar, 2007; Foyle et al., 1993). Regarding these mixed results, it is not entirely clear which setup results in better driver performance. The influence distractor-response bindings might have on performance with head-up and head-down displays, might contribute to solving this problem. Thus, another aim of Experiment 7 was to investigate whether the setup of warning display presentation (head-up display vs. head-down display) can influence possible effects of distractor-response binding. In Experiment 7a both tasks were presented in the same spatial location, resembling the layout of a HUD. In Experiment 7b the tasks were spatially distributed (i.e., one presented above the other), resembling the layout of HDDs.

9.2. Experiments 7a and 7b

9.2.1. Method

Participants. A total of nineteen students (8 women) from Saarland University participated in Experiment 7a; they were paid 8 € for participation. The median age was 24 years with a range from 20 to 30 years. The data of one participant were excluded due to an extreme number of missed trials (110 of 256). Another sample of nineteen students (14 women) from Saarland University participated in Experiment 7b; they were paid 8 € for participation. The median age was 23 years with a range from 19 to 28 years. The data of one participant were excluded

due to an extreme number of missed trials (94 of 256). None of the participants reported impairment in color vision.

Design. For both experiments, the design essentially comprised two within-subjects factors, namely response relation (repetition vs. change) and distractor relation (repetition vs. change).

Materials and Procedure. Throughout the experiments, a black rectangle (horizontal va.: 11.61° , vertical va.: 7.25°) was presented on the white screen. The continuous task was adapted from a paradigm used in inattention blindness research and included the tracking of two white letters ('o') which moved within the black rectangle. Both letters never left the rectangle: each time an 'o' made contact with one of the rectangle's sides, it bounced off the side, changing direction. Participants were instructed to count these bounces. Every 30 seconds a window appeared prompting the participant to report the number of bounces counted since the last prompt. For the speeded response task, the same stimuli and response mapping as in Experiment 5 were used. The displays had a horizontal visual angle of 4.30° and a vertical visual angle of 2.86° . Display sides could appear in four different colors and four different icons could be presented in the center of the displays, resulting in sixteen different stimuli. Participants responded to the color category of the warning displays via two foot pedals. A white (Experiment 7a) or black (Experiment 7b) plus sign was presented at the center of the screen. Participants were instructed to fixate the plus sign throughout the experiment. In Experiment 7a the black rectangle for the continuous tracking task was presented in the center of the screen and the displays appeared in the lower part of the rectangle (HUD layout). In Experiment 7b the black rectangle was presented 0.29° va. above, and the warning displays were presented 0.29° va. below the fixation marker (HDD layout). A single prime-probe sequence included the following events (cf. Figure 9.1): the prime warning display appeared in the lower part of the rectangle (Experiment 7a) or below the rectangle (Experiment 7b) and remained on the screen until the participant responded by pressing the foot pedal, corresponding to the color category. In case of an incorrect response, feedback appeared at the display location, indicating an error. After 500 ms, in which no warning display was shown, the probe warning display appeared in the lower part of the black rectangle (Experiment 7a) or below the rectangle (Experiment 7b) and remained on the screen until participants' response. Participants responded to the probe color by pressing the according foot pedal. As on the prime, if the response was incorrect, feedback was presented, indicating an error. The inter stimulus interval varied randomly between 2000 and 4000 ms. The

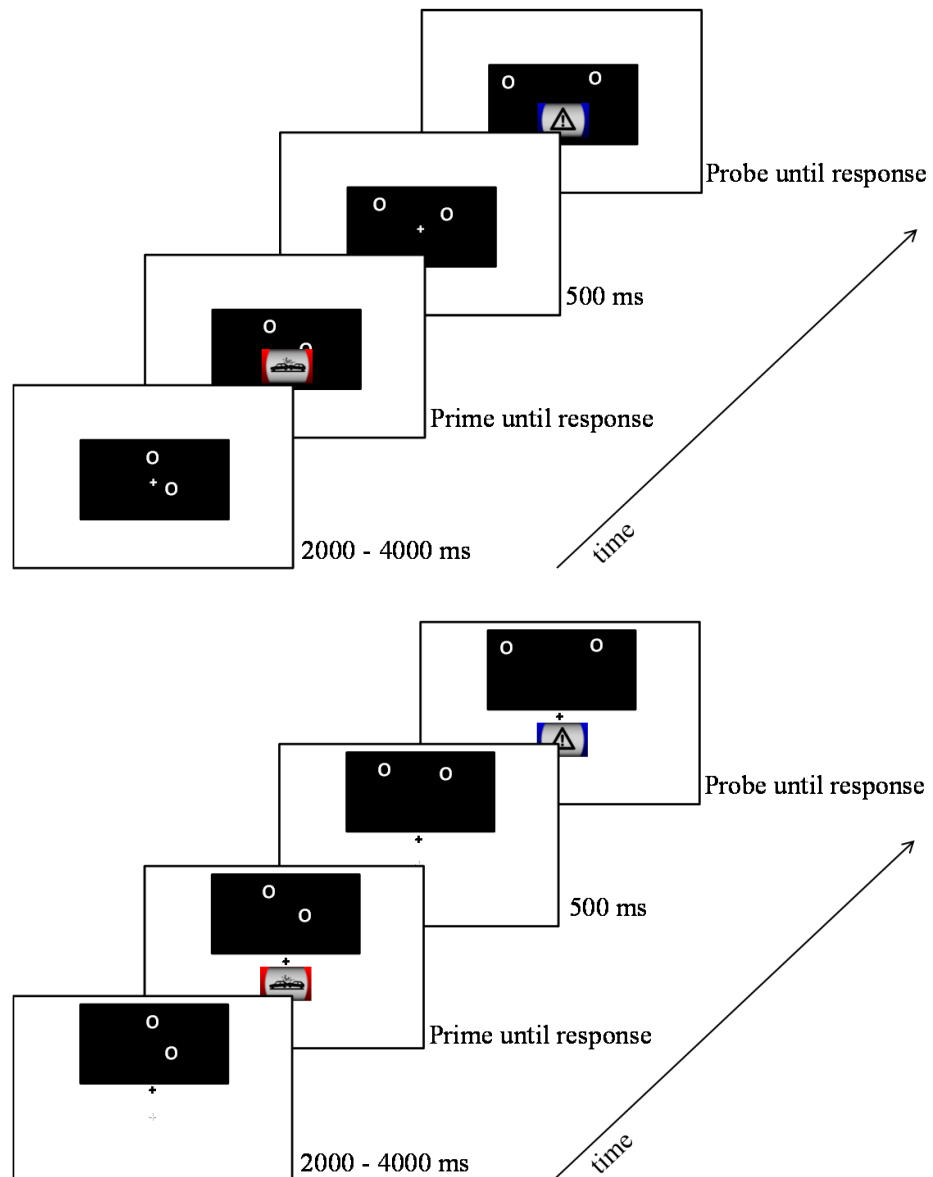


Figure 9.1.: Sequence of events in Experiment 7a (upper panel) and 7b (lower panel). Participants reacted to the color category of the display sides by pressing a corresponding foot pedal and tracked the movement of the two letters at the same time. Stimuli are not drawn to scale.

four possible conditions, RRDR (response repetition and distractor repetition), RRDC (response repetition and distractor change), RCDR (response change and distractor repetition), and RCDC (response change and distractor change) were realized as in Experiment 5. In addition, in some trials only one warning display was presented. These trials were included to increase the impression of occasional warnings. Every participant worked through 288 randomly presented trials during the experimental block. The four trial types (RRDR, RRDC, RCDR, and RCDC) were realized in 64 trials each. 32 trials with only one warning display were included. An experimental session consisted of three practice blocks and one experimental block. In the first practice phase, participants learned the response to the warning displays. This phase included 16 trials. During the second practice phase, participants were familiarized with counting the ‘o’-bounces. Finally, during the third practice phase, participants practiced the complete dual task: counting the bounces while responding to the warning displays for 48 trials.

