ACADEMIC
PRESS

Available online at www.sciencedirect.com

SCIENCE DIRECT®

Cognitive Psychology 46 (2003) 302–358

Cognitive
Psychology

www.elsevier.com/locate/cogpsych

Preparing for perception and action (I): The role of grouping in the response-cuing paradigm☆

Jos J. Adam,[a,*] Bernhard Hommel,[b] and Carlo Umiltà[c,1]

[a] *Department of Movement Sciences, Maastricht University, P.O. Box 616,*
Maastricht, 6200 MD, The Netherlands
[b] *Leiden University, Wassenaarseweg 52, P.O. Box 9555, 2300 RB Leiden, The Netherlands*
[c] *Universitá di Padova, via Venezia, 8, 35131 Padova, Italy*

Accepted 28 April 2002

Abstract

Human skilled behavior requires preparatory processes that selectively make sensory and motor systems more efficient for perceiving the upcoming stimulus and performing the correct action. We review the literature concerning these preparatory processes as studied by response-cuing paradigm, and propose a model that accounts for the major findings. According to the Grouping Model, advance or precue information directs a dynamic process of subgroup making—that is, a process of stimulus- and response-set reconfiguration—whereby the internal representation of the task is simplified. The Grouping Model assigns a critical role to the unit of selection, with Gestalt factors and interresponse dependencies mediating the formation and strength of stimulus and response subgroups. In a series of five experiments, we manipulated perceptual and motoric grouping factors, and studied their independent and interactive effects on the pattern of precuing benefits. Generally, the results were consistent with the Grouping Model's account of response-cuing effects.

Keywords: Preparation; Spatial cuing; Response-cuing; Gestalt principles

---

☆ We thank Gordon Logan and two anonymous reviewers for their extensive and constructive comments on an earlier version of this paper.

[*] Corresponding author. Fax: +31-43-3670972.

E-mail address: jos.adam@bw.unimaas.nl (J.J. Adam).

[1] Carlo Umiltà was supported by a grant from MURST.

doi:10.1016/S0010-0285(02)00516-9

1. Introduction

The visual world usually contains many objects, each of them often allowing a great number of possible actions. Hence, since we normally can do only one target activity at a time, there is a critical need for selection both at the input side (which object is processed) and at the output side (which action is performed). Behaviorally relevant action, therefore, requires the efficient operation—and cooperation—of at least two basic abilities. First, to focus selectively on a particular source of visual information, and, second, to select and prepare an adaptive response. In this paper, we present new evidence on the relation between input selection and output selection and in particular on their cooperation in preparing the cognitive system for action.

A characteristic feature of human action is anticipation and preparation. For instance, a traffic light turning orange may induce preparatory activities that will allow one to quickly detect the occurrence of the impending red signal but also, if necessary, to stop the car immediately. Furthermore, most voluntary movements are preceded by postural adjustments that anticipate the associated changes in the body's center-of-gravity. As these examples attest, actions typically do not occur in a perceptual or motoric vacuum but often are embedded in a context and therefore are sensitive to past and future events. In fact, a large number of our actions appear to be designed not (only) to reach a goal immediately but rather to prepare for a future action. Thus, in a natural sequence of actions, any part may be considered preparatory to the next (Requin, Brener, & Ring, 1991). Note that such preparatory processes are not limited to directly observable movements but also include modifications or reconfigurations occurring within the central nervous system. These cognitive preparatory processes are the topic of the present study.

Traditionally, at least two types of reconfiguration processes are distinguished, those preparing the cognitive system for perceiving (one of) a particular set of stimulus events, and those preparing the system for performing (one of) a particular set of actions (e.g., Broadbent, 1971; van der Heijden, 1992). Most studies so far examined either perceptual preparatory processes (e.g., Posner, 1980) or motor preparatory processes (e.g., Rosenbaum, 1980), a state of affairs probably reflecting the stage approach advocated by Sternberg (1969). More recent approaches, however, emphasize the intimate link and close cooperation between perception and action, and seriously question the idea that perceptual and motor processes can be cleanly separated and studied independently (e.g., Cohen & Shoup, 1997; Craighero, Fadiga, Rizzolatti, & Umiltà, 1999; Müsseler & Hommel, 1997; Tipper, Lortie, & Baylis, 1992; for an overview, see Prinz & Hommel, 2002). It is in the spirit of this latter view that we examine in this paper the commonalities among and possible interactions between perceptual- and action-related preparatory processes as they participate in the response-cuing task.

2. Effects of location cuing

A useful strategy to study preparatory processes in perception and action is to give people advance information about an upcoming stimulus or response and to analyze whether this information can improve performance. There are many ways to do that: Precues may refer to all, many, or just one feature of a particular stimulus or response and thus may reduce stimulus or response uncertainty to zero—if a single event is precued—or they may leave some uncertainty to exist—such as when, say, two out of four possible events are cued. In other words, preparation—defined as the processes by which organisms are readied for perceiving future events and reacting to them—can be broadly conceived as a behavioral mechanism that reduces uncertainty (Requin et al., 1991).

There is considerable evidence that people can make use of advance information about the upcoming stimulus to improve perceptual analyzes, especially when this information is spatial in nature. In studies on stimulus-location cuing, participants are forewarned by a cue about the location of an upcoming target stimulus. The cue may be a centrally presented, symbolic cue (e.g., an arrow pointing at some location) or a locally presented, peripheral cue (e.g., a marker or a light flash). Sometimes the predictive value of the cue is manipulated, so that effects of valid cues (indicating the target location) and invalid cues (indicating a nontarget location) can be compared. Typically, valid spatial cuing yields substantial benefits in speed and/or accuracy of responding to the target, whereas invalid spatial cuing yields substantial costs. In particular, stimulus-location cuing has been shown to affect *target detection* (e.g., Posner, Snyder, & Davidson, 1980), *target identification* (e.g., Eriksen & Rohrbaugh, 1970), and *target discrimination* (e.g., Henderson, 1991). It is commonly agreed that the underlying mechanism is a shift of attention: The spatial cue directs attention to the future target location and thereby enables perceptual processing resources to be allocated to the most relevant source of information (e.g., Eriksen, 1990; Posner, 1980).

There is also ample evidence that people can make use of advance information about the required response. A good example is the response-related analog of the stimulus-cuing technique, the so-called *response-cuing task* devised by Miller (1982), who modified Rosenbaum's (1980, 1983) movement precuing technique (see also, Leonard, 1958). In this task, the spatial cue provides information about which fingers to use for responding. In particular, participants are forewarned about the location of an upcoming response or, more precisely, about a particular subset of possible responses. Typically, horizontally defined stimuli are reacted to by spatially compatible discrete keypress responses with the index and middle fingers of the two hands. The visual display usually consists of three horizontal rows of symbols, representing warning, cue, and target stimulus, respectively (see Fig. 1). The warning stimulus consists of four plus signs, indicating the four possible stimulus–response locations. The cue, that follows after a fixed delay, consists of two plus signs, indicating a subset of possible stimulus–response locations. After a certain preparation interval, that may vary between 100 ms and 3 s, the target stimulus is presented, a single plus sign that indicates the location of the required response.

The functional significance of the response cue is that it logically transforms the original four-choice reaction task into a two-choice reaction task. Four cue or preparation conditions can be distinguished. In the *hand-cued* condition, the cue specifies two fingers of the same hand (e.g., the left-middle and left-index fingers). In the

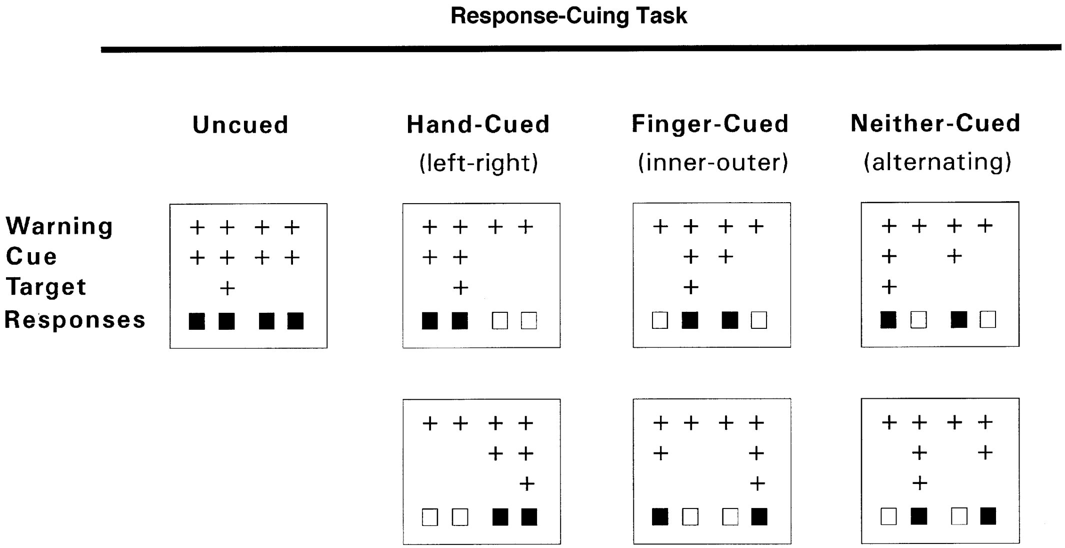


Fig. 1. A schematic representation of the response-cuing paradigm as developed by Miller (1982). The black squares indicate the possible responses indicated by the cue, and thus reflect the number and type of prepared responses. Note that in all conditions only one response was actually required, namely the finger response indicated by the single target stimulus.

finger-cued condition, the cue specifies the same finger on different hands (e.g., the left-index and right-index fingers). In the *neither-cued* condition, the cue specifies different fingers on different hands (e.g., the left-middle and right-index fingers). Also, an *uncued* condition is included; here the cue contains four plus signs, so that no selective preparation is possible. This condition is a necessary control condition because it leaves the basic, 4-choice task unaltered. Since two-choice responses normally yield shorter reaction times (RTs) than four-choice responses (Hick, 1952; Hyman, 1953), cue effectiveness is inferred from a significant RT advantage for the 2-choice cue conditions (i.e., hand-cued, finger-cued, and neither-cued) over the control, 4-choice (uncued) condition.

A robust finding from the response-cuing task is a pattern of differential precuing benefits: RTs are shortest for the hand-cued condition and longest for the neither-cued condition, with the finger-cued condition laying in between (see for a review Reeve & Proctor, 1990). Importantly, this pattern is only observed with short preparation intervals (i.e., shorter than 1500 ms) but not with longer preparation intervals (i.e., 3 s), where all three cue conditions show comparable RTs.

On first sight, the stimulus-cuing task and the response-cuing task appear not to have much in common—after all, the former is thought to affect perceptual processes, while the latter is believed to have an impact on action planning. In fact, accounts of stimulus-cuing do not usually consider action-related processes and accounts of response-cuing (to be described below) do not usually include stimulus-related processes. This seems to be a natural consequence of the stage approach to information processing. However, in this paper we will argue that there may be more important commonalities between the processes that mediate and produce stimulus- and response-cuing benefits than hitherto assumed. In particular, we propose that performance in the response-cuing task is determined by grouping operations that mediate both the selective intake of information and the selective planning for action. Hence, the present study sought to elucidate the role of grouping factors in the response-cuing task.

3. Previous accounts of response-cuing benefits

The question of precisely where in the information-processing system response-cuing benefits arise, is fiercely debated. In fact, three different loci have been proposed. Originally, Miller (1982, 1985) interpreted the pattern of differential cuing benefits in terms of differential response preparation processes. That is, Miller attributed the advantage of the hand-cued condition to characteristics of the motor system that would allow more efficient preparation when the two cued responses are on the same hand than when the responses are on different hands. Although Miller was not very specific as to what would count as "motoric" in this context, and although he did not provide direct evidence in support of this claim, subsequent psychophysiological studies showed that response-cuing effects reside, at least partially, in the (pre)motor cortex (e.g., De Jong, Wierda, Mulder, & Mulder, 1988; Leuthold, Sommer, & Ulrich, 1996; Requin, Riehle, & Seal, 1993).

Reeve and Proctor (1984, 1985, 1990; Proctor & Reeve, 1986, 1988) interpreted the effect in terms of differential stimulus–response translation processes, or, in other words, of how fast the responses indicated by the cue can be identified and selected. Reeve and Proctor provided a strong case for their account by showing that with an overlapped placement of hands (i.e., with fingers of both hands alternating on response keys in the order "right index, left middle, right middle, left index") the usual advantage for the hand-cued condition (two fingers on the same hand) turns into an advantage for the neither-cued condition (two fingers on different hands). In other words, the hand-cued advantage really seems to be an advantage for the two leftmost and two rightmost stimulus–response locations, not for the left or right hand per se. According to Reeve and Proctor (1984, 1985, 1990) this implies the stimulus–response translation stage as the locus of the "hand advantage" or, more appropriately, the "left–right" advantage (see also Hendrikx, 1986; but see Miller, 1985).[2]

More recently, Adam (1994) noted that the left–right advantage also allows for a perceptual interpretation. Adam argued that the left–right cue might enjoy an early perceptual encoding advantage because it constitutes a strong perceptual subgroup. Adam (1994) bolstered this claim by showing that a minor manipulation of the stimulus display (i.e., moving the two center or inner stimulus positions each one position inwards) significantly reduced the left–right advantage. According to Adam, this manipulation of the spatial arrangement of the stimulus display reduced the "good grouping" of the two leftmost and two rightmost positions and strengthened the perceptual grouping of the two inner positions; hence, a reduced left–right advantage.