9.2.2. Results

Experiment 7a. Only blocks in which the number of bounces reported by the participant differed from the correct number of bounces by two or less, and only trials with correct answers to the prime and the probe were considered. Reaction times that were more than 1.5 interquartile ranges above the third quartile of the reaction time distribution of the participant (Tukey, 1977), and those that were shorter than 200 ms were excluded from the analysis. Due to these constraints, 16.5 % of all trials were discarded (probe error rate was 2.3 %, prime error rate was 2.9 %). Mean response times and error rates for probe displays are depicted in Table 9.1, upper part.

In a 2 (response relation: repetition vs. change) \times 2 (distractor relation: repetition vs. change) ANOVA on response times with Pillai’s trace as the criterion, the main effect of response relation reached significance, $F(1, 17) = 21.40, p < .001, \eta_p^2 = .56$. Reactions were faster if they were repeated from prime to probe (782 ms) than when the response had to be changed from prime to probe (831 ms). The main effect of distractor relation was not significant. Importantly, the interaction of response relation and distractor relation was also significant, $F(1, 17) = 5.45, p = .032, \eta_p^2 = .24$ (cf. Figure 9.2, left panel), indicating that a repetition of the distractor led to faster response times only if the response had to be repeated from prime to probe, $t_{RR}(17) = 2.53, p = .022$, but not if the response

Table 9.1.: Mean reaction times (in ms) and mean error rates (in percentage) as a function of response and distractor relation and experiment.

	<i>Response Relation</i>	
	<i>Response Repetition (RR)</i>	<i>Response Change (RC)</i>
<i>Experiment 7a (HUD layout)</i>		
Distractor Change (DC)	796 (2.3)	823 (2.0)
Distractor Repetition (DR)	768 (2.4)	838 (2.3)
Priming Effect ^a	+28 [11]	−15 [12]
<i>Experiment 7b (HDD layout)</i>		
Distractor Change (DC)	832 (2.1)	882 (1.3)
Distractor Repetition (DR)	832 (2.8)	875 (2.3)
Priming Effect ^a	0 [12]	+7 [7]

Note. ^a Priming Effect is computed as the difference between Distractor Change minus Distractor Repetition, standard error of the mean in squared brackets.

had to be changed from prime to probe, $t_{RC}(17) = -1.25, p = .229$. The same ANOVA on error rates revealed no significant effects.

Experiment 7b. According to the same criteria as those in Experiment 7a, 13.9 % of all trials were discarded (probe error rate was 2.1 %, prime error rate was 2.5 %). Mean RTs and error rates for probe displays are depicted in Table 9.1, lower part. In a 2 (response relation: repeated vs. changed) \times 2 (distractor relation: repeated vs. changed) ANOVA on response times with Pillai's trace as the criterion, the main effect, of response relation reached significance, $F(1, 17) = 11.62, p = .003, \eta_p^2 = .41$. Reactions were faster if they had to be repeated from prime to probe (832 ms) than when the response had to be changed from prime to probe (878 ms). The main effect of distractor relation was not significant. Importantly, the interaction of response relation and distractor relation was not significant either, $F(1, 17) < 1, \eta_p^2 = .012$ (cf. Figure 9.2, right panel). The same ANOVA on error rates revealed no significant effects.

Comparison of the Experiments 7a & 7b. To compare Experiments 7a and 7b, a mixed model repeated-measures ANOVA with experiment (HUD layout in Experiment 7a versus HDD layout in Experiment 7b) \times distractor relation (repetition vs. change) \times response relation (repetition vs. change) was computed. The main

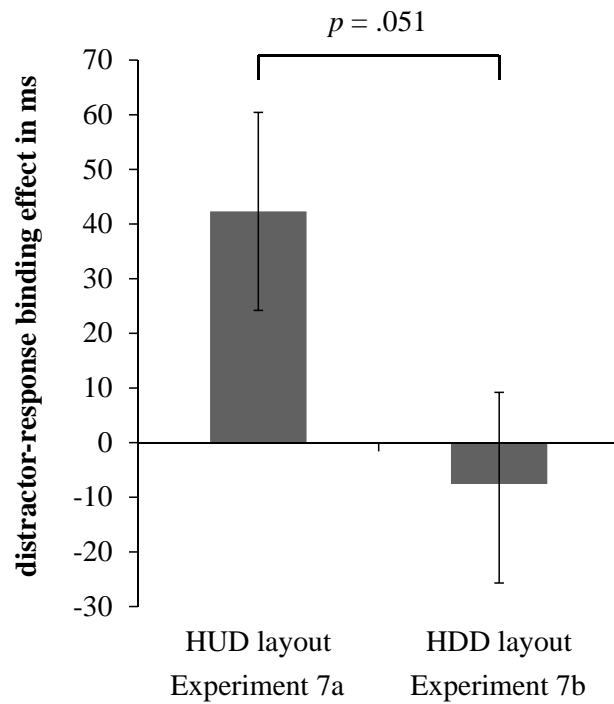


Figure 9.2.: Distractor-response binding effects (i.e., the interaction of response and distractor relation) for reaction times as a function of experiment (7a: HUD layout versus 7b: HDD layout). Distractor-response binding effects are computed as the difference between the distractor repetition effects in response repetition and response change trials. Error bars indicate the standard error of the mean.

effect of response relation was significant, $F(1, 34) = 30.64, p < .001, \eta_p^2 = .47$. Importantly, the three-way interaction of experiment, distractor relation, and response relation was also significant, $F(1, 34) = 4.08, p = .051, \eta_p^2 = .12$, indicating an interaction of response relation and distractor relation in Experiment 7a with a HUD layout but not in Experiment 7b with a HDD layout. None of the other effects reached significance. The same ANOVA on error rates revealed no significant effects.

9.2.3. Discussion

In sum, the results imply that in a dual task situation, the repeated presentation of irrelevant aspects of warning displays might retrieve an earlier response. Our results show for the first time that retrieval due to distractor repetition occurs in a dual task situation. This is highly relevant for advanced driver assistance systems, because a retrieved response can sometimes be inadequate in the current situation and might therefore lead to longer response times or errors in critical situations. However, such retrieval only seems to occur if the warning is presented in gaze direction, like it would be in a head-up display. In contrast, no retrieval was found in a set up resembling a head-down display. This might be a drawback of head-up displays compared to head-down displays. One conclusion might be to avoid head-up displays in future driver assistance systems. However, the presentation of information via head-up display generally seems to increase performance as compared to a presentation via head-down displays (e.g., Sojourner & Antin, 1990). Therefore another conclusion might be to consider the effect of distractor-response binding in the design of advanced driver assistance systems.

In sum, the experiments of Series 2 evidence that distractor-response binding effects are very likely to influence response times of drivers. Both relatively complex stimuli and responses likely to be required while driving a car can become part of distractor-response bindings. Even more important, this is also the case, if speeded responses to warnings are carried out as one of two simultaneously performed tasks. Consequently, distractor-response binding effects might lead to delayed or inaccurate responses if a driver reacts to the warnings of the driver assistance system described earlier. It is highly advisable to adjust such systems in order to prevent decreased performance due to distractor-response binding.

Part IV.

General Discussion

Summary

10.1. Hypotheses

The leading question for this thesis was in which way different kinds of distractors might influence different kinds of actions. The effect of distractor-response binding has been shown to be very reliable in different paradigms of visual studies. Performance was shown to be influenced by the response retrieval due to distractor repetition for simple letter identification tasks, but also for word categorization and responses to stimulus locations (e.g., Frings & Rothermund, 2011; Frings & Moeller, 2010; Giesen & Rothermund, 2011). Moreover, even distractors that are completely irrelevant for the required responses can become integrated with these responses and retrieve them on a subsequent presentation (Giesen et al., in press). Regarding these results, my first aim for the current thesis was to generalize the effect of distractor-response bindings even further to the auditory and the tactile modality as well as across modalities. In particular, I hypothesized that the distractor-response binding effect would occur with auditory stimuli and that, similar to findings in the visual modality, the grouping of target and distractor sound would modulate the effect of distractor-response binding. I also assumed that the effect of distractor-response binding would occur with tactile stimuli, i.e., that a tactile distractor stimulus can be integrated with a response and retrieve it on a subsequent encounter. Further, I assumed that distractor-response binding effects would also occur if target and distractor stimuli were of different modalities and if the distractor modality changed from prime to probe.