In sum, the pattern of differential response-cuing effects has been attributed to three different loci in the information-processing system, to the motor system, to stimulus–response translation, and to perceptual encoding, and each of these interpretations has received some support. It is interesting to note, however, that most previous studies focused on, and hence manipulated, only one single independent variable. Unfortunately, this represents a serious, general limitation, since this way, and per definition, only *one* processing locus could be determined. However, providing evidence for one locus does not preclude the possibility that there may be other loci as well. Indeed, it is the main goal of this paper to show that response-cuing effects do not have a single, invariant origin, but are the combined result of several dynamic and often interacting processes, including perceptual and motoric. In the next section, we present the outlines of our account.

4. The grouping account

Although we agree with previous authors that perceptual- and action-related processes are involved in response-cuing benefits, our own approach attempts to bring

---

[2] In keeping with the importance of *locations* as opposed to *fingers* in the pattern of differential precuing effects, from here onwards we will use the terms left–right, inner–outer, and alternating (cues) instead of hand-, finger-, and neither (-cues), respectively.

into sharp focus the interaction between stimulus-set coding and response-set coding. Thus, the response-cuing model we propose is not meant to contradict previous accounts and considerations, but rather to combine them into a more comprehensive, integrated framework.

Here is the foundational idea of the Grouping Model: If the cue indicates a strong, good subgroup of stimuli that corresponds closely with a strong and similar grouping of responses, then a fast, automatic selection (activation) of the cued responses occurs. If, on the other hand, the cue indicates stimuli belonging to different subgroups, or if there is a mismatch between the grouping of the stimuli and the grouping of the responses, then a slower, effortful process is needed to create a good, finely tuned subgroup. In the latter case, selection and preparation of the cued subset of responses is delayed in time because it draws upon slow, central, top-down processes.

4.1. Stimulus-set coding

Let us begin our theoretical analysis with the characteristics of the cue itself, which in the informative cuing conditions usually consists of a spatially extended two-element display, just as shown in Fig. 1. If responses are mapped onto stimuli in a one-to-one fashion, information about possible responses also informs about possible stimuli. Thus the spatial cue provides the observer/actor with the opportunity to focus his or her attention onto a reduced set of possible stimulus locations, thereby facilitating the processing of the forthcoming target stimulus. Since a visual cue is used, it seems fair to assume that this part of the preparation process is mediated by the visual attentional system. Note, however, that, strictly speaking, attention can not be allocated to the locations in space themselves, but rather to the codes or *representations* of these locations (Farah, Brunn, Wong, Wallace, & Carpenter, 1990). This notion has the following two important implications.

Firstly, for a code to represent a location some *frame of reference* is needed that provides the spatial coordinates of the code (e.g., Logan, 1995; Palmer, 1992). Two main frames of reference have been proposed: A viewer-based (or egocentric) frame of reference, according to which locations of objects are coded relative to the viewer; and, a scene-based (or allocentric) frame of reference, according to which locations of objects are coded with respect to a fixed, external frame. There is strong behavioral and neurophysiological evidence that the brain codes visual information in multiple frames of reference, with the frame of reference dominating performance being dependent on the task demands (e.g., Allport, 1989; Baylis & Driver, 1993; Kosslyn, 1994; Lamberts, Tavernier, & d'Ydewalle, 1992; Roswarski & Proctor, 1996; Tipper & Behrmann, 1996; Vecera & Farah, 1994).

Secondly, if selection operates on representational codes, the efficiency of selection should be affected by the way these codes are organized. In the case of visual stimuli, it is well established that preattentive organizational factors, such as embodied in Gestalt principles, have a strong impact on attentional selection. In fact, there is abundant evidence that visual attention operates on structural units or *perceptual groups* that are derived from an early, hierarchical segmentation of the visual scene according to Gestalt principles (e.g., Adini & Sagi, 1992; Goldsmith, 1998;

Kahneman, Treisman, & Gibbs, 1992; Prinzmetal, 1981; Yantis, 1992). For instance, it has been shown that stimulus features are easier to judge if they together form a perceptually well-defined group (e.g., Baylis & Driver, 1992; Gehrke & Hommel, 1998; Hommel, Gehrke, & Knuf, 2000), and that distracting features can be ignored better if they belong to a different rather than to the same object than the target feature (e.g., Harms & Bundesen, 1983; Hommel, 1995).

Consideration of the fact that the efficiency of selection depends on preattentive[3] grouping processes leads one to suspect that at least some part of the pattern of differential cuing benefits observed in the response-cuing task may in fact be unrelated to response preparation. The main idea then would be that the left–right advantage might simply reflect the stronger grouping of the two leftmost and two rightmost stimulus elements. This is most obvious for the studies of Miller (1982), Reeve, Proctor, Weeks, and Dornier (1992, Experiments 1–2, the separated displays), and Adam (1992). In these studies, the possible stimulus locations were not evenly distributed across the visual field, such as shown in Fig. 1, but the distance was much larger between the two innermost locations than between the two leftmost or rightmost locations. Consequently, this may have resulted in a stronger grouping for the two leftmost and rightmost stimulus pairs than for any other two-element stimulus pair. Given the available evidence for grouping effects on attentional selection, it is suggestive then to attribute some, if not all, of the left–right advantage observed in these studies to interactions between preattentive grouping and attentional selection processes, not to response-related factors.

We admit that a visual-grouping account may seem more convincing for displays containing grouped stimulus locations than for displays with equal distances between the possible stimulus locations. True, the salient-features approach of Proctor and Reeve (e.g., Reeve & Proctor, 1990) has already made heavy use of the assumption that left–right cues are more salient than others—and so our grouping assumption can be understood as a direct continuation and generalization of the salient-features theme. Unfortunately, though, previous considerations about saliency were nearly always tied to findings from response-cuing tasks, which makes the notion of saliency rather descriptive and circular.

Note, however, that there is independent evidence in support of our left–right grouping account—even with equally spaced stimulus elements. This evidence is based on studies showing that humans spontaneously and naturally divide the visual space into right-side and left-side parts (Corballis & Beale, 1983, Chap. 3). This right–left partition is based on egocentric reference axes such as the body midline, the head midline, and the vertical retinal meridian (Corballis & Beale, 1983; Parsons,

---

[3] Preattentive processes are defined as those which occur early, are automatic, fast, operate in parallel across the visual field, and underlie the perception of objects which "pop-out." These preattentive processes set up the potential candidates for subsequent attentional processing. Preattentive processes contrast with attentional ones in that the latter occur later, are slower, sequential and spatially constrained (Mack, Tang, Tuma, Kahn, & Rock, 1992). Moreover, such preattentive processing should be distinguished from that which occurs *without* attention, for instance, when attention is focused on some other stimulus (Rock, Linnett, Grant, & Mack, 1992).

1987), even though the position of attention also might bring about a powerful left–right organization (McCloskey & Rapp, 2000; Nicoletti & Umiltà, 1989). If then, as we assume, all these egocentric reference axes are aligned with the center of the four-element stimulus array, then a natural and automatic left–right organization may materialize in the response-cuing task, even with equally spaced stimulus locations. And this is what the available evidence suggests. The left–right advantage emerges both with displays that contain a clear left–right distinction and with displays containing equally spaced elements.

Note, however, that displays exhibiting a clear left–right distinction may yield a larger left–right advantage than equally spaced displays. This was demonstrated in a much neglected study by Reeve et al. (1992, Experiment 2) who used three types of display: (1) the together display (+ + + +); (2) the separated display (+ +   + +); and (3) a partitioned display (+   + +   +). Results showed a larger left–right advantage for the separated display than for the together display. Furthermore, with the partitioned display, which was organized to emphasize the inner–outer grouping, the precuing benefit was largest for the inner–outer cue. These findings demonstrate that the spatial organization of the stimulus set is a powerful mediator of the pattern of precuing benefits.

4.2. Response-set coding

Although we do wish to emphasize that perceptual contributions to response-cuing benefits are important, we are not arguing against contributions from response preparation processes. Clearly, the major purpose for presenting response cues in the response-cuing task is to allow participants to effectively reduce the number of response alternatives and, in fact, there is evidence that this reduction does have an impact on motor preparation. But how is this achieved?

In our view, selecting and preparing a spatial response, or a subset of spatial responses, is not too different from selecting a stimulus or a subset of spatially distributed stimuli. Indeed, it has been proposed that spatial keypress responses are cognitively represented by codes of their relative location (Hommel, 1997; Nicoletti, Umiltà, & Ladavas, 1984; Wallace, 1971). That is, selecting a particular response amounts to activating a response code that represents the required response's location. In some sense, this process is equivalent to spatial stimulus selection, which also can be described as activating a code that represents the required target's location (e.g., Treisman, 1988; Wolfe, 1994).

One important implication of this view is that the selection of (subsets of) spatially distributed stimuli and of responses should follow similar selection rules, which again suggests that grouping processes may not only be observed in perception, but in action planning as well. In fact, we argue that alternative responses may not, or not always, be represented in exactly the same way, but may cluster into particular groups. There is some evidence for this view.

In an important experiment, Miller (1985) showed that the spatial separation of the hands can modify the magnitude of the left–right advantage. In particular, Miller (1985) reported that the left–right advantage was greater when the hands were separated by a distance of 14 cm than when the hands were adjacent. This outcome suggested to Miller (1985) that precuing effects depend on a match between cuing information and a spatial response code because the most obvious correlate of the distance between hands is the extent to which the response locations (or fingers) are perceived as two separate *groups*.

Notwithstanding the commonalities, there are some important differences between stimulus and response coding that a model of response preparation needs to take into account. First, while visual events might be coded within a scene- and/or viewer-based frame of reference, response codes are likely to be coded within an action-centered reference frame (e.g., Lippa, 1996; Tipper et al., 1992)—although, again, multiple action-coding frames may be concurrently active (Hommel, 1998).

Second, in humans, vision is an extremely efficient modality for the precise localization of spatial stimuli. This is not—or to a lesser extent—true for propriocepcis, the modality that informs about the position of fingers in space. In fact, vision is so superior to propriocepcis that—in case of conflict—vision often dominates (Rock & Victor, 1964).

There are several factors that may affect response coding, with effector location being a most dominant candidate. In fact, studies on S–R compatibility have consistently shown that effector location has a much stronger impact on spatial action coding than (perceived) anatomical identity (e.g., Simon, Hinrichs, & Craft, 1970; Wallace, 1971), and this is even true for artificial effectors, such as a hand-held tool (Riggio, Gawryszewski, & Umiltà, 1986). However, it is important to note that effector identity is not without impact. For instance, if response hands are crossed, hand location does have a much bigger influence on response coding than has hand identity, but crossed-hands responses are usually slower and produce somewhat smaller compatibility effects than parallel-hands responses (e.g., Hommel, 1993; Riggio et al., 1986). This shows that effector identity is not completely ignored, but rather suggests that both effector location and effector identity are concurrently coded, with the weight given to each code depending on the task and on the actor's intention (Hommel, 1993).

Interestingly, support for the idea that responses are coded both with respect to effector location and effector identity may also be found in the famous Reeve and Proctor's experiments that manipulated hand placement (i.e., the normal, adjacent hand placement versus the overlapped hand placement, where the fingers of both hands alternated on the response keys). As noted before, the typical finding is that the usual advantage for the "hand-cued" condition (two fingers on the same hand) with the adjacent hand placement switches to an advantage for the "neither-cued" condition (two fingers on different hands) with the overlapped hand placement. Hence, it is commonly concluded that there exists a precuing advantage for the two leftmost and two rightmost locations that depends on the relative spatial positions, not on the specific fingers assigned to the locations (Reeve & Proctor, 1984). However, in the following we will argue that this might be an overly simplified conceptualization.

A careful and detailed re-analysis of Reeve and Proctor's data reveals an interesting and hitherto overlooked phenomenon: Namely, that the time course of the left–right precuing benefit might be different for the adjacent and the overlapped hand placement conditions. If true, this might suggest an important qualification to the standard conclusion that hand coding does not play a role in these precuing experiments.[4] To be specific, with the short preparation interval of 375 ms, the left–right precuing benefit is about twice as large for the adjacent than for the overlapped hand placement condition (i.e., 52 versus 26 ms, respectively, in Reeve & Proctor, 1984, Experiment 1; 66 and 35 ms, respectively, in Proctor & Reeve, 1988, Experiment 1, Session 1). With the longer preparation interval of 750 ms, this difference in precuing benefit for the two hand placement conditions has disappeared. In other words, the speed with which left–right cues generate precuing benefits does seem to depend—at least in part—on the specific fingers assigned to these locations. Unfortunately, at this point, the available data are not conclusive because the relevant statistical information is lacking. To remedy this problem, in Experiment 5, we will address this issue directly and report supportive statistical evidence.

4.3. Interactions between stimulus- and response-set coding

For response-set reconfiguration to work in the response-cuing task, the spatial information provided by the cue is to be transformed into selective response activation. If it is correct that both stimulus codes and response codes are not linearly represented but are clustered or grouped, then the requirement to translate stimulus into response information brings into play the correspondence or compatibility between stimulus and response groups (see also Kornblum, Hasbroucq, & Osman, 1990).

When the default groupings in the stimulus and response sets match, stimulus–response compatibility is high and precue information associated with the default groupings activates directly the relevant response codes, resulting in a RT advantage. Sometimes, however, the stimulus and response organizations are different. This poses the question how the two sets are coordinated when there is a conflict.

Vision, typically the relevant stimulus modality in the response-cuing paradigm, often provides more precise spatial information than the kinesthetic-tactile senses. In fact, as mentioned before, vision is so superior to propriocepcis that in—case of conflict—priority is often given to the visual modality. The dominance of vision is further illustrated by the phenomenon of ventriloquism where visual and auditory judgments of extent and spatial position mismatch. Moreover, as Allport (1989) has pointed out, the driving source of control in the response-cuing task is the appearance of the (visual) cue, suggesting that perceptual grouping logically precedes, and thus may drive, the motoric grouping.

These observations suggest to use the stimulus-related frame for both stimulus and response coding whenever possible, that is, whenever the spatial arrangement of stimulus locations can at least roughly be mapped onto the response organization.

---

[4] Interestingly, Proctor and Reeve (1988) reported evidence that extensive practice may lead to hand coding in addition to spatial coding (supposedly, because practice makes the hand distinction more salient). Furthermore, Proctor and Reeve (1986) showed that, with minimal practice, hand coding does play a role in a precuing task that used *vertical* stimulus and response arrangements. According to Proctor and Reeve (1986), the use of a vertical response arrangement necessitated the hands to be turned inward, thereby making the hand distinction more salient.

Evidence in support of this claim comes from an experiment conducted by Reeve et al. (1992, Experiment 1) that manipulated factorially the spatial characteristics of the stimulus and response sets. Results showed a pattern of precuing benefits that generally followed the grouping manipulation in the stimulus set, not the grouping manipulation in the response set. However, the nature of the response set is not always without influence. There are circumstances where the response set will not allow easy adaptation in order to match the spatial configuration of the stimulus set. For instance, when four fingers of one hand are used instead of two fingers of both hands, the anatomically based left–right grouping in the response set is eliminated. Consequently, the left–right cue loses its salient, hand-based, left–right distinction in the motor buffer, and the left–right advantage should disappear. This is what Proctor and Reeve (1986, Experiment 2) found when using a single-hand response set. This result shows that the nature of the response set may constrain the process of translating visual information into selective response activation.

In sum, the above analysis suggests that stimulus factors dominate or drive the reorganization or reconfiguration of the response set, with response (anatomical) factors providing important constraints.

4.4. The grouping model

Optimal performance in the response-cuing task requires that cue encoding processes reduce the number of stimulus–response alternatives from four to two. In other words, the functional significance of the cue is to get rid of unwanted (i.e., irrelevant) members in the stimulus and response set, and thus to reduce uncertainty. Hence, the cue can be considered to direct a process of subgroup making—that is, a process of stimulus- and response-set reconfiguration—whereby the internal representation of the task is simplified—that is, changed from a 4- to a 2-element reaction task. How is this achieved?

Essentially, our model assumes that on each trial a visual buffer and a motor buffer is created, containing multiple codes of the possible stimuli and responses, respectively. The representations within each of these buffers can be organized in a variety of different ways. Importantly, each stimulus set and each response set has a default organization established preattentively by the bottom-up computation of perceptual and motoric units or subgroups based on Gestalt principles; this process is fast and automatic. With additional processing, however, alternative organizations can be attained. Thus, the pattern of effects that emerge in response-precuing tasks critically depend on the nature of these default groupings and on the time available to reorganize these representations, if necessary. When there is a conflict between the stimulus and response organizations, the Grouping Model assumes a process of response buffer reorganization that attempts to match the configuration of the visual buffer. Grouping factors and interresponse dependencies in the motor buffer, however, may constrain this process. In the following we will explicate some of the details of this model.

Consider, for example, Fig. 2 which represents a 4-element stimulus–response set. Note, however, that the spatial arrangement strongly suggests a grouping of the two

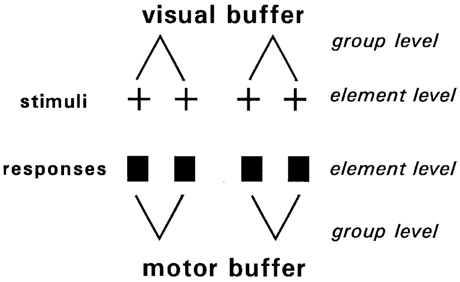


Fig. 2. Hierarchical representation of the stimulus and response set.

leftmost and the two rightmost elements, both in the stimulus and the response domain. As indicated by the binary-tree structure, we assume that such an implicit grouping scheme leads to a hierarchically clustered representation of the stimulus and response sets, with the two elements on either side forming a common cognitive representation (i.e., a chunk) on what one might call the "grouping level."

If representations like this would be involved in the response-cuing task then a left–right advantage would be expected. That is, a cue covering the two left- or rightmost positions would represent a unitary, well-defined "left" stimulus group that would correspond directly and unambiguously with an—equally well-defined—"left" response group. Thus, a "left" and "right" cue would directly activate the two relevant stimulus and response representations, thereby allowing swift and efficient selection.

In contrast, cues that appear in any other pair of locations would activate elements belonging to two different groups, the left and the right group, in both the stimulus and response dimension. Hence, in this situation, code activation at the grouping level does not unequivocally identify the two cued elements, which requires a more detailed analysis of the information provided by the cue. This additional processing step might be considered akin to the "attentional zooming" process described by Stoffer (1991).

Stoffer argued that in order to identify an object (e.g., a letter) that is part of a larger object (e.g., a word), attending to the larger group or superobject might not be sufficient; instead, attention may need to "zoom in" from the higher-order level representation to the lower-order level. Accordingly, whereas left–right cues would allow a fast, automatic selection of a distinctly, preattentively defined, subgroup, other two-element cues would require an additional, time-consuming process to create or identify such a subgroup. Of course, this would be necessary for both the stimulus-set and response-set reconfiguration.

Preliminary support for the Grouping Model of response-cuing effects comes from two lines of evidence. First, consider the results of Miller's (1982) very first experiment that demonstrated the left–right advantage. For subjects who were not explicitly instructed to prepare, Miller found that there was a precuing benefit *only* when the cue indicated the preparation of the two leftmost and rightmost fingers. This was true even for the longest preparation interval of 500 ms, where the inner–outer, alternating, and uncued conditions all showed similar RTs. This was in sharp contrast with the left–right cue condition which already showed a substantial RT benefit after less than 250 ms of preparation time (for a replication see Adam, 1992). These findings are compatible with our claim that the left–right cues engage fast, automatic cue encoding processes, whereas inner–outer and alternating cues need slower, more effortful preparatory processes to establish a selective set.

Second, consider a study by Adam, Keyson, and Paas (1997) that employed *tactile* stimuli. In contrast to the visual precuing task, where precues visually specify a subset of potential finger responses, the tactile precuing task specifies a subset of finger responses (vibro-)tactually, and hence more directly. According to the Grouping Model, this manipulation should eliminate the left–right advantage because all precues specify the cued responses directly and automatically, thereby eliminating any potential differences in subgroup making. Consistent with this prediction, the results showed no left–right advantage. In fact, there was a striking and significant advantage (27 ms) for the inner–outer cues over the left–right cues; this inner–outer advantage was evident for all preparation intervals (range 300–1250 ms).

Adam et al. (1997) noted that the advantage of the inner–outer over the left–right cue condition accords with the results of other studies showing that standard two-choice RTs typically are shorter with a between-hands response repertoire (i.e., fingers of different hands) than with a within-hand repertoire (i.e., fingers of the same hand) (e.g., Alain, Buckolz, & Taktak, 1993; Hasbroucq, Mouret, Seal, & Akamatsu, 1995). In other words, between-hands choices are faster than within-hand choices. This phenomenon was first reported by Kornblum (1965), which is why we will call it the *Kornblum effect*.

The Kornblum effect is important for the following reasons. First, it suggests that when precues establish cleanly defined two-element response sets there should be no left–right advantage but rather an inner–outer advantage. Second, it suggests that most of the published (visual) precuing experiments did not succeed in creating finely tuned two-element response subsets, possibly because the preparation intervals were not long enough, or possibly because the preparation instructions were not explicit enough (to be discussed later, see Experiment 5). Third, it suggests the potential importance of the process of within-subgroup discrimination (that follows the process of subgroup making) in the generation of precuing benefits. This process has often been overlooked, but is explicitly acknowledged in our treatment of response-cuing effects.

5. Purpose of the study

The Grouping Model of response-cuing effects has two major tenets. First, it assigns a critical role to grouping operations in the input and output buffer that define the basic units of selection. Second, the Grouping Model assigns a critical role to the mode of selection by distinguishing between fast, automatic subgroup selection, and slow, effortful subgroup creation. The goal of the present paper was to provide evidence in support of (or against) the idea that grouping operations in the visual and motor buffer conjointly determine the pattern of precuing effects. In a separate paper, we develop and test the automatic vs. effortful processing notion (see Adam, Hommel, & Umiltà, 2002).

The grouping assumption states that response-cuing effects are mediated by interacting perceptual and motoric grouping factors. Hence, precuing effects may arise at multiple loci in the information-processing system, and therefore we investigated the impact of a number of different stimulus- and/or response-related grouping factors on response-cuing benefits. In Experiment 1, the response set was varied to manipulate response-grouping processes. In Experiments 2 and 3, both the stimulus and response sets were varied in an orthogonal fashion in order to study interactions between stimulus- and response-grouping processes. In Experiment 2 we used a two-hands response set; in Experiment 3 a single-hand response set. In Experiment 4, we combined a four-alternative stimulus set with a two-alternative response set, in an attempt to bypass response-selection processes and, thus, to test for contributions from processes concerned with within-subgroup discrimination. Finally, in Experiment 5, we examined the time course of the left–right precuing benefit for the adjacent and overlapped hand placement conditions.

6. Experiment 1: Response set variation

Experiment 1 sought to demonstrate and explore the contribution from response grouping processes. We presented participants with stimuli that clearly suggested grouping in terms of left and right, as can be seen in Fig. 3 (first row). What varied between four different sessions was the response set, that is, the spatial configuration of the response locations and, for obvious anatomical reasons, the fingers placed in these locations.

In one session, participants received the standard *Index-Middle Fingers* response set that was used previously by almost all investigators of differential response-cuing benefits. This set contains a clear, anatomically and perceptually well-defined left–right distinction, and, hence, should produce the common left–right advantage, at least with short preparation intervals. This condition served as a control condition.

In another session, participants received an *Index-Little Fingers* response set. This set still contains the anatomical separation between the two hands, thereby still supporting the grouping of the two left- and rightmost responses. At the same time, however, both the anatomical and perceptual distance between the two same-hand fingers is increased as compared to the standard response set, while the distance between the two index fingers (i.e., between-hands distance) is decreased. This modification was assumed to strengthen the grouping of (the index) fingers across different hands and at least partially work against the common grouping of fingers on the same hand. Thus, it should be more difficult to impose the left–right structure suggested by the stimulus arrangement onto this response set, and consequently the left–right advantage should diminish.

In two more sessions, participants were assigned a *Left-Hand* and a *Right-Hand* response set, respectively. These sets do not only comprise four evenly spaced

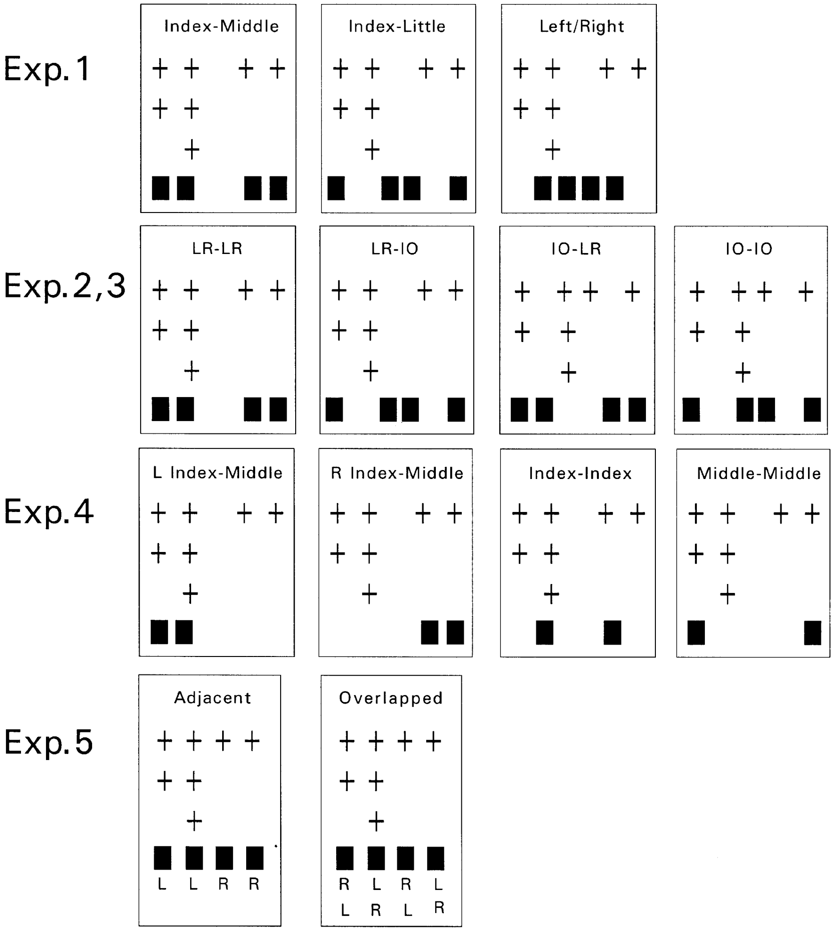


Fig. 3. Overview of the stimulus–response sets used in the five experiments of this study. The plusses and black squares represent the relative locations of the stimulus and response locations, respectively. (*Note.* L, left; R, right; I, inner; O, outer.)

response locations, they also contain four fingers of the same (left or right) hand and, thus, do not provide a structural basis for an anatomically based left–right distinction. Accordingly, imposing the left–right stimulus grouping onto this response set should be even harder than with the Index-Little set (which still contains a left–right distinction due to the use of two hands), so that we expected the left–right advantage to vanish completely.