On the one hand, an occurrence of the distractor-response binding effect in different modalities has important theoretical implications, which I will discuss in detail later. On the other hand, the relevance of distractor-response bindings in everyday life is even higher with their occurrence within different modalities as well as across modalities. Especially while human-machine interaction becomes increasingly complex, more signals in different modalities are used to deliver information to the person interacting with the machine. Possibly the most familiar human-machine interaction for many of us is the interaction of a driver with the car. This interaction is also a good example for an increasing use of different modalities for information transfer. For example, the driver is informed about the speed via a visual display, information from the parking sensors is transmitted auditory, and lane change warnings can take the form of a steering wheel vibration. With the current development of information transfer we increasingly find ourselves in situations in which visual, auditory, and tactile signals are delivered at the same time. Most of the time we will only react to some of those signals and ignore the others. Therefore it becomes increasingly relevant if and in which way those ignored visual, auditory, and tactile stimuli influence our behavior.

Thus, the second aim of this thesis was to take a closer look at a specific case of human-machine interaction – the interaction of a person with a driver assistance system – and investigate possible influences distractor-response bindings might have on drivers' performance. The most obvious differences between an experimental situation, in which distractor-response bindings have been investigated so far, and the situation of a driver interacting with a driver assistance system, include three factors. First, the stimuli a driver responds to are much more complex than most stimuli used in laboratory settings. Second, drivers' responses are typically the turning of the steering wheel or the pressing of a foot pedal and not the pressing of a key on a computer keyboard, as in most experimental settings. Third, drivers always complete more than one task at once, while up till now, the effect of distractor-response binding has only been investigated with participants completing one task at a time. With the second series of experiments, I aimed to implement a first approximation of response requirements during a driving task and investigated if distractor-response bindings hold under such circumstances. In particular, I hypothesized that also relatively complex stimuli and foot responses that are likely to occur in a driver-car interaction can become part of distractor-response bindings. Finally, I assumed that distractor-response bindings can also occur in dual task situations, possibly influenced by the spatial arrangement of the two tasks.

10.2. Experiments and Results

Seven Experiments were implemented to test the mentioned assumptions. In all experiments presented here, the two factors response relation (repetition vs. change) and distractor relation (repetition vs. change) were varied orthogonally. Therefore, the effect of distractor-response binding was always indicated by an interaction of response relation and distractor relation: distractor repetition had a facilitating effect if the response was repeated, but impeded responses if the response had to be changed. The first series of experiments was intended to evidence that the distractor-response binding effect generalizes to the auditory and tactile modality as well as across modalities.

In Experiment 1, participants heard target and distractor sounds either simultaneously at both ears (grouped condition) or separately at the left and right ear (non-grouped condition). Participants always identified one of the sounds (i.e., the target) and ignored the other (i.e., the distractor). The effect of distractor-response bindings occurred with auditory stimuli in both conditions. As predicted, the mode of presentation (grouped vs. non-grouped) modulated the effect. A significantly larger effect of distractor-response binding was found with grouped than with non-grouped presentation. Apparently, an auditory distractor stimulus is more readily integrated with the response and can more easily retrieve it in a subsequent presentation, if distractor and target stimuli are perceived to belong to the same group, as opposed to cases in which target and distractor are perceived to belong to different groups. This result parallels findings in studies that presented stimuli in the visual modality (see e.g., Frings & Rothermund, 2011).

In Experiment 2, tactile stimuli were used and participants' task was to identify one rhythm while ignoring a second one. Four different rhythms were mapped to four different fingers. Two different rhythms were delivered to the palms and participants responded by pressing a key with the finger mapped to the target rhythm. An effect of distractor-response binding occurred, both in response times and error rates.

In Experiment 3, pictures or sounds of four different animals (frog, chicken, lamb, singing bird) had to be categorized by pressing one of four keys. In each trial, a target and a distractor stimulus were presented simultaneously in different modalities. That is, either the target was presented visually and the distractor auditory or the target was presented auditory and the distractor visually. Target modality switched randomly between trials. As a consequence, repetition of a

distractor animal on prime and probe either occurred within the same modality (i.e., picture – picture; sound – sound) or across modalities (i.e., picture – sound; sound – picture). Hence, repetition of a distractor was not restricted to the same presentation mode, which allows to investigate whether distractor-response bindings extend to a conceptual level as well. Effects of distractor-response bindings were found regardless of distractor modality switches from prime to probe. That is, even the repetition of the distractor *concept* retrieved responses given on the prime.

Together, the results of Experiments 1 through 3 provide evidence that distractor-response bindings occur in the auditory and in the tactile modality. And further that one reason for this general effect might be that distractors are integrated with the response at a conceptual level. Implications of these findings are discussed in detail below (see Chapter 11, *Implications of the current findings*).

In the second series of experiments stimulus features, response features, and features of the situation were approximated to a driving task. This series of experiments was intended to test whether distractor-response bindings might influence drivers' responses. In Experiments 4 through 7, rectangular displays similar to warning displays that are currently designed for the project simTD were used as stimuli. Participants always responded to the color of the display sides and ignored the icons presented in the center of the display. In Experiment 4, participants responded by finger-key presses, as in Experiments 1 through 3. That is, Experiment 4 focused on the stimulus side, to investigate whether such complex distractor stimuli (i.e., icons) can become integrated with and later on retrieve responses. The results clearly demonstrate that distractor-response bindings are indeed possible for stimuli that resemble warning displays.

Experiments 5 and 6 focused on the response side of approached driver car interactions. In Experiment 5 participants responded to the display color by pressing one of two pedals with their left or right foot. Results again indicate distractor-response binding effects. Foot responses were integrated with the distractor icons and were retrieved by a succeeding presentation of them. To further approach responses required by a driver, the withholding of a response was introduced as one of two possible responses in Experiment 6. Once more distractor-response binding effects were revealed. Even if no response to a certain display was required, a repeated distractor retrieved an earlier response.

The driver of a car is always required to complete more than one task at the same time. Therefore, in Experiment 7 a second task was introduced. Participants monitored moving letters while completing the same task as in Experiment 5

(i.e., responding to the color of warning displays via two foot pedals). Notably, the warning displays could appear either within the area containing the moving letters (resembling a head-up display layout) or below that area (resembling a head-down display layout). Distractor-response binding effects occurred with a head-up display arrangement, indicating that completing more than one task at the same time does not prevent an integration of responses with distractor stimuli. Interestingly, no effect of distractor-response binding was found with a head-down display arrangement.

Together the experiments of the second series provide evidence that distractor-response bindings are likely to influence responding in a driving situation. The implication of these findings, especially for the design of systems enabling human-machine interaction, might be extensive. They will be discussed in detail in the next chapter.

Implications of the Current Findings

11.1. Modulation of Distractor-Response Binding

As stated above, an important goal of the presented experiments was to generalize the mechanism of distractor-response binding. One question regarding a generalization of binding mechanisms is, whether binding of perception and action is different depending on the modality of the percept. Evidence for stimulus-response binding was shown in the visual (e.g., Hommel, 1998), the auditory (e.g., Zmigrod & Hommel, 2009), and the tactile (e.g., Zmigrod et al., 2009) modality. Nevertheless, one could have expected to find different effects for the binding of *distractors* to responses in the different modalities. Visual irrelevant information is relatively easy filtered out by shifting the gaze to a different location or simply by closing the eyes. In contrast, auditory and tactile senses are not as easily protected from additional information. Since we have not as many options to protect ourselves from irrelevant auditory or tactile input as we do in vision, one might assume internal processes that prevent an integration of distractor stimuli and responses. In fact, behavioral studies found evidence for differences in distractor processing depending on the modality (e.g., Soto-Faraco et al., 2002; Spence, 2010; Spence et al., 2004). Yet, the direction of the differences varied across studies. Some studies revealed larger distractor effects for visual than for tactile stimuli (e.g., Rock & Harris, 1967; Pettypiece et al., 2010), whereas others

found larger effects for tactile than for visual distractors (e.g., Frings et al., 2011). Further, cortical processing in the different modalities seems to be different. For example, Dijkerman and de Haan (2007) pointed out that the processing of ‘what’ and ‘how’ information is more closely intertwined in the tactile modality than in the visual modality. Thus, the type of difference between distractor processing in the different modalities is unclear. In fact, for the two series of experiments reported here, the effect sizes for tactile ($\eta_p^2 = .26$), auditory (mean $\eta_p^2 = .54$), crossmodal ($\eta_p^2 = .18$) and visual (mean $\eta_p^2 = .24$) distractor-response binding effects were high in all experiments in which the effect occurred, and mostly very similar. This can be interpreted as an indication for similar processes of distractor-response binding in the different modalities, regardless of differences in the cortical processing of action and perception.

However, the story might be more complex. If the processes responsible for distractor-response binding effects are indeed similar in all three modalities tested, similar factors of influence should modulate the effect. For visual stimuli Frings and Rothermund (2011) demonstrated that the grouping of target and distractor stimuli enlarged the distractor-response binding effects. In particular, effect sizes were large if target and distractor were presented in a grouped fashion whereas effect sizes were small if target and distractor were presented in a non-grouped fashion (see also Giesen & Rothermund, 2011; van Dam & Hommel, 2010). The same modulation of the distractor-response binding effect was found in the current auditory experiment. Distractor-response binding had a larger effect on response times if target and distractor sounds were presented simultaneously to both ears (grouped condition) than if the target sound was presented to one and the distractor sound to the other ear (non-grouped condition). That is, the results of Experiment 1 might indicate that visual and auditory distractor-response binding processes work in a similar way.

In Experiment 2 (using tactile stimuli), target and distractor stimuli were always presented at different hands, which could be interpreted as a non-grouped presentation (in contrast of presenting targets and distractors to the same hand, for example). In fact, it has been shown that participants are better able to focus their attention on a tactile target and ignore a tactile distractor if target and distractor are presented at different hands as compared to the same hand (e.g., Evans & Craig, 1991, 1992). Thus, with respect to distractor-response bindings in vision and audition one might have expected to find a small or no effect of distractor-response binding in a tactile task with a non-grouped presentation of stimuli. The result,

that we still observed a distractor-response binding effect might be due to the fact that cortical processing pathways for perception and action features are less distinct in the somatosensory system.

However, in contrast to visual and auditory stimuli, the location of a tactile stimulus depends not only on the body site which is stimulated (the somatotopic frame of reference). As pointed out by Craig and Johnson (2000), another factor influencing tactile spatial perception is proprioception (e.g., Overvliet, Anema, Brenner, Dijkerman, & Smeets, 2011), that is, the perceived position of the stimulated body site in space (the external frame of reference). Consequently, tactile stimulus locations can differ in their somatotopic distance *and* their distance in external space which complicates the possible influence of spatial grouping on distractor-response binding. For example, if the right hand is positioned close to the left hand and one tactile stimulus is presented to each hand, the somatotopic distance of the stimulated areas is relatively large, while the distance in external space is rather small. A number of studies indicate that the distribution of tactile stimuli in external space plays an important role in tactile location perception (Spence et al., 2004; Craig, 2003; Kennett, Eimer, Spence, & Driver, 2001; Kennett, Spence, & Driver, 2002; Rinker & Craig, 1994; Shore, Spry, & Spence, 2002; Spence, Pavani, & Driver, 2000). In contrast, Evans and colleagues found that the variation of hand position in external space did not influence the amount of interference induced by a tactile distractor stimulus (Evans, Craig, & Rinker, 1992). Yet, participants in Evan et al.'s study received tactile stimuli at their individual fingers. Haggard, Kitadono, Press, and Taylor-Clarke (2006) provide evidence suggesting a difference between the neural representation of fingers and that of hands. They argued that finger identification is achieved using somatotopic information, and is insensitive to spatial and postural factors. In contrast, hand identification is strongly dependent on body posture and location in egocentric external space. In the present study, participants' palms were stimulated and their hands were always placed close together. With regard to the findings cited above, it is likely that target and distractor were perceived to be at the same position (they were perceived as being grouped) rather than two different positions. In addition, all tactile rhythms used in the present study had a synchronized one second interval. Compared to visual stimuli, which typically share merely the onset and the offset, this synchronization might have enhanced grouping even further. Taken together, the grouping of target and distractor seems to have a similar effect on distractor-response binding for visual and auditory stimuli. However, it remains an interesting question for future research, whether the grouping of stimuli in

external space can modulate tactile distractor-response binding in a similar way. That is, whether grouped presentation of tactile target and distractor stimuli would result in a larger distractor-response binding effect as compared with non-grouped target and distractor presentation.

Another factor influencing distractor-response bindings besides the grouping of target and distractor stimuli is the time that passes between prime and probe (see Section 2.1.3, *Integration of Action and Ignored Stimuli: Distractor-Response Binding*). Frings (2011) found no effect of distractor-response binding if approximately 2500 ms passed between prime and probe onset. In contrast, distractor-response binding effects did reveal in Experiment 2 in which tactile stimuli were used. In this experiment prime and probe stimulus onsets were also separated by about 2500 ms. This might indicate that the critical period the binding has to survive is the time elapsing between prime-response and probe presentation. This is also in line with the assumption of the theory of event coding that stimuli present around the time of the response ‘success’ can become integrated into the event file (Hommel, 2005b). On average, participants had response times of almost 2000 ms in the tactile experiment. The probe target was presented 500 ms later, which means that from the prime response to the probe target onset distractor-response bindings had to survive only 500 ms. In contrast, response times in the study by Frings (2011) were around 500 ms and the probe target appeared 2000 ms after the prime response. That is, between prime response and probe target onset distractor-response bindings had to survive for 2000 ms. Thus, one might assume that distractor-response bindings did not survive for a longer timespan in the tactile experiment than in previous studies. However, it is still likely that distractor-response binding can persist for various amounts of time, depending on the task and on stimulus modality. For example, it has been shown that the temporal integration window for collecting information into an object file can be influenced by the task requirements (Akyürek, Toffanin, & Hommel, 2008). Similarly, the requirement to process tactile stimuli might have changed temporal prerequisites for distractor-response binding to influence responses. Interestingly, stimulus-response binding effects have been found with a paradigm including a timespan between stimulus-response integration and response retrieval that was in the range of minutes (Horner & Henson, 2011).

Studies investigating distractor-response binding (including all of the experiments presented earlier in this thesis) typically used a small stimulus set and presented few stimuli repeatedly. If we assume that the persistence of binding adapts according to the current task requirements, distractor-response bindings

might be expected to persist for longer periods than a couple of seconds, for example if each stimulus appears only twice during the entire experiment.

11.2. Distractor-Response Binding and Distractor Inhibition

The integration of distractor stimuli and a later retrieval of the response was demonstrated not only for all three tested modalities, but in all seven experiments presented in this thesis, as well as in various previous studies (e.g., Frings & Rothermund, 2011; Giesen & Rothermund, 2011; Mayr & Buchner, 2006; Rothermund et al., 2005). However, it has already been mentioned that the effect of distractor inhibition is another important account for the role of distractors in action control (see Theoretical Background, 2.1.4, *Selective Attention*). In fact, the design used to investigate distractor-response binding also allows for an analysis of distractor inhibition. A general distractor inhibition is evidenced by the main effect of distractor relation: response times in trials with repeated distractors are faster than response times in trials with changed distractors. A general positive priming effect of distractor-to-distractor repetitions is exactly what an inhibition account would predict (Frings & Wühr, 2007a; Houghton & Tipper, 1994): it should be easier to process the target and to select the appropriate response if the probe distractor still suffers from the inhibition that it received during the prime.