Finally, we included a preparation interval of 3 s in order to examine the possibility that with a longer preparation interval the left–right advantage (for the Index-Middle Fingers response set) might switch into an inner–outer advantage because of the Kornblum effect.

6.1. Method

6.1.1. Participants

Twenty-four students from Maastricht University, 13 male and 11 female, with a mean age of 22.0 years (range 19–27) participated.

6.1.2. Apparatus and stimuli

The stimuli were plus (+) signs. The two leftmost and two rightmost plus signs were separated by one blank space covering 3 mm; the two inner positions were separated by two blank spaces covering 6 mm. We used four different response sets. In the *Index-Middle Fingers* condition, the index and middle fingers of both hands were placed on the keys (Z), (X), (.), and (/) (the two left-most and two right-most keys on the bottom row of the keyboard). In the *Index-Little Fingers* condition, the index and little fingers of both hands were placed on the keys (Z), (B), (N), and (/). In the *Left-Hand* condition, the little, ring, middle, and index finger of the left hand were placed on the adjacent keys (V), (B), (N), and (M), respectively. In the *Right-Hand* condition, the little, ring, middle, and index finger of the right hand were placed on the keys (M), (N), (B), and (V), respectively. In all response sets, the center of the response set was aligned with the center of the stimulus set.

6.1.3. Procedure

Participants took part in four sessions on separate days with either the Index-Middle Fingers, Index-Little Fingers, Left-Hand, or Right-Hand response set. In each session, participants received a series of 100 trials for each of the five preparation intervals (60, 250, 500, 1000, and 3000 ms). Within a block of 100 trials there were 20 trials for the uncued condition (5 for each of the 4 stimulus conditions), 40 trials for the left–right cue (10 for each of the 4 stimulus positions), and 40 trials for the inner–outer cue (also 10 for each of the 4 stimulus positions). The order of these preparation conditions within a block of 100 trials was random. Order of response set and order of preparation interval was counterbalanced. Twenty practice trials preceded each block of 100 test trials.

6.1.4. Analysis

RTs below 150 ms or in excess of 1250 ms were considered outliers and were excluded from data analyzes; 0.08% of the trials were removed using this criterion. Mean correct RTs and proportions of errors were calculated for each subject as a function of response set, preparation condition, preparation interval, and stimulus–response position. An ANOVA was performed on mean RTs and percentage errors with response set (index-middle fingers, index-little fingers, left-hand, and right-hand), preparation condition (left–right and inner–outer), preparation interval (60, 250, 500, 1000, and 3000 ms), and stimulus–response position (1–4, from left to right) as within-subject variables. Whenever appropriate, in this and all further experiments, the tests were adjusted for heterogeneity of variance and covariances using the Huynh-Feldt corrected significance values. Post-hoc analyzes concerning main effects were carried out using Tukey's honestly significant (hsd) procedure.

Interaction effects were analyzed by tests on simple main effects or by transforming the factorial design into a set of smaller factorials (Keppel, 1982).

6.2. Results

Reaction time. The factor response set was highly significant, $F(3,69) = 9.68$, $p < .001$, and interacted with preparation condition, $F(3,69) = 8.98$, $p < .001$. This interaction indicated that the response sets with fingers on two hands (Index-Middle Fingers and Index-Little Fingers) showed an advantage for the left–right cues, whereas the response sets with fingers on one hand (Left- and Right-Hand) showed an advantage for the inner–outer cues (see Fig. 4a).

There were also two significant three-way interactions: Response Set × Preparation Condition × Preparation Interval, $F(12,276) = 3.97$, $p < .001$, and Response Set × Preparation Condition × Stimulus–Response Position, $F(9,207) = 8.78$, $p < .001$. These three-way interactions are shown in Figs. 5 and 6, respectively.

Errors. The factor response set approached significance, $F(3,69) = 2.72$, $p = .051$, but was qualified by a Response Set × Preparation Condition interaction, $F(3, 69) = 15.50$, $p < .001$. Just as with the RT data, this interaction indicated that the response sets with fingers on two hands showed an advantage for the left–right cues, whereas the response sets with fingers on one hand showed an advantage for the inner–outer cues (see Fig. 4b). This picture was further qualified by a significant three-way interaction involving the factors response set, preparation condition, and stimulus–response position, $F(9,207) = 11.91$, $p < .001$. The relevant data are presented in Table 1.

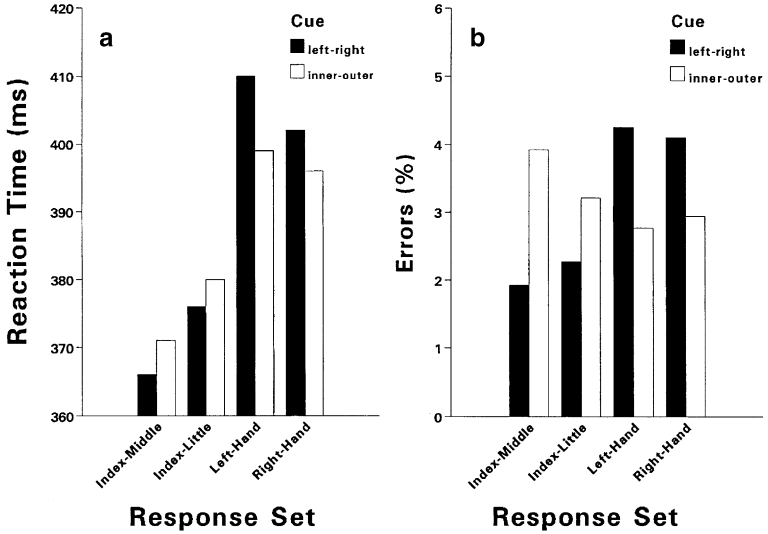


Fig. 4. (a) Mean reaction time and (b) percentage of errors in Experiment 1 as a function of cue condition and response set. Note, data are collapsed across preparation interval.

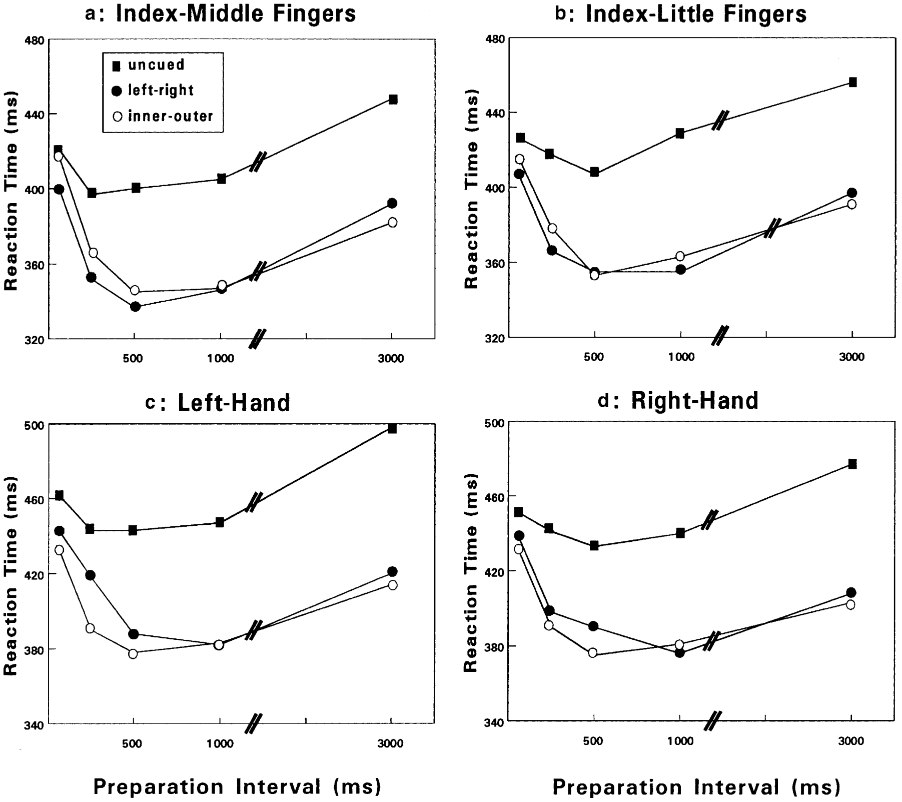


Fig. 5. Mean reaction time in Experiment 1 as a function of cue condition and preparation interval for the four different response sets.

To understand the exact nature of all these 3-way interactions, we conducted separate ANOVAs on the individual response sets. These ANOVAs included three within-subject factors: preparation condition (left–right and inner–outer cue) preparation interval, and stimulus–response position.

6.2.1. Index-middle fingers

Reaction time. Fig. 5a depicts mean RT as a function of preparation condition and preparation interval. There was a near-significant main effect of preparation condition, $F(1, 23) = 3.32, p = .081$, indicating a small left–right advantage. Importantly, however, preparation condition interacted with preparation interval, $F(4, 92) = 6.11$, $p < .001$, indicating that the left–right advantage was only present with the shortest preparation intervals (i.e., up to 500 ms). The longest preparation interval of 3 s showed a reversed effect: an advantage of 10 ms for the inner–outer cues ($p < .01$). This probably reflects the Kornblum effect. Preparation condition also interacted with stimulus–response position, $F(3, 69) = 18.65$, $p < .001$, indicating that the left–right advantage was restricted to the two inner positions (see Fig. 6a).

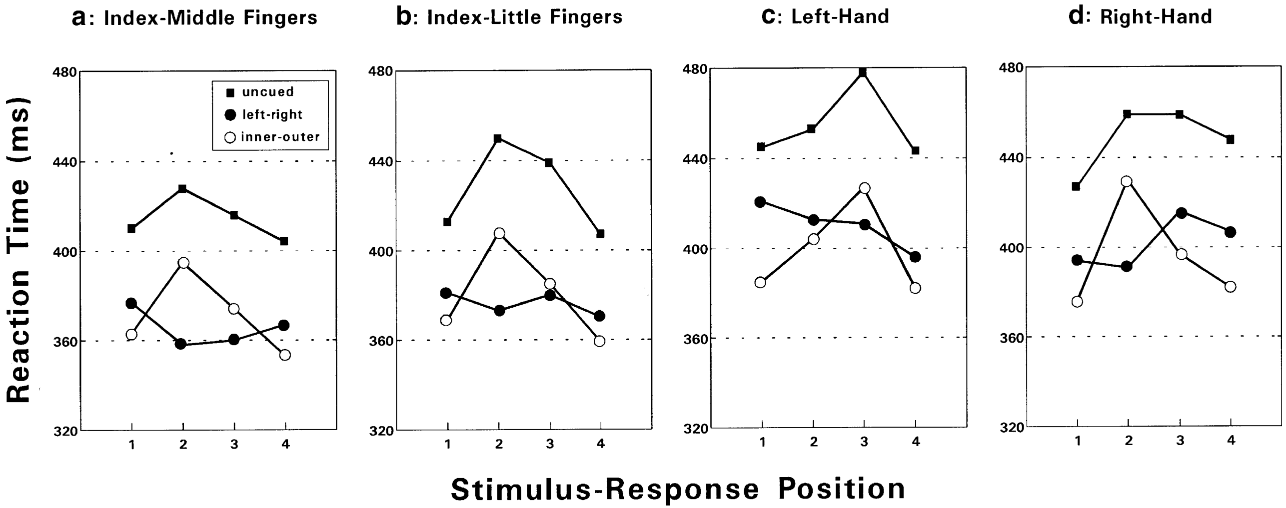


Fig. 6. Mean reaction time in Experiment 1 as a function of cue condition and stimulus–response position for the four different response sets. Nos. 1–4 denote left-to-right positions, respectively. Data are collapsed across preparation interval.

Table 1
Error rates (%) as a function of preparation condition, response set, and stimulus–response position in Experiment 1

Response set	Preparation condition											
	Uncued				Left–right				Inner–outer			
	1	2	3	4	1	2	3	4	1	2	3	4
Index-middle fingers	4.3	5.5	4.0	4.3	2.3	0.8	2.3	2.3	2.5	5.8	5.0	2.6
Index-little fingers	4.2	3.7	4.5	2.8	2.6	2.6	1.5	2.4	1.9	4.6	4.7	1.7
Left-hand	6.3	6.7	7.8	1.8	2.3	8.4	4.9	1.3	1.0	2.7	6.5	0.9
Right-hand	1.2	5.5	5.7	5.2	1.7	3.8	7.5	3.4	0.5	7.6	2.6	1.1

Note. Nos. 1–4 denote left-to-right stimulus–response positions.

Errors. Mean error rate was 3.5%. The ANOVA on the error data yielded similar results as the RT analysis. That is, the left–right advantage was most prominent for the shortest preparation intervals, $F(4, 92) = 4.78$, $p < .01$, and, moreover, was restricted to the two inner positions, $F(3, 69) = 6.36$, $p < .001$.

6.2.2. Index-little fingers

Reaction time. There was no main effect of preparation condition, $F(1, 23) = 1.87$, $p > .15$, nor did preparation condition interact with preparation interval, $F(4, 92) = 1.92$, $p > .12$ (see Fig. 5b). Thus, with the index-little fingers response set, there was no reliable overall RT advantage for the left–right cues. However, the left–right cues still showed an advantage for the second stimulus–response position (see Fig. 6b), as indicated by the significant Preparation Condition × Stimulus–Response Position interaction, $F(3, 69) = 12.58$, $p < .01$.

Errors. Mean error rate was 3.1%. The left–right condition yielded fewer errors than the inner–outer condition (2.3 and 3.2%, respectively, $F(1, 23) = 5.53$, $p < .05$). This advantage was restricted to the inner positions, $F(3, 69) = 7.06$, $p < .01$.