Notably, the inhibition effect in the tactile (Experiment 2) and auditory (Experiment 1) modality seemed to be larger than that in all other experiments (see Table 11.1). In fact, Experiments 1 and 2 were the only experiments in which a significant facilitation due to distractor repetition also occurred for trials in which the response had to be changed from prime to probe. Interestingly, as evidenced by longer response times, the first two experiments were much more demanding for the participants (mean RTs: Experiment 1: 1098 ms, and Experiment 2: 1940 ms) than all other experiments reported here (mean RTs: Experiment 3: 794 ms, Experiment 4: 407 ms, Experiment 5: 567 ms, Experiment 6: 401 ms, Experiment 7a: 806 ms, and Experiment 7b: 855 ms)¹.

¹The dual task experiments might be an exception. Completing both tasks at the same time was very demanding as well. However, the task of responding to the warning displays itself (from which distractor inhibition effects were computed) was equally easy as in Experiments 4 through 6.

11. IMPLICATIONS OF THE CURRENT FINDINGS

Table 11.1.: Mean effects of distractor repetition in ms (computed as the difference between RTs in distractor change minus RTs in distractor repetition trials) in all current experiments.

<i>Experiment</i>	<i>Distractor Repetition Effect</i>
Auditory grouped	161**
Auditory non-grouped	95**
Tactile	116**
Crossmodal	23*
Applied stimuli	8*
Response	−1
Response go	3
Dual task HUD	13
Dual task HDD	7

* $p < .05$, ** $p < .001$; two tailed

Indeed, various studies found evidence for more distractor inhibition with more demanding tasks. For example, Ruthruff and Miller (1995) varied selection difficulty in a negative priming paradigm and found the negative priming effect to diminish with easier selection. If selection was especially easy, negative priming effects were completely absent. Similarly, in particularly difficult tasks, negative priming effects have even been observed even without probe distractors or without prime distractor offset – circumstances under which no negative priming effect was found in easy tasks (Frings & Wühr, 2007b; Frings & Spence, 2011)². This is in line with the account of flexible inhibition proposed by Tipper, Weaver, and Houghton (1994). In general only properties of a distractor directly competing with the target in terms of the response need to be inhibited. Yet, as selection becomes more demanding, inhibition is proposed to become rather diffuse and can also affect properties not associated with the response. Thus, one explanation why more distractor inhibition occurred in the current auditory and tactile experiments

²negative priming has been accounted for by other mechanisms as well (e.g., response retrieval). However, if we assume that negative priming is at least in part due to distractor inhibition, we can assume that distractor inhibition increases with increasing task difficulty.

than in the others can be that the identification task was more difficult in these experiments than in all other experiments reported here.

Inhibition effects in the tactile experiment were marginally larger if prime *distractor* and probe target were presented to the same hand than if prime *target* and probe target were presented to the same hand. One might argue that this is an effect of perceived interference. During each prime and each probe, attention is directed to the target hand and is likely to remain there until the next stimulus set is presented. If the distractor in this next set is presented to the same hand as the target in the previous presentation, the distractor will initially be attended, resulting in enhanced perception of interference. However, target and distractor location randomly changed from prime to probe and between prime-probe sequences. That is, prime-distractor/probe-target sequences on each hand were equally often preceded by targets as by distractors on the same hand (and the same is true for prime-target/probe-target sequences). Thus, the described sequential effect of interference cannot account for the finding that probe responses were marginally slower if the prime distractor had been presented to the same hand as the probe target than if the prime target had been presented to the same hand. Instead, this modulation seems to indicate that not only the distractor object, but also the distractor location was inhibited.

Importantly, distractor inhibition cannot account for the difference in distractor repetition effects for response repetition and response change trials. Instead, an inhibition account assumes equal amounts of distractor repetition benefits if the response is repeated from prime to probe and if the response changes. Thus, the interaction of response relation and distractor relation that occurred in all experiments (except Experiment 7b) clearly indicates distractor-response binding. In fact, Giesen et al. (in press) demonstrated that the effect of distractor-response binding and the effect of distractor inhibition are independent of each other and can work in parallel. Particularly, they found distractor inhibition but not distractor-response binding to be modulated by response relevance of the distractor stimuli.

In sum, the results of the present experiments indicate an occurrence of distractor-response bindings, evidenced by the interaction of distractor relation and response relation as well as an occurrence of distractor inhibition, evidenced by the main effect of distractor relation. Further, it is likely that distractor inhibition was in effect to a varying degree in the different experiments and that these effects occurred independently and in addition to distractor-response binding effects (see Giesen et al., in press).

In contrast to distractor inhibition, distractor-response binding effects were evidenced in all seven presented experiments. Distractor integration and response retrieval due to distractor repetition has now been demonstrated in the visual, the auditory, and the tactile modality. Moreover, the effect of distractor-response binding was of similar size in all three modalities. Hence, it might be speculated that the effect in all modalities is due to the same general mechanism. To get a better understanding of the representational level a distractor is integrated with the response, I will next consider the results of Experiment 3.

11.3. Conceptual Distractor-Response Binding

In Chapter 6, *Multimodal Findings*, it was shown that even if a repeated distractor switched the modality, it retrieved the last stimulus-response episode including the response to the target. This result can be interpreted as evidence for conceptually mediated effects of distractor-response binding. Let us take a closer look at the result to decipher its meaning. First, this indicates that even distractors are processed up to a conceptual representation level. Second, we have to assume that in addition to the perceptual features the conceptual or semantic features of the distractor are integrated with the other aspects of the prime episode (including the response to the target). Third, we have to assume the same processes on the probe; that is, again the distractor is processed up to a conceptual representation and when a part of the conceptual representation of the prime stimulus set repeats on the probe, it will retrieve the last stimulus-response episode in which the repeated part became integrated. Thereby, the results of Experiment 3 effectively extend distractor-response binding (and stimulus-response binding mechanisms in general) to the integration of a semantic or conceptual representation level with response features. Since previous studies analyzing distractor-response binding used perceptually identical distractors for distractor repetitions, they yielded evidence only for direct links between perception and action.

Hence, the results of Experiment 3 evidence the mechanism of distal coding, which has been assumed within the framework of the Theory of Event Coding. In fact, most of the studies indicating stimulus-response binding and all of the studies finding distractor-response binding, only provided evidence for an integration of response features with proximal features (but see Horner & Henson, 2011 for stimulus-response binding). A repetition of the stimulus always meant an exact repetition of the perceptual features. The current Experiment 3 provides the first

evidence, that not only the perceptual or proximal, but also conceptual or distal features of an ignored stimulus can be integrated with the response. After distal features of an ignored stimulus have been bound to a response, a perceptually different ignored stimulus also including the integrated distal features can trigger a retrieval of the response.

In this regard a study of Spapé and Hommel (2008) is relevant that also yielded evidence that more than perceptual features and responses can be bound into an event file. They demonstrated that context modulations of cognitive control processes are due to episodic retrieval; that is, they showed that task-specific control information can be integrated together with the stimuli and actions in an event file. Thus, reactivation of a part of such an episode can also retrieve some form of executive control. For example, the modulation of Stroop-like effects in trial *n* due to the compatibility of trial *n*-1 was only observed if some aspects of the context (here a female versus male voice) repeated.

It is noteworthy that the effect of distractor-response binding in Experiment 3 was not modulated by distractor modality switches from primes to probes. Response retrieval due to a repeated distractor was the same both for distractor modality repetition (i.e., participants ignored either the picture or the sound both on the prime and the probe) and for distractor modality change (i.e., participants either ignored the picture on the prime and the sound on the probe or they ignored the sound on the prime and the picture on the probe). This result seems surprising at first. One might have expected to find a larger effect of binding if both conceptual *and* perceptual features of the distractor were repeated from prime to probe and thus more information had the potential to trigger retrieval. For example, Horner and Henson (2011) propose that both stimuli and responses of stimulus-response bindings are represented at multiple levels of abstraction (i.e., also at a perceptual level). The authors implemented a study-test design in which participants saw words and pictures at study and decided whether each object was bigger than a shoebox. During the test old and new stimuli were presented as pictures and the reference object was changed thus allowing both for congruent (same answer at study and test) and incongruent ('yes' at study and 'no' at test or vice versa) test responses. Similar to the results of the present Experiment 3, Horner and Henson found congruency effects both for presentation type change (picture vs. word) and presentation type repetition. However, in contrast to the findings of Experiment 3, a larger congruency effect revealed if presentation type repeated from study to test than if words were presented at study and pictures at test (or vice versa). While the presentation type (word vs. picture) in the study

by Horner and Henson (2011), was changed within the visual modality, a switch of presentation type in Experiment 3 always meant a change *across* modalities. Together, these results might indicate that perceptual features are more likely to be integrated into an event file if the same modality can be expected on both encounters with the stimulus.

Another possibility is that representations of stimuli we respond to are richer than those of ignored stimuli. Participants in the study by Horner and Henson showed retrieval effects due to repeated *targets* to be larger for perceptually identical stimulus repetitions, as compared to stimuli presented in a perceptually different manner on the probe. In contrast, in Experiment 3 retrieval effects due to perceptually different or identical *distractors* were investigated. Additionally, participants' task in the study by Horner and Henson was to compare the size of animals and objects, whereas participants in Experiment 3 merely identified animals. According to the levels of processing account (Craik & Lockhart, 1972) it is likely that due to a deeper processing the memory trace contained more details (i.e., perceptual information) in the study by Horner and Henson than in the current Experiment 3.

In Experiment 3, distractor stimuli were drawn from the same set as target stimuli. In addition, since the target stimulus could be presented in different modalities, the task always required the identification of the stimulus concept. Both aspects might have contributed to a rather deep processing of the distractors and consequently to an integration of the distractor concept with the response. In fact, earlier studies finding distractor stimuli to be processed up to a conceptual level, also used setups facilitating conceptual distractor processing. Gordon and Irwin (2000) used a prime-probe paradigm without responses to the prime display. All stimuli on the prime had to be ignored (i.e., were distractors) and the single stimulus on the probe (i.e., the target) had to be responded to. Interestingly, conceptual representation of the (ignored) prime stimuli occurred although targets were always presented as pictures and distractors always as words. However, the stimuli on the prime sometimes referred to the same object shown as the target on the probe and participants were required to name target pictures. This might have triggered stimulus encoding up to a conceptual representation on the prime. Similarly, Chen and Spence (2010) found picture identification to be facilitated by congruent and to be impeded by incongruent sounds, suggesting a conceptual processing of the sounds. Again, both targets (pictures) and distractors (sounds) referred to the same set of objects.

Note that in Experiment 3 only two modalities were used. Hence, every

repeated distractor was either presented in the same modality as on the prime (i.e., perceptually identical to prime distractor presentation) or in the same modality as the stimulus triggering the prime response. One can speculate that in modality switch trials the attention lingered on the prime target modality, increasing the probability for any stimulus in this modality to be processed up to a conceptual level. Thus if the probe distractor is presented in the same modality as the prime target, processing of the probe distractor and in turn retrieval of the prime response might be enhanced. Possibly, probe distractors presented in a different modality than the prime target are not as easily processed up to a conceptual level. That is a probe distractor that does not match the prime target modality might not be able to retrieve the prime response via the distractor concept. An exact repetition of the distractor percept might be an exception: although not necessarily processed up to a conceptual level, perceptually identical features of the prime and probe distractors might enhance the retrieval of the prime response. To investigate such a possibility, probe distractors would have to be presented in a modality that neither matches that of the prime distractor nor that of the prime target.

Especially regarding driver-car interactions it is important to understand the prerequisites for distractor-response binding with changing distractor modalities: the driver of a car ignores stimuli of various modalities, most of which are not even response relevant. Further research is needed to investigate under which circumstances distractors are integrated on a conceptual level. Yet, other implications for driver-car interactions can already be drawn from the results of experiments 4 through 7.

11.4. Potential Impact of Distractor-Response Binding in Driving Situations

In Chapter 7, investigating the stimulus side of driver-car interactions, I described a driver assistance system that is currently being developed for the project simTD. This system uses graded local danger warnings that include information icons and color coded response indications. In a pre-warning, concerning a rear-end collision, an icon depicting colliding cars is presented together with a color prompting the driver to be attentive, while he has not yet reached the critical situation. Once the driver has arrived at the following hazardous situation, the same icon is presented together with a different color prompting the driver to

brake. The results of Experiments 4 through 7 indicate that distractor-response binding effects are likely to influence the drivers' responses to this kind of local danger warning, leading to late or incorrect reactions.

In Experiment 4, I implemented the same design as used in the experiments of Series 1. Participants saw a relevant and an irrelevant feature and they responded via key presses on a computer keyboard. In order to investigate whether stimuli resembling a local danger warning can lead to effects of distractor-response binding, the displays that were used as stimuli included a color (i.e., target) that was always response relevant and an icon (i.e., distractor) that was always response irrelevant. The results indicate that the ignored icons retrieved the prime response if they were repeated from prime to probe. That is, even stimuli resembling local danger warnings can influence response times via distractor-response bindings. One important difference between the distractors used in the first series of experiments and those used in Experiment 4 (as well as in all other experiments of Series 2) concerns the response relevance of the distractors. In Experiments 1, 2, and 3 targets were always drawn from the same stimulus set, whereas distractors and targets in Experiments 4 through 7 were always drawn from separate sets. In turn, distractors in the first series of experiments were always response incompatible to the target and competed with the target for the response, while distractors in the second series of experiments were always response neutral. Nevertheless distractor-response binding effects were found both with response incompatible and with response neutral distractors. In line with this, Giesen et al. (in press) demonstrated that distractor-response binding effects are not modulated by response relevance of distractor stimuli.

The results of Experiment 5 and 6 indicate that distractor-response binding effects can also influence manual responses carried out by the feet. To estimate the influence distractor-response binding has on reactions in a driving situation, this finding is especially important. None of the responses of a driver include a key press on a computer keyboard. Instead, the pressing of a foot pedal is a rather common action of a driver. It was evidenced that such a foot pedal press can be integrated with and subsequently be retrieved by an irrelevant aspect of a display resembling a local danger warning. Since a common foot response of a driver is to brake, this implies that ignored features of a warning might lead to a braking reaction that is unexpected by all surrounding road users. In turn, it is highly advisable to prevent this kind of response retrieval in future driver assistance systems.

It should be noted that in Experiment 6, using a go/no-go task, distractor

repetition had neither a facilitating nor an impeding influence on probe response times if the response had to be withheld on the prime. Responses were equally fast for distractor changes and distractor repetitions, when participants did not respond to the prime and then responded to the probe (i.e., in response change trials with a go-probe). This might indicate that no event file was created if no response was required on the prime. However, the interaction of response relation and distractor relation was significant, indicating a general effect of distractor-response binding in Experiment 6. It is therefore possible that both an integration of non-response-distractor binding and distractor inhibition occurred on no-go primes. In that case, the fact that no difference between distractor change and distractor repetition trials was found for response change trials might be due to both effects working in parallel. If the distractor is repeated, distractor inhibition would facilitate responding while the retrieval of the prime 'response' would hamper responding as compared to trials in which the distractor changes from prime to probe (see discussion above). Yet, a closer look at participants' performance in trials with no-go probes indicates that the effect of distractor-response binding indeed hinges on the trials requiring a response on the prime. Error percentages on no-go probes were the same for distractor change and distractor repetition if the no-go response was repeated (i.e., if the response was withheld in reaction to the prime and probe). This indicates no facilitation (i.e., no fewer errors) due to a repeated distractor if the response had to be restrained both on the prime and the probe. In contrast, distractor repetition hampered response restraintment (leading to more errors on the probe) if a response was executed on the prime. Together the results of go and no-go probes indicate an integration of distractor and response on the prime only if a response had to be executed and not if the response had to be withheld. In contrast, research using a stop-signal paradigm indicates that the information not to respond can be retrieved by repeated distractor stimuli (Giesen & Rothermund, in prep.). The stopping of a response on the prime seemed to be integrated with the distractor. If the distractor was repeated after a stop on the prime, responding was generally hampered on the probe, regardless which response was required. While the withholding of the response in a go/no-go paradigm is consistently mapped to the same stimulus, participants in a stop-signal paradigm prepare a response to every presented stimulus. On some trials an additional stop signal is presented after stimulus onset and on these trials participants try and stop their initiated response. Therefore, the different results might be due to the different amounts of control needed for response restraintment in stop-signal and in go/no-go tasks. The need of control to hold back the already