6.2.3. Left-hand

Reaction time. The main effect of preparation condition, $F(1, 23) = 13.07$, $p < .001$, indicated shorter RTs for the inner–outer cue than for the left–right cue (399 vs. 410 ms, respectively). As depicted in Fig. 5c, this main effect interacted with preparation interval, $F(4, 92) = 6.11$, $p < .001$, indicating that the inner–outer advantage only materialized for the shortest preparation intervals. Moreover, the significant interaction between preparation condition and stimulus–response position, $F(3, 69) = 13.29$, $p < .01$, indicated that the inner–outer advantage was mainly evident for the outer positions (see Fig. 6c).

Errors. Mean error rate was 4.2%. The inner–outer cues produced less errors than the left–right cues (2.8 and 4.3%, respectively; $F(1, 23) = 12.36$, $p < .01$). This advantage was evident for all but the third stimulus–response position, $F(3, 69) = 9.36$, $p < .001$.

6.2.4. Right-hand

Reaction time. RTs tended to be shorter for the inner–outer cues than for the left–right cues (396 and 402 ms, respectively). However, this effect did not reach conventional significance, $F(1,23) = 3.69$, $p = .067$, nor did it interact with preparation interval, $F(4,92) = 1.86$, $p > .12$ (see Fig. 5d). However, there was a significant interaction between preparation condition and stimulus–response position, $F(3,69) = 27.26$, $p < .001$, indicating that the inner–outer advantage materialized mainly for the two outer positions (see Fig. 6d).

Errors. Mean error rate was 3.8%. The inner–outer cues produced less errors than the left–right cues (2.9 and 4.1%, respectively, $F(1,23) = 7.76$, $p < .05$). This advantage was evident for all but the second stimulus–response position, $F(3,69) = 14.42$, $p < .001$.

6.3. Discussion

In this experiment different response sets were mapped onto the same stimulus-cue display. The results showed a complex pattern of response-cuing effects that depended on the grouping constraints provided by the respective response set. The control condition (the Index-Middle Fingers response set), which suggested a clustering of responses in terms of left and right, showed the expected left–right advantage, but only for preparation intervals shorter than 1 s. With the preparation interval of 3 s this advantage turned into a disadvantage, because, with finely tuned two-element subsets, between-hand choices are faster than within-hand choices (the Kornblum effect).

Furthermore, the left–right advantage was restricted to the two inner positions. Inspection of the data, however, shows that this phenomenon is in fact a disadvantage for the two inner positions (see Fig. 6a). This is a rather pervasive disadvantage effect, which has been reported before (Adam, 1992, 1994; Adam et al., 1998), and which will be shown to emerge in all further experiments reported in this paper. According to the Grouping Model, it depends on the fact that the two inner positions are not easily coded as belonging to a group, because the spatial cue indicating the two inner positions specifies two elements that intrinsically belong to different groups (i.e., the left–right groups). Hence, controlled processing is needed to break or overrule the low-level, bottom-up formation of left–right subgroups. Thus, when grouping is weak or complex—as is the case with the spatial "inner" cue—it must be supported by a slow, effortful top-down process (Duncan & Humphreys, 1989).

Apparently, however, this is not the case for the two outer positions. Adam (1992, 1994) attributed this latter finding to the special status of outmost positions as landmark or anchor points (for a discussion of anchor points in spatial cognition see e.g. Sadalla, Burroughs, & Staplin, 1980). The importance of the end or border positions (as natural spatial anchors) in providing an organizational structure that facilitates stimulus processing has been demonstrated by experiments showing that, for linear arrays, end items are more quickly and accurately localized than middle items (Merikle, 1974; Mewhort & Campbell, 1978). In addition, the data depicted in Fig. 6 revealed an inverted-U or bowed-shaped RT function for the *uncued* (i.e., the control, 4-choice) condition as a function of stimulus–response position. This finding too demonstrates that choice RTs are shorter for outer than for inner stimulus–response positions in linear arrays. Elsewhere, we have suggested that inner items are more confusable than outer items in 4-element linear arrays because inner items have two neighbors, whereas outer (or end) items have only one (Adam et al., 1998). This greater discriminability for outer positions may facilitate their grouping.

As predicted by the Grouping Model, the special benefit associated with the left–right cues was no longer reliable with the Index-Little Fingers response set, which was assumed to weaken the left–right distinction by strengthening the grouping of fingers from different hands (i.e., the two index fingers). Furthermore, when the anatomical basis for left–right response coding was removed, as with the Left-Hand and Right-Hand sets, the left–right advantage did not only disappear but tended to turn into an advantage for the inner–outer cue. This inversion was reliable for the Left-Hand set only, not for the Right-Hand set; yet, given the mirror-symmetrical result patterns for the two response sets (see Figs. 6c and d), there can be little doubt that both sets affected response-cuing benefits in the same way. Moreover, it should be noted that Proctor and Reeve (1986) also reported an advantage for the inner–outer cue condition with a single hand placement. This finding constitutes a marked deviation of the usual pattern of differential precuing benefits, and reflects the superior grouping of the two outer elements.

Why yielded the single-hand configurations inner–outer advantages whereas the Index-Little Fingers response set did not? This result might seem surprising because the former configurations were less inner–outer configured than the latter. Note, however, that the Index-Little Fingers configuration in fact supported *two* (conflicting) response organizations: one supporting the left–right (i.e., hand) distinction (because the four fingers still were on different hands) and another supporting the inner–outer distinction. Thus, the Index-Little Fingers response organization was somewhat ambiguous, and consequently there was no clear advantage for either type of cue. Furthermore, and as noted before, the fact that the single-hand configurations showed an advantage for the inner–outer cues is due to the superior grouping of the two outer elements (that is, the outer-cue condition). This advantage of the two outer elements was also, albeit to a lesser degree, present in the two-hands response sets (see Figs. 6a and b), but was overridden by the dominant left–right cues, thereby creating the left–right advantage.

In sum, the results of Experiment 1 demonstrated that the nature of the response set is a crucial determinant of response-cuing effects. This conclusion is consistent with the Grouping Model that stresses, among other things, the importance of response grouping processes.

7. Experiment 2: Stimulus and response set variation using fingers on two hands

In the standard response-cuing task, visual cues must be mapped onto finger responses. In our view, this requires the mapping of a visual buffer (or the elements located therein) onto a motor buffer (or the elements located therein). In Experiment 1 we showed that response-related manipulations may affect the pattern of response-cuing benefits, suggesting that grouping processes take place and mediate performance in the motor buffer. However, in Experiment 1 the response factor was manipulated in isolation only, which does not provide too much information about possible interactions between stimulus- and response-related grouping processes. In Experiment 2 we sought to demonstrate such interactions by orthogonally manipulating the nature of the stimulus and response sets. Note that we did not only employ the standard stimulus and response sets with a clear *left–right* distinction—the stimulus–response set combination producing the typical left–right advantage—but we also used stimulus and response sets with a clear *inner–outer* distinction. This latter organization was realized by grouping the two inner stimulus positions closer together than the two left-most and two right-most stimulus positions (see Fig. 3, row 2), and by using the index and little fingers from both hands. The orthogonal combination of these two stimulus sets and two response sets resulted in four different stimulus–response mappings: a left–right stimulus display combined with either a left–right or an inner–outer response set, and an inner–outer stimulus display combined with either a left–right or an inner–outer response set.

The Grouping Model would predict the following results. The standard combination of the left–right stimulus display and the left–right response set should produce the usual left–right advantage, that is, better performance with the left–right than with the inner–outer cues. In contrast, the combination of the inner–outer stimulus display and the inner–outer response set should show the opposite effect, that is, an advantage for the inner–outer cues. These are the predictions for the compatible stimulus–response ensembles (i.e., ensembles where the groupings in stimulus and response sets correspond).

The expectations for the incompatible stimulus–response ensembles are as follow. If vision is the driving agency in stimulus–response translation, as the Grouping Model assumes, we expected the pattern of precuing benefits generally to follow the grouping implied by the stimulus set, on condition that the response set would be amenable to the perceptually salient grouping principle. This latter constraint is critical and results in different predictions for the two incompatible stimulus–response ensembles. Consider first the left–right stimulus display coupled with the inner–outer response set. Given the saliency of the left–right groups in the present stimulus display (seven blank spaces separated the left and right groups, whereas only one blank space separated the elements within the left and right subgroup), we expected a similar grouping principle to be implemented in the inner–outer response set. This is so because the inner–outer response set, even though containing an inner–outer feature, also holds the hand (i.e., left–right) distinction thereby providing an anatomical basis for the left–right grouping principle. Consequently, we expected a pattern of precuing benefits for this condition that would not be too different from the stimulus–response set that combined the left–right stimulus display with the left–right response set.

For the inner–outer stimulus display coupled with the left–right response set the situation is different because the left–right response set—while exhibiting a strong left–right distinction—does not contain an implicit or inherent inner–outer grouping. As a result, the inner–outer grouping implied by the inner–outer stimulus-display might not easily be transferred to the response set, thereby diluting a possible advantage for the inner–outer cues over the left–right cues.

7.1. Method

7.1.1. Participants

One hundred and nineteen students, 50 male and 69 female, with a mean age of 20.8 years (range 18–26) participated.

7.1.2. Apparatus and stimuli

Stimuli were plus (+) signs. There were two stimulus sets. In the *left–right display*, the two left-most and two right-most plus signs were separated by one blank space covering 3 mm; the two inner positions were separated by seven blank spaces covering 21 mm. In the *inner–outer display,* the two left-most and two right-most plus signs were separated by four blank spaces covering 12 mm; the two inner positions were separated by one blank space covering 3 mm. There were also two response sets. In the *left–right response set*, the index and middle fingers of both hands were placed on the keys (Z), (X), (.), and (/) (the two left-most and right-most keys on the bottom row of the keyboard). In the *inner–outer response set*, the index and little fingers of both hands were placed on the keys (Z), (B), (N), and (/).

7.1.3. Design and procedure

Stimulus set and response set were orthogonally combined to produce four stimulus–response conditions: (a) left–right display/left–right response set; (b) left–right display/inner–outer response set; (c) inner–outer display/left–right response set; and (d) inner–outer display/inner–outer response set. Participants were randomly assigned to one of these four conditions (i.e., 31, 30, 31, and 27 participants, respectively).

There were two preparation intervals (60 and 1500 ms) and three preparation conditions (uncued, left–right cue, inner–outer cue). Participants received a series of 100 trials for each of the two preparation intervals. Within a block of 100 trials there were 20 trials for the uncued condition (5 for each of the 4 stimulus positions), 40 trials for the left–right cue (10 for each of the 4 stimulus positions), and 40 trials for the inner–outer cue (also 10 for each of the 4 stimulus positions). The order of these preparation conditions within a block of 100 trials was random. Order of preparation interval was counterbalanced. Twenty practice trials preceded each block of 100 test trials.

7.1.4. Analysis

Using the outlier-criteria of Experiment 1, 0.19% of the trials were removed. Mean correct RTs and proportions of errors were calculated for each subject as a function of response set, stimulus set, preparation condition, preparation interval, and stimulus–response position. An ANOVA was performed on mean RTs and percentage errors with response set (left–right and inner–outer response set) and stimulus set (left–right and inner–outer display) as between-subjects variables, and with preparation condition (left–right and inner–outer cues), preparation interval (60 and 1500 ms), and stimulus–response position (1–4) as within-subject variables.

7.2. Results

7.2.1. Reaction time

There were no main effects of stimulus set and response set (*p*s $> .13$). However, there was a significant interaction involving these two factors, $F(1,115) = 4.81$, $p < .05$. This interaction, depicted in Fig. 7a, reflects the typical set-level stimulus–response compatibility effect (see Kornblum et al., 1990), that is, correspondence between stimulus and response sets produces shorter RTs than noncorrespondence.

The factor stimulus set entered into several significant interactions. In particular, there was a significant Stimulus Set × Preparation Condition × Preparation Interval interaction, $F(1,115) = 41.07$, $p < .001$, as well as a significant Stimulus Set × Preparation Condition × Stimulus–Response Position interaction, $F(3,345) = 10.35$, $p < .001$. These interactions are presented in Figs. 8 and 9, respectively.

Figs. 8a and c indicate that the left–right stimulus display produced the standard left–right advantage with the short preparation interval and the usual cue-equivalence with the longer interval, regardless of response set. This was statistically confirmed by an ANOVA conducted on the data of Fig. 8a and c that included cue condition and cue interval as within-subject variables, and response set as between-subjects variable. This analysis indicated a significant interaction between cue condition and preparation interval, $F(1,60) = 88.8$, $p < .001$, that was independent of response set, $F(1,60) < 1$.

With the inner–outer stimulus display this particular pattern of cuing benefits disappeared, that is, there was no advantage for the left–right cue anymore (see Figs. 8b and d). In fact, examination of the data for the inner–outer stimulus and inner–outer

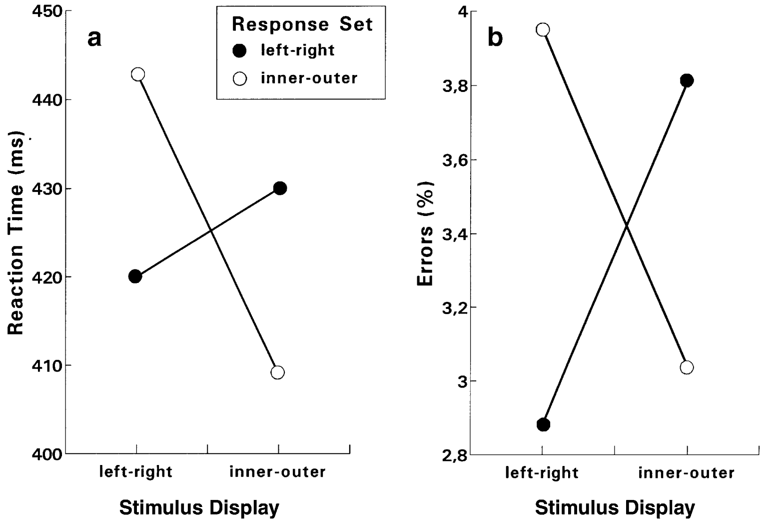


Fig. 7. (a) Mean reaction time and (b) percentage of errors in Experiment 2 as a function of stimulus display and response set.

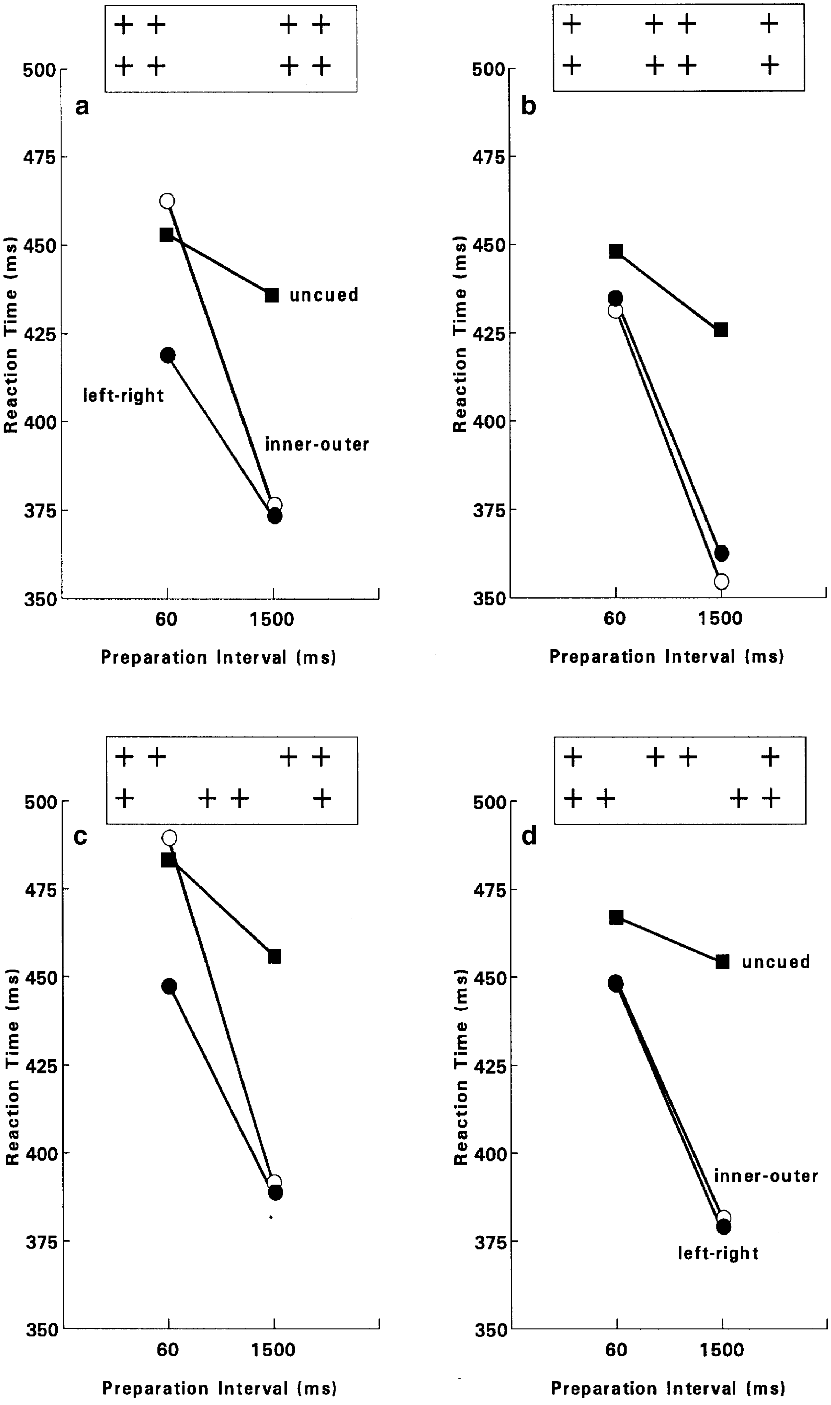


Fig. 8. Mean reaction time in Experiment 2 as a function of cue condition and preparation interval for the four different stimulus–response arrangements.

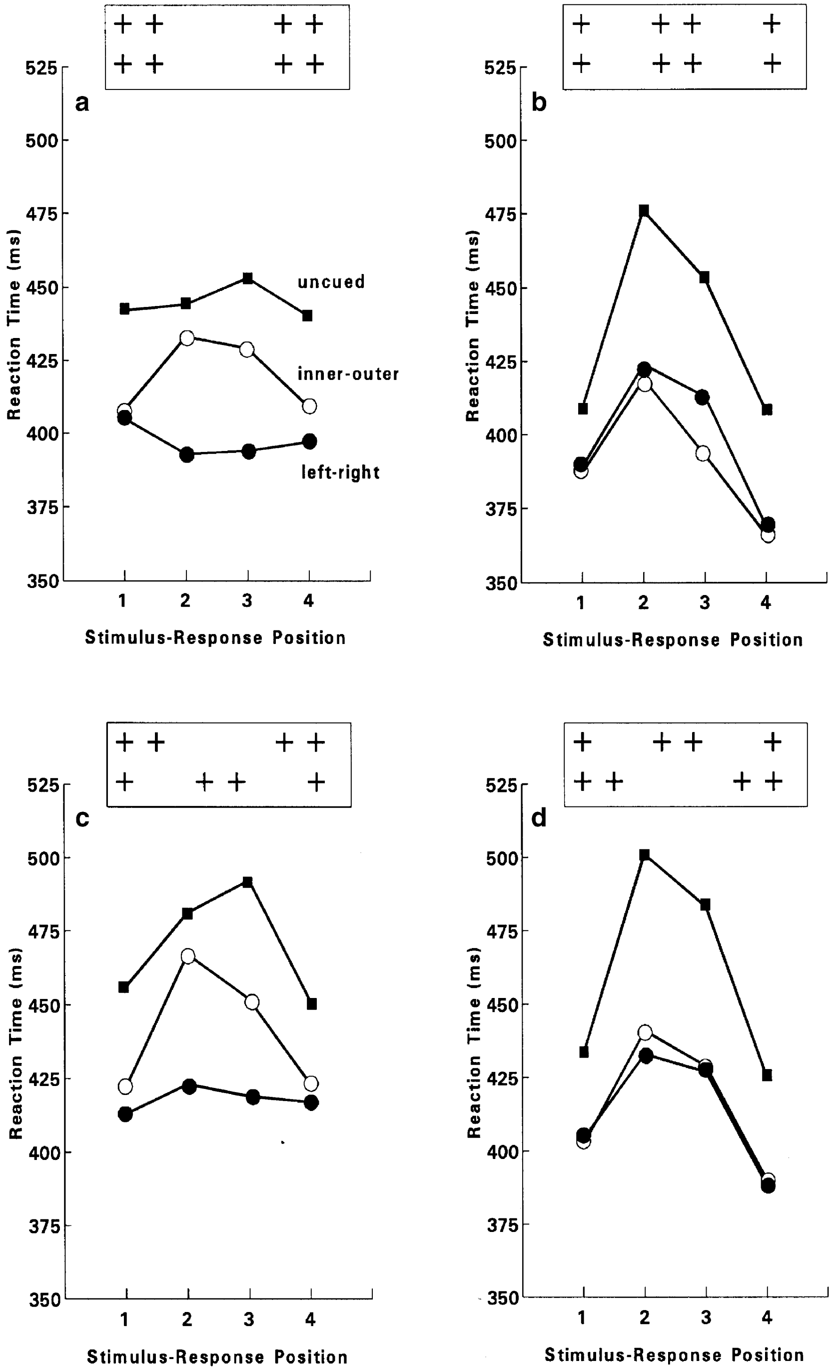


Fig. 9. Mean reaction time in Experiment 2 as a function of cue condition and stimulus–response position for the four different stimulus–response arrangements. Nos. 1–4 denote left-to-right positions, respectively.

response set (i.e., the compatible inner–outer stimulus–response configuration; see Fig. 8b), revealed a main effect of cue condition, $F(1,26) = 4.25$, $p < .05$, indicating a small, though significant advantage for the inner–outer cue over the left–right cue. Moreover, when the inner–outer display was coupled with the left–right response set, this advantage for the inner–outer cue disappeared, $F(1,29) < 1$ (see Fig. 8d). This difference in inner–outer cue effectiveness depending on the response set was statistically substantiated by a significant interaction between response set and cue condition, $F(1,55) = 4.03$, $p < .05$.

Fig. 9 indicates that the left–right advantage (Figs. 9a and c) and the inner–outer advantage (Fig. 9b) was restricted to the two inner stimulus–response positions (all relevant interactions $p < .05$).

7.2.2. Errors

Mean error rate was 3.4%. There were no main effect of stimulus set nor of response set (ps $> .3$), but again there was a significant interaction, $F(1,115) = 4.77$, $p < .05$. This interaction is shown in Fig. 7b, and mirrors the RT data. That is, compatible stimulus–response sets produced fewer errors than incompatible sets. This reflects a spatial stimulus–response compatibility effect.

As with the RT data, the factor Stimulus Set entered into two significant 3-way interactions, namely Stimulus Set × Preparation Condition × Preparation Interval, $F(1,115) = 10.89$, $p < .001$, and Stimulus Set × Preparation Condition × Stimulus–Response position, $F(3,345) = 2.80$, $p < .05$. Generally, the nature of these interactions resembled closely those of the RT data presented in Figs. 8 and 9 (see Table 2).

7.3. Discussion

Experiment 2 examined the joint influence of stimulus- and response-related grouping manipulations on the pattern of response-cuing effects. With the compatible stimulus–response arrangements the left–right grouping produced a left–right advantage, while the inner–outer grouping yielded the opposite effect (i.e., an advantage for the inner–outer cues). With the incompatible stimulus–response

Table 2
Error rates (%) as a function of preparation condition, stimulus set, response set, and stimulus–response position in Experiment 2

Stimulus set	Response set	Preparation condition											
		Uncued				Left–right				Inner–outer			
		1	2	3	4	1	2	3	4	1	2	3	4
Left–right	Left–right	3.6	2.3	2.9	1.6	1.0	0.6	1.0	1.5	3.4	6.1	7.3	3.4
Left–right	Inner–outer	1.9	5.8	4.5	3.2	1.6	1.9	2.3	2.6	4.7	6.3	7.1	5.5
Inner–outer	Left–right	2.7	5.7	7.3	2.3	1.2	4.2	2.3	1.3	2.0	5.8	5.7	1.5
Inner–outer	Inner–outer	1.1	8.5	1.9	2.6	1.5	5.0	4.3	1.7	1.3	4.3	3.2	1.3

Note. Nos. 1–4 denote left-to-right stimulus–response positions.

arrangements, the pattern of cuing effects generally followed the grouping characteristics of the stimulus set, with the response set providing important constraints. That is, whereas the inner–outer response set allowed efficient implementation of the perceptually salient left–right distinction, the left–right response set did not allow easy implementation of the perceptually salient inner–outer distinction. These results are in accordance with the Grouping Model according to which visual factors drive the reorganization of stimulus and motor buffers, with response-related factors constraining the options suggested by the perceptual system.

8. Experiment 3: Stimulus and response set variation using fingers on one hand

The previous experiment showed an asymmetry in the relative effectiveness of the two grouping manipulations: Whereas the left–right grouping principle created a strong left–right precuing advantage (with the short preparation interval), the inner–outer grouping principle succeeded only marginally in producing an inner–outer advantage (compare Figs. 8a and b, respectively). The Grouping Model accounted for this asymmetry by assuming that the hand-distinction was also present in the inner–outer response set, thereby allowing left–right cues to be effective too; this reduced the relative effectiveness of the inner–outer cues.

The present experiment tested this conjecture by replicating the previous experiment, but now using a response set that did not contain the hand distinction. That is, in Experiment 3, the response set contained four fingers selected from *one single* hand—the right hand. The left–right distinction in this response set was implemented by using the first two digits (i.e., thumb and index finger) and the last two (i.e., ring and little fingers); the inner–outer distinction was implemented by using the first and last digit (i.e., thumb and ring finger) and the second and third (i.e., index and middle fingers). Thus, by using four fingers of one hand, we removed the dominant, hand-based left–right distinction, and, hence, reduced the relative strength of this grouping principle on the response side. Consequently, in Experiment 3, relative to Experiment 2, we expected a reduced left–right advantage and a stronger inner–outer advantage (that is, for the compatible left–right and inner–outer sets, respectively).

Furthermore, by using fingers from one hand only, the different response set groupings could be considered arbitrary and artificial, and hence were not expected to constrain much the groupings suggested by the perceptual system. Hence, according to the Grouping Model, compatible and incompatible stimulus–response sets should show the same pattern of precuing benefits, that, generally, would be determined by the grouping implied by the stimulus set.

8.1. Method

8.1.1. Participants

Eighty students, 36 male and 44 female, with a mean age of 20.2 years (range 18–25) participated.