initiated response in a stop-signal paradigm is considerably larger than the control required if the withholding of a response is consistently mapped to a certain stimulus. Therefore, response restraint might be perceived much more like an actual response if it was successful in a stop-signal paradigm than if it was indicated from the beginning of stimulus presentation in a go/no-go paradigm. Importantly, Experiment 6 also evidenced that even if the required reaction is to withhold the response, distractor-response bindings might influence the driver's performance by retrieving an inadequate response. For the human-car interaction this implies that a driver might retrieve a braking reaction in response to an information display that does not require responding yet. This can lead to braking at unexpected times for a following driver and in turn increase the number of rear-end collisions. Unexpected braking is all the more dangerous because drivers oftentimes do not keep sufficient distance to the car in front. Therefore the present results indicate that the influence of distractor-response binding effects has to be considered also in the design of information displays that are not supposed to trigger responses.

The last experiment (Experiment 7) aimed to compare the effect distractor-response binding is likely to have on responses to warning signals presented via head-up as compared to head-down displays. Participants completed a continuous tracking task and the same speeded response task as in Experiment 5 at the same time. In Experiment 7a the stimuli for both tasks were arranged in the same spatial location, resembling a head-up display setup. In contrast, in Experiment 7b the stimuli for the tracking task were presented above the stimuli for the speeded reaction task (i.e., the task of responding to the warning display).

Responses were integrated with and later retrieved by the ignored icons of the warning displays (i.e., the distractor) only in the head-up display setup (Experiment 7a). In contrast in the head-down display setup responses were not retrieved by repeated distractors. Reason and Mycielska (1982) argued that even for automatic activity a minimum level of attention is required. That is, it can be assumed that distractors can only influence responses if at least some attention is distributed to them. Given the relatively large shifts of attention, necessary to complete both tasks, it seems possible that not even this minimal amount of attention was distributed to the distractor icons in Experiment 7b. One might speculate that in Experiment 7b, using the head-down display setup, other stimuli than the distractor icons (i.e., the moving letters in the tracking task) were integrated with the response. Although the moving letters were irrelevant to the categorization task, the second task (counting the bounces) required attention to them throughout

the experiment. Consequently, assuming fast attention shifts between the two tasks, both letters and target might have been perceived in the same time frame (see Akyürek et al., 2008) with the response, resulting in an integration of letters and response. According to the gestalt principle of proximity however, it is likely that the black area containing the moving letters and the warning displays were perceived to belong to the same object only in the head-up display set up but not in the head-down display set up. In that case it can be assumed that the letters in the tracking task were more likely to be integrated with the response in Experiment 7a than in Experiment 7b (Frings & Rothermund, 2011). Along the same lines, van Dam and Hommel (2010) found irrelevant objects to be integrated with the response only if target and distractor objects were superimposed upon each other (as in Experiment 7a) but not if they were spatially separated (as in Experiment 7b). However, in both experiments the moving letters and the warning displays were always separated by *task*. I therefore assume, that the black rectangle with the moving letters and the warning displays were perceived as different objects and in turn that the letters were neither integrated with responses in Experiment 7a nor in Experiment 7b. Instead, it is likely that in Experiment 7b no distractors were integrated with the responses at all – possibly due to the large attention shifts.

Together the results of Experiment 7 indicate that distractor-response binding effects influence responding to head-up but not to head-down displays. On the one hand, the present results might simply add to the evidence that head-up displays have several drawbacks as compared with head-down displays. They increase optic clutter (e.g. Fischer et al., 1980; Foyle et al., 1993; Oppitek, 1973), lead to problems with accommodation (see Edgar, 2007), and have now been shown to be susceptible to response retrieval which might result in delayed or incorrect responding. On the other hand, bearing in mind that head-up displays are increasingly integrated in current cars, the results indicate that it is important to take influences of distractor-response binding into account in the design of driver assistance systems. In fact, besides the mentioned problems of head-up displays, information presentation via head-up displays has generally been shown to lead to better driving performance than information presentation via head-down displays (e.g., Sojourner & Antin, 1990). Therefore, it is worthwhile to adjust the design of warnings to prevent inadequate response retrieval due to repeatedly presented distractors, rather than to waive head-up displays entirely.

In contrast to the local danger warnings designed for the project simTD, warnings of driver assistance systems are increasingly presented non-visually. An

advantage of auditory messages is that their perception is independent of viewing direction, which is especially desirable in a driving situation. Yet, a disadvantage is that they are much more transient than an image that can stay on a display. A modality that provides both the advantage of being independent of gaze direction and the option of lasting stimulation is the tactile modality. Thus, tactile warnings can be assumed to be very efficient in a driver assistance system (but see Ho et al., 2006 for effects on attention allocation due to vibrotactile cues). In fact, lane change warnings in various current cars are presented haptically³. The results of Experiment 2, using tactile stimuli, are a first indication that even in the design of such tactile warnings, distractor-response binding effects should be taken into account. Regarding the results of Experiment 1, the same is true for the design of auditory warnings.

In terms of the warning modality, the results of Experiment 3 might be especially relevant for the design of human-machine interfaces. Experiment 3 evidenced that distractors of a different modality than the target can become integrated with the response. Given that in addition to visual signals, auditory and tactile signals are increasingly used in driver-car communication, it is likely that an ignored stimulus at the time of a response to a warning is of a different modality than the warning signal. The results of Experiment 3 are a first indication that even stimuli of a different than the attended modality can influence response times and have to be taken into account in the design of driver assistance systems. That is, signals of driver assistance systems have to be carefully adjusted with regard to all other warnings presented in a car, regardless of their modality.

Warnings that are designed to prevent effects of distractor-response binding, might avoid exact distractor repetitions. For example, a rear-end collision warning may be presented via two different icons in the pre-warning and in the warning that requires a different response. A new form of icons, so called ‘auditory icons’, has recently been proposed to be used in driver assistance systems (McKeown & Isherwood, 2007; Vilimek & Hempel, 2005). Auditory icons are natural everyday sounds that signal events by analogy. For example screeching tires might be used to indicate a required braking response or a rumbling sound might indicate a straying from the street. To prevent distractor-response bindings, one might assume that a driver assistance system should present additional information, such

³see e.g., <http://www.kfz.net/autonews/adac-testet-vier-spurhalteassistenten-17996/>, <http://www.daimler.com/>; downloaded Dec. 3rd, 2011

as the icons in the present experiments, as visual icons in the pre-warning and as auditory icons in the response requiring situation.

However, the solution most likely is not as simple as that. Experiment 3 provides evidence that it can be the concept or distal code of a distractor that is bound to and retrieves the response. Thus, a mere change of the distractor modality (i.e., a change in the percept of the distractor) does not prevent distractor-response bindings in general. Yet, distractors in Experiment 3 were always mapped to a response that was incompatible to the target response. In contrast, irrelevant parts of warnings presented by a driver assistance system can be neutral regarding the response required by the warning. Thus, more research is required investigating whether the concept of response neutral distractors can become part of distractor-response bindings as well. In the mean time it might be safest to present different icons in pre-warnings and in the actual hazard situation. For example, a warning display might first indicate the specific upcoming situation by the respective icon and then prompt any different response by a general warning icon (such as the warning triangle used in the present experiments). More generally, if the same response is required on two consecutive occasions, it is advisable to keep even the irrelevant features of the warning constant. On the other hand, if a different response is required, any feature repetition should be prevented. One might argue that due to distractor inhibition the repetition of distractors might facilitate responding even in cases of a response change, as it was found in the present auditory and tactile experiments. Note however that the effect of distractor inhibition was found to be small for response irrelevant distractors (Giesen et al., in press). In addition, in the present thesis three out of four experiments approaching responding in a human-car interaction did not indicate a general facilitation due to distractor inhibition (see Table 11.1). Thus, it can be assumed that a possible distractor inhibition effect does typically not outweigh response retrieval in driving situations in which two different responses are required in fast succession.