8.1.2. Apparatus and stimuli

The two stimulus sets, the left–right display and the inner–outer display, were the same as those of Experiment 2. The two response sets used fingers from the right hand only. The *left–right response set* consisted of the thumb, index, ring, and little finger. The *inner–outer response set* consisted of the thumb, index, middle, and little finger. The fingers were placed on a specially designed response box with response keys placed on locations that followed the shape of the hand.

8.1.3. Design and procedure

As in Experiment 2, stimulus and response sets were orthogonally combined to produce four stimulus–response conditions: (a) left–right display/left–right response set; (b) left–right display/inner–outer response set; (c) inner–outer display/left–right response set; and (d) inner–outer display/inner–outer response set. Participants were randomly assigned to one of these four conditions (i.e., 20 participants in each of the four conditions). Otherwise the design and procedure were as those of Experiment 2.

8.1.4. Analysis

The outliers procedure removed 0.26% of the trials. The analysis was identical to that of Experiment 2.

8.2. Results

8.2.1. Reaction time

The significant main effect of stimulus set, $F(1,76) = 6.45$, $p < .05$, indicated an overall advantage for the inner–outer display over the left–right display (417 vs. 451 ms, respectively).There was no the main effect of response set, $F(1,115) < 1$, nor was there an interaction between stimulus set and response set, $F(1,76) < 1$. Importantly, there was a significant three-way interaction between stimulus set, response set, and preparation interval, $F(1,76) = 9.93$, $p < .01$. This interaction is depicted in Fig. 10 and indicates that the typical set-level stimulus–response compatibility effect (i.e., correspondence between stimulus and response sets produces shorter RTs than noncorrespondence) emerged only for the short preparation interval of 60 ms, where we observed a significant interaction between stimulus set and response set, $F(1,76) = 4.98$, $p < .05$. However, with the longer preparation interval of 1.5 s there was no interaction, nor were there main effects (all *p*s > .3).

As predicted by the Grouping Model, the factor stimulus set entered into several additional significant interactions; the factor response set did not. In particular, there was a significant Stimulus Set × Preparation Condition × Preparation Interval interaction, $F(1,76) = 11.09$, $p < .001$, as well as a significant Stimulus Set × Preparation Condition × Stimulus–Response Position interaction, $F(3,228) = 2.83$, $p < .05$. These interactions are presented in Figs. 11 and 12, respectively.

An ANOVA conducted on the data underlying Figs. 11a and c indicated a significant interaction between cue condition and preparation interval, $F(1,38) = 23.81$, $p < .001$, that was independent of response set ($p > .7$). This interaction indicated

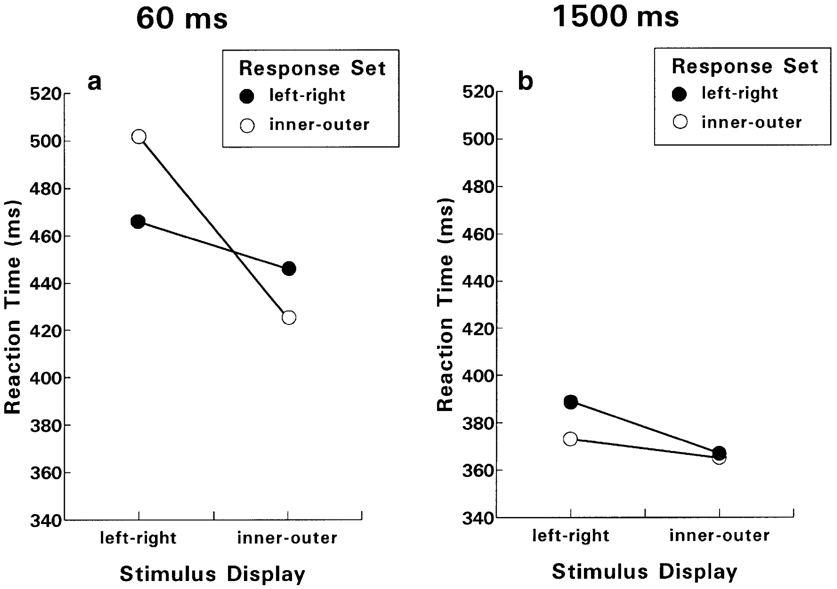


Fig. 10. Mean reaction time in Experiment 3 as a function of stimulus display and response set for (a) the short preparation interval and (b) the long preparation interval.

a small, marginally significant left–right advantage with the short preparation interval of 60 ms ($p < .1$), and a strong inner–outer advantage with the 1500 ms preparation interval ($p < .001$). With the inner–outer stimulus display there was an overall advantage for the inner–outer cue, $F(1, 38) = 56.79$, $p < .001$, that was independent of preparation interval, $F(1, 38) < 1$, and response set, $F(1, 38) = 1.46$, $p > .2$ (see Figs. 11b and d).

As indicated in Fig. 12, the significant Stimulus Set × Preparation Condition × Stimulus–Response Position interaction, indicated that the inner–outer advantage with the inner–outer display materialized mainly for the two inner stimulus–response positions.

8.2.2. Errors

Mean error rate was 4.1%. There were no main effects for stimulus and response set, and there was no interaction between these two variables (*p*s > .3). However, there was a significant 3-way interaction involving the factors stimulus set, cue condition, and stimulus–response position, $F(3, 228) = 3.56$, $p < .05$. This interaction indicated fewer errors for the inner–outer cue, but only for the inner–outer stimulus display and only for the two inner stimulus–response positions. The five-way interaction involving the additional factors response set and preparation interval, $F(3, 228) = 4.65$, $p < .01$, qualified this picture somewhat by indicating that this effect was most pronounced for the inner–outer stimulus set combined with the inner–outer response set and for the long preparation interval (Table 3).

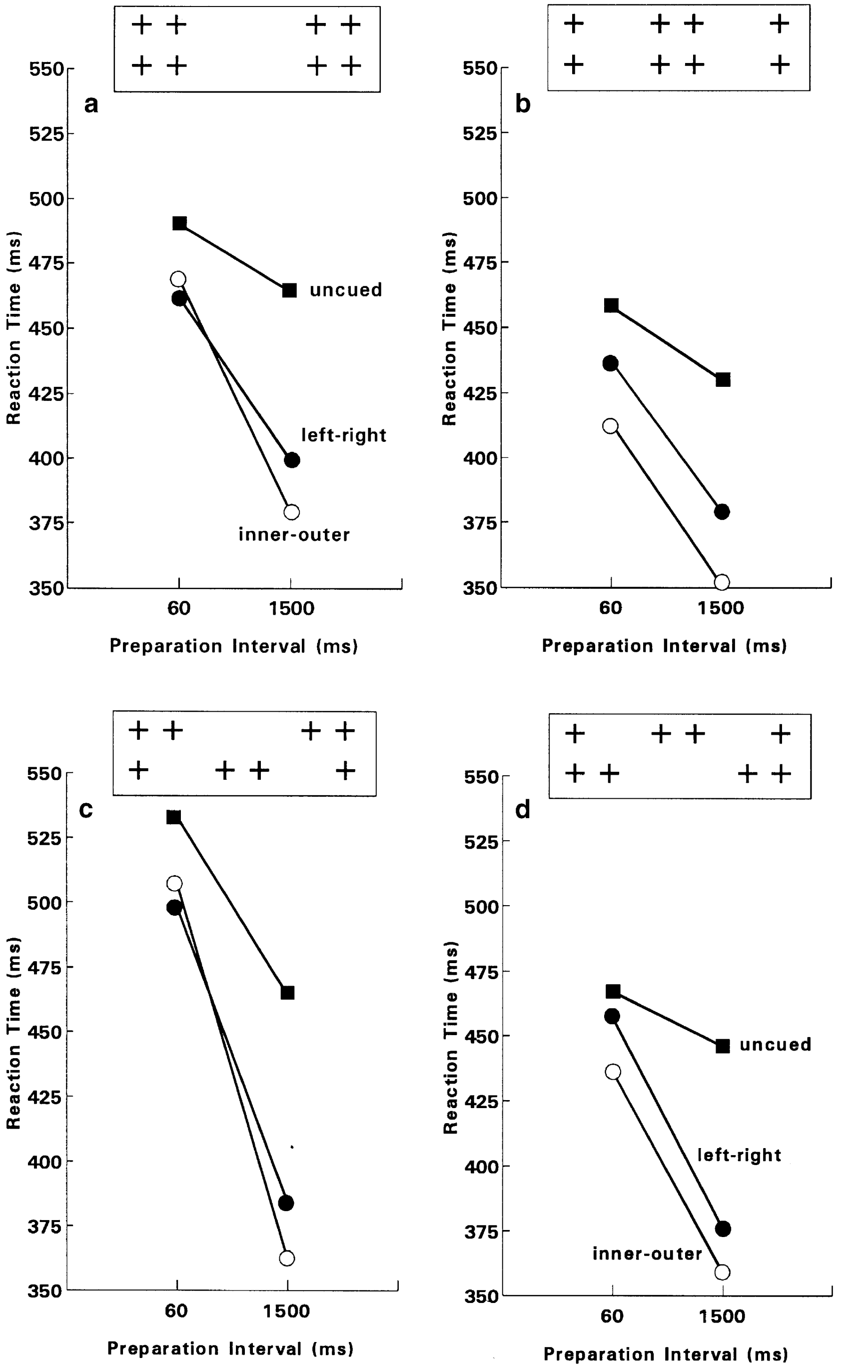


Fig. 11. Mean reaction time in Experiment 3 as a function of cue condition and preparation interval for the four different stimulus–response arrangements.

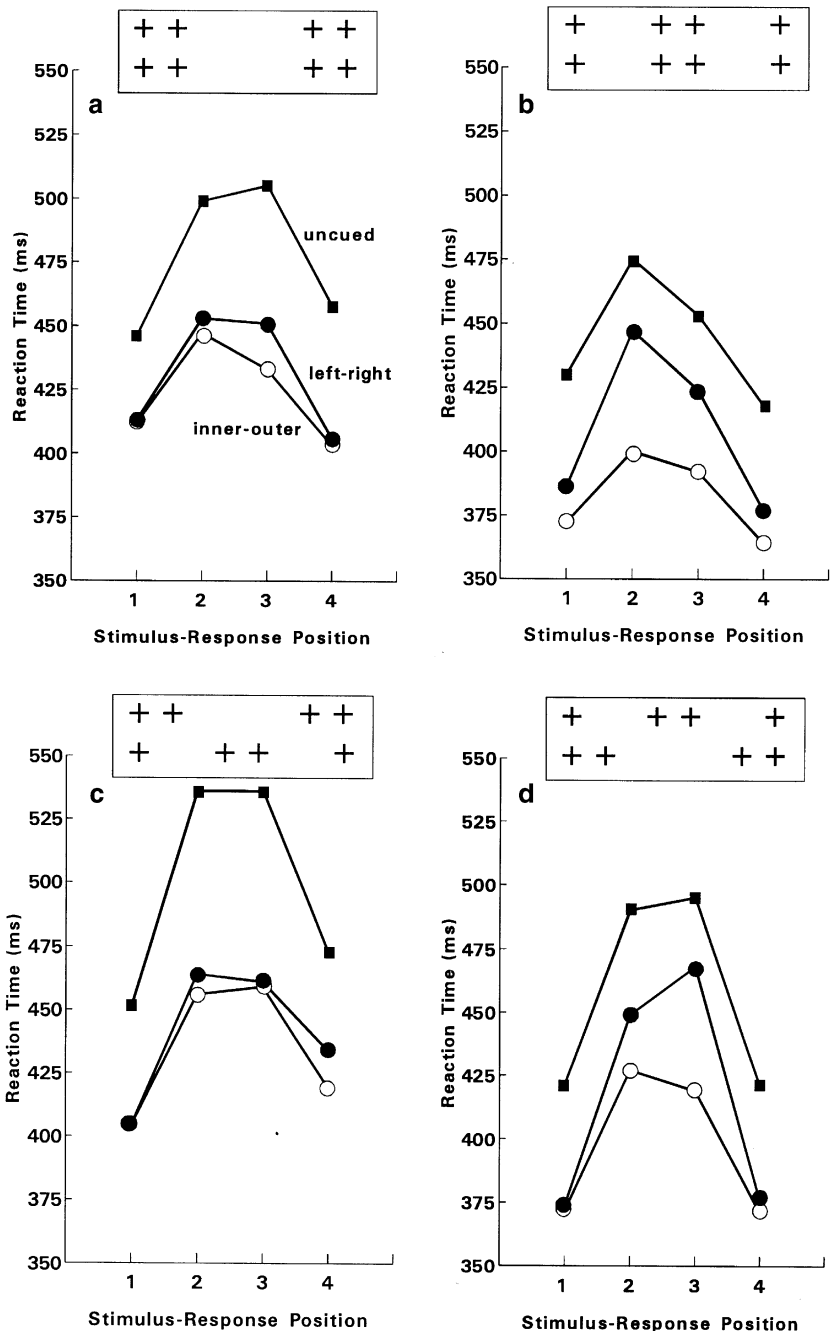


Fig. 12. Mean reaction time in Experiment 3 as a function of cue condition and stimulus–response position for the four different stimulus–response arrangements. Nos. 1–4 denote left-to-right positions, respectively.

Table 3
Error rates (%) as a function of preparation condition, stimulus set, response set, and stimulus–response position in Experiment 3

Stimulus set	Response set	Preparation condition											
		Uncued				Left–right				Inner–outer			
		1	2	3	4	1	2	3	4	1	2	3	4
Left–right	Left–right	5.0	7.5	8.5	7.0	2.8	5.5	4.3	4.3	6.0	5.5	3.8	3.5
Left–right	Inner–outer	3.0	9.0	3.5	1.5	1.3	7.3	3.5	2.3	2.3	6.8	4.5	1.0
Inner–outer	Left–right	4.5	7.5	2.5	2.5	3.3	5.5	7.3	1.3	2.5	4.5	2.3	1.3
Inner–outer	Inner–outer	5.5	6.5	0.2	0.5	2.8	12.8	4.8	1.5	2.5	2.3	1.3	0.8

Note. Nos. 1–4 denote left-to-right stimulus–response positions.