In sum, regarding action control in driver-car interactions, the most important finding of the current experiments is that distractor-response binding seems to be relevant for reactions to driver assistance systems. Most of the time a driver will respond to a local danger warning in a certain way (e.g., by braking). In those cases the present results imply that it is likely that even irrelevant aspects of a warning that is presented via a head-up display, become integrated with the response. Hence, the same irrelevant aspect can later retrieve the response, possibly leading to delayed or inadequate reactions even in situations in which no response is

required. Especially in driving situations, in which people move at extremely high velocities, late or incorrect responses can have serious consequences.

11.5. Limitations

Finally, I need to point out some limitations of the present experiments. It should be mentioned that in Experiments 1, 2, and 4, response repetition always also meant that the target stimulus was repeated, resulting in the repetition of the exact same stimulus percept on the probe in response repetition / distractor repetition trials. Note however, that the interaction of response relation and distractor relation does not hinge on this condition. Past research evidenced that the effect of distractor-response binding also occurs if the target identity changed independently of response relation (e.g., Frings et al., 2007; Frings & Moeller, 2010; Giesen & Rothermund, 2011). Additionally, in the other four experiments presented here, response relation between prime and probe was independent of target percept repetition from prime to probe and distractor-response binding effects were observed, nevertheless.

A difference between the two experimental series was the possible influence of response compatibility of the distractor stimuli. In contrast to the experiments of Series 2, distractors in the first three experiments were task relevant (i.e., belonged to the same stimulus set as the targets) and always competed with the target for response selection (i.e., were always response incompatible). Since irrelevant aspects of warnings in a driver assistance system are likely to be response neutral, it is possible that not all findings of the first three experiments hold for distractor influences in human-car interaction. However, Giesen et al. (in press) found distractor-response binding to be unaffected by distractor relevance. Therefore it seems save to assume similar effects of distractor-response binding for response neutral distractors presented in the auditory and the tactile modality that might occur in warning by a driver assistance system.

It should also be pointed out that the distractor icons in Experiment 4 through 7 were not only response neutral, but also completely irrelevant for the task of the participants. Therefore, it is likely that participants tried to actively ignore the icons in the present experiments. The driver of a car, on the other hand, is likely to generally pay attention to additional information presented by a warning display. That is, it can be argued that an information icon is more salient in a driving situation than it was in Experiments 4 through 7. Note however, that

a greater salience of the distractor is more likely to further its integration into the event file than to impede it (Hommel, 2004). Thus, it can be assumed that distractor-response binding effects are rather larger for real warning displays than those found in the present experiments of Series 2.

In addition, all experiments intended to approach a driving situation, were conducted in a laboratory. Consequently, I was able to carefully control most of the variables and thus it is possible to infer differences in performance to result from the effect of distractor-response bindings. However, it should be pointed out that the laboratory setup differs from a real driving situation in some important aspects. That is, a limitation of the second series of experiments is the relatively low ecological validity of the situation participants were tested in. For example, the driver of a car has to carry out several tasks at the same time (e.g., steering, listening to the navigational system, shifting gears, etc.; see Theoretical Background, Section 2.2, *Action Control in Human-Machine Interactions*). In contrast, participants in Experiment 7 only completed two tasks at the same time. Yet, it has been suggested that the spare capacity in a multiple task situation remains relatively constant as processing demands increase (Stager & Laabs, 1977). Hence, even if a driver processes more than two tasks at the same time, distractor-response binding will likely affect performance in this situation. However, because of the relatively low ecological validity, more research is needed to fully transfer the findings of the present experiments to a real driving situation.

Outlook

In sum, the present results indicate that the effect of distractor-response binding influences reactions to stimuli in the visual, the auditory, and the tactile modality. This is the case, regardless of whether all stimuli are presented in a single modality and even if stimulus modality changes between distractor-response integration and retrieval. This implies that distractor-response binding functions on a conceptual level and further that the processes responsible for the distractor-response binding effect are likely to be the same for stimuli presented in different modalities. Further, I presented evidence that distractor-response binding also occurs with relatively complex stimuli such as warning displays, with responses carried out with the feet, and even in a dual task situation combining both with a second task. It can be inferred that distractor-response binding most likely affects responses in a driving situation. Taken together, these findings have important implications for the design of future driver assistance systems. Even if an increasing number of warnings is presented in an auditory, tactile, or multimodal manner, possible distractor-response binding effects should be taken into account for the design of the system, in order to prevent delayed and incorrect reactions.

From the considerations above it becomes clear that one important path for future work is to differentiate conceptual and perceptual distractor-response binding. The results of the current Experiment 3, including changes of distractor modality indicate that it is the concept of a distractor that is integrated with the response. Yet, it is possible that the binding of perceptual features enhances the effect of distractor-response binding in certain situations. An experimental setup that might help solving this question, could introduce different processing requirements

for the target stimuli. If the task includes categorization of perceptual features, it is possible that also perceptual features of the distractor are integrated with the response. In addition, it would be worthwhile to investigate whether even distractors that do not compete with the target for a response can be integrated with responses at a conceptual level.

It should also be investigated whether distractor-response bindings can persist over longer periods of time than has been found up till now. Using very small stimulus sets, past studies presented the same stimuli in (nearly) every trial. Thus, it is possible that the event files in past studies were too similar to be able to survive in parallel. In order to analyze possible long time distractor-response binding, a study-test paradigm including distractor stimuli could be implemented.

Further, the present results indicate that distractor-response binding effects are likely to influence drivers' reactions and also that they occur for visual, auditory and tactile stimuli. However, stimuli used in the series of experiments approaching a driving situation (i.e., Series 2) were exclusively visual. It has been proposed that multimodal warnings might be most effective in alerting a driver to hazardous situations (e.g. Ho, Reed, & Spence, 2007). The next step will be to investigate influences of signals in various modalities on drivers' responses.

To be able to control most variables in the experimental Series 2, even the experiments applying distractor-response bindings were set in a laboratory and the results are therefore not directly transferable to real driving situations. Therefore, another path of future research is to investigate the effect of distractor-response bindings in more realistic situations, for example in a driving simulator or in a real driving situation. If the current findings also hold for real life situations, another future path of work is to adjust driver assistance systems to prevent the negative influence of distractor-response binding on drivers' reactions. In particular, if the same response is prompted in quick succession, even the irrelevant features of the signal should be repeated. However, if two successive responses differ, a signal prompting the second response should be carefully designed not to repeat irrelevant features of the first prompt. Moreover, potential response retrieval due to different signals occurring simultaneously, has to be taken into account as well.

Finally, the present results indicate that distractor-response binding effects have a wide range of influence. On a larger scale it is therefore likely that they influence reactions in other human-machine interaction besides driving as well. For example that can be the case in operating industrial machines or in the interaction with a computer. Further studies are needed however, to confirm this assumption.

At the start of this thesis, I introduced a person responding to a driver assistance

system, and asked what might influence his reactions to a warning. Now I can conclude that most likely both attended and ignored aspects of the warning affect the speed and accuracy of his response. Driving is one situation in which delayed or inaccurate responding can have serious consequences. Others should be identified and secured against possible negative influences of distractor stimuli.

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Eidesstattliche Erklärung

Hiermit erkläre ich an Eides statt, dass ich die vorgelegte Dissertation selbst angefertigt und alle von mir benutzten Quellen und Hilfsmittel in der Arbeit angegeben habe.

Trier, den 14. Dezember 2011

Birte Möller