8.3. Discussion

Experiment 3 examined the joint influence of stimulus- and response-related grouping manipulations on the pattern of response-cuing effects using a one-hand response repertoire. The one-hand response set was chosen to get rid of the powerful anatomically based left–right distinction that permeated all response configurations in Experiment 2, and that was held responsible for the observed effects, that is, a relatively strong left–right advantage and a relatively small inner–outer advantage. As predicted by the Grouping Model, the results of Experiment 3 showed that by eliminating the hand-distinction the superiority of the left–right cues disappeared. That is, with the compatible stimulus–response arrangements (and with the short preparation interval) the left–right grouping produced a small, marginally significant left–right advantage, while the inner–outer grouping yielded a strong, robust inner–outer advantage. Moreover, because the one-hand response set did not contain a low-level, inherent grouping bias as did the two-hands response set in Experiment 2, the Grouping Model predicted that both the incompatible stimulus–response combinations would show a pattern of cuing effects that would mirror the grouping characteristics of the stimulus set. This is what we observed. With the one-hand response set, the motor set did not differentially constrain the options provided by the perceptual system. This pattern of results supports the notion that—with response factors neutralized—the grouping of the stimulus display dominates and determines the nominal (distal) grouping of the response set.

Note that this conclusion only holds for the short preparation interval of 60 ms where the left–right stimulus display tended to show a left–right advantage and the inner–outer display an inner–outer advantage. With the longer preparation interval of 1.5 s there was an overall advantage for the inner–outer cue condition, regardless of stimulus set and response set. This outcome supports the idea that with sufficient time (and with a single hand response set), stimulus and motor buffers may be reorganized into equally efficient 2-element subgroups, independent of the grouping-characteristics of the stimulus and response set. The overall advantage of the inner–outer cue with the long preparation interval is probably related to the process of within-subgroup discrimination that follows the process of subgroup making.

That is, judgement of relative position of two stimuli is easier when the two stimuli are on opposite sides of the perceptual midline than when they are on one side. According to this idea, the inner–outer advantage with long preparation intervals is some kind of perceptual variant of the Kornblum effect.

Finally, it is relevant to note that the typical set-level stimulus–response compatibility effect (i.e., correspondence between stimulus and response sets produces shorter RTs than noncorrespondence) emerged only for the short preparation interval of 60 ms and not for the longer preparation interval of 1.5 s (see Fig. 10). This was not the case in Experiment 2 where this stimulus–response compatibility effect materialized for both preparation intervals. This differential outcome underscores the weak and transient nature of the response grouping manipulation with the single-hand response set in Experiment 3 as compared to the more sustained effect obtained with the two-hands response repertoire in Experiment 2.

9. Experiment 4: Discrimination within stimulus–response subgroups

The Grouping Model holds that response-cuing effects are mediated by processes that select two out of four possible stimulus–response alternatives, hence with discrimination *between* stimulus–response subgroups. However, as argued before, performance in the response-cuing task does not only call for selective subgroup making, it also requires the subsequent selection of one single stimulus–response alternative from this 2-element subset. In other words, it also requires a process of discrimination *within* the selected stimulus–response subgroup. Hence, logically, it is possible that differential response-cuing benefits are not so much (or not only) a function of processes concerned with the creation (or selection) of 2-element subgroups, but also (or only) depend on processes concerned with the eventual discrimination of elements within such a subgroup. Therefore, in principle, the pattern of cuing effects might be due to within- rather than between-subgroup discrimination, or it might reflect some joint contribution of both types of process.

To investigate the role of, and the possible contributions from, within-subgroup discrimination, in Experiment 4 we attempted to eliminate the processes concerned with the creation or selection of response subgroups. If, despite this modification, the same pattern of precuing benefits would be found as in our previous experiments, then the Grouping Model with its emphasis on response grouping (i.e., between-subgroup discrimination) might not be correct. In that case, response-cuing effects might be more parsimoniously attributed to the later stage of within-subgroup discrimination.

To allow for the elimination or bypassing of processes having to do with response (sub-)grouping, we modified the response-cuing task by asking participants to place *two* (instead of four) fingers on the response keys (i.e., *either* the index and middle fingers of the left hand, *or* the index and middle fingers of the right hand, *or* the two index fingers, *or* the two middle fingers) and to make a left–right discrimination. This motoric left–right discrimination was coupled with the standard cuing procedure, so that each target stimulus was preceded by either left–right cues or inner–outer cues. The participants' task was to indicate the relative position of the target stimulus within the cued subset of stimulus positions (left or right) by pressing respectively the left or right key with one of the two response fingers. In other words, left and right stimuli were responded to by left and right key press responses, but only relative, not absolute spatial stimulus–response correspondence was relevant. Thus, whereas the typical response-cuing task calls for the creation of a new, different response subgroup on each trial, the present task eliminated this requirement by using fixed 2-element response sets throughout a block of trials.

For this modified cuing task, the Grouping Model provides a different set of predictions than for the standard task version. In particular, it would predict discrimination to be *more* difficult for perceptual cues constituting a strong subgroup than for cues constituting a weak subgroup. Consider, for instance, the left–right cue that supposedly supports fast, preattentive grouping. According to our considerations, discriminating this group from other possible groups should be easy, because good grouping facilitates between-group discrimination (i.e., fast subgroup selection). However, if preattentive grouping has the effect that the grouped elements are more likely to be processed together, it should be more difficult to discriminate the constituent members of a strong group from each other than the constituent members of a weak group (Schneider, 1995). That is, good grouping hampers within-group discrimination. Therefore, our model would predict slower discriminations with left–right cues than with inner–outer cues. Importantly, this should mainly be true for short preparation intervals, where differences in subgroup making are evident. In other words, the Grouping Model would predict a *reversal* of the left–right advantage, but only with short preparation intervals.

Moreover, because of the Kornblum effect, we would expect an overall advantage for the between-hands response sets (i.e., two fingers on different hands) over the within-hand response sets.

9.1. Method

9.1.1. Participants

Forty-four students, 20 male and 24 female, with a mean age of 21.2 years (range 18–28) participated.

9.1.2. Apparatus and stimuli

Stimuli were plus (+) signs. The two left-most and two right-most plus signs were separated by one blank space covering 3 mm. The two inner positions were separated by two blank spaces covering 6 mm. There were two cue conditions: *left–right cues* and *inner–outer cues*. As usual, the target stimulus always appeared in one of the positions signaled by the cue. Participants indicated the relative position of the target stimulus within the cued subset of stimulus positions (i.e., left or right) by pressing the left or right response key, respectively. Keys were operated by four different combinations of two response fingers: (a) the index and middle fingers of the left hand; (b) the index and middle fingers of the right hand; (c) the index fingers of both hands; and (d) the middle fingers of both hands. The first two response conditions made up the *within-hand* response set, the last two the *between-hands* response set. The index and middle fingers of the left and the right hand were assigned to the two left-most and two right-most keys on the bottom row of the keyboard ((Z), (X), (.), and (/)). Note, however, that depending on the response condition, only two fingers were actually placed on keys.

9.1.3. Design and procedure

Response conditions and preparation intervals (60 and 1000 ms) were orthogonally combined to create eight conditions. Participants received a series of 80 trials for each of these eight conditions. Within a block of 80 trials there were 40 trials for the left–right cue condition (10 for each of the 4 stimulus positions), and 40 trials for the inner–outer cue condition (also 10 for each of the 4 stimulus positions). The order of these conditions within a block of 80 trials was random. Order of preparation interval and response condition was counterbalanced. Twenty practice trials preceded each block of 80 test trials.

9.1.4. Analysis

Using the outlier-criteria of Experiment 1, 0.65% of the trials were removed. Mean correct RTs and proportions of errors were calculated for each subject as a function of response condition, cue condition, preparation interval, and stimulus–response position. An ANOVA was performed on mean RTs and percentage errors with response set (within-hand and between-hands repertoire), cue condition (left–right and inner–outer cues), preparation interval (60 and 1000 ms), and stimulus position (1–4) as within-subject variables.

9.2. Results

9.2.1. Reaction time

All main effects were highly significant (*p*s < .001), indicating RT advantages for the between-hands response set, the preparation interval of 1000 ms, the inner–outer cue, and the two outer stimulus positions. These main effects, however, were qualified by two 3-way interactions.

The Response Set × Cue Condition × Preparation Interval interaction, $F(1, 43) = 20.12$, $p < .001$, shown in Fig. 13, reflected two basic results: First, with the short preparation interval of 60 ms, there was an overall advantage of 33 ms for the inner–outer cue, $F(1,43) = 153.37$, $p < .001$, and, moreover, an interaction between response set and cue, $F(1,43) = 36.78$, $p < .001$. This interaction indicated that with the between-hands response set the inner–outer cue yielded shortest RTs, while with the within-hand response set the left–right cue yielded shortest RTs. This finding may be attributed to the relative spatial correspondence between the set of cues and the set of active response fingers, hence another kind of set-level stimulus–response compatibility effect (Kornblum et al., 1990).

Second, with the longer preparation interval of 1000 ms, there were main effects of response set, $F(1,43) = 30.77$, $p < .001$, and of cue condition, $F(1,43) = 10.23$, $p < .01$, but no interaction, $F(1,43) < 1$. The effect of cue condition indicated a

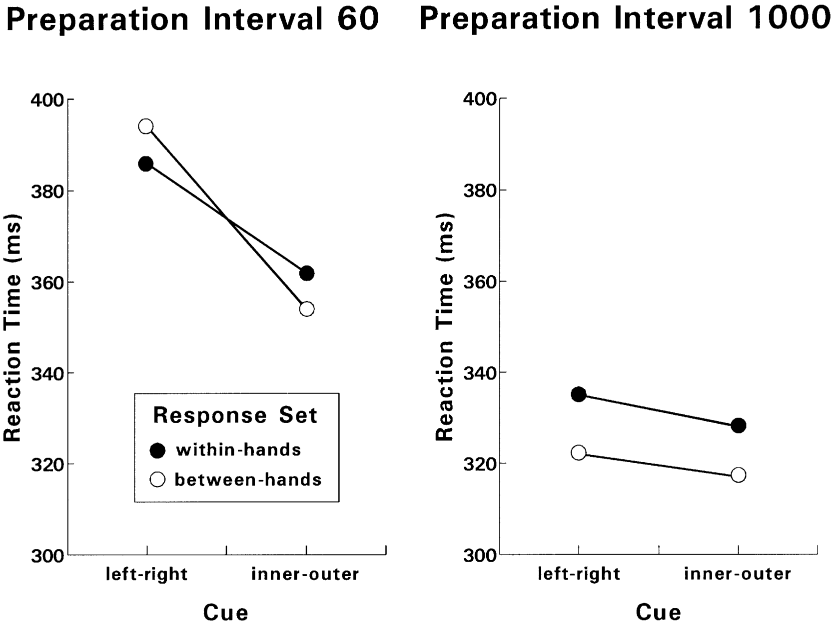


Fig. 13. Mean reaction time in Experiment 4 as a function of cue condition and response set for the 60 and 1000 ms preparation interval.

small advantage (6 ms) for the inner–outer cue, and the effect of response set indicated an advantage (10 ms) for the between-hands response set. This latter finding reflects the Kornblum effect.

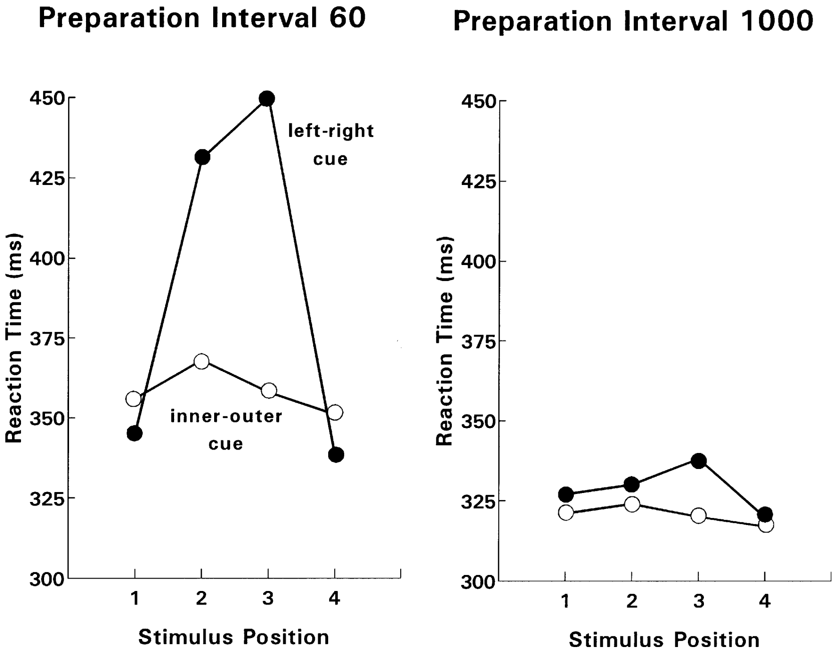
The Cue Condition × Preparation Interval × Stimulus Position interaction, $F(3, 129) = 75.29, p < .001$, is shown in Fig. 14. It indicated that the advantage of the inner–outer cues materialized only for the two inner stimulus positions, and substantially more so with the short preparation interval than with the long preparation interval.

9.2.2. Errors

Mean error rate was 3.5%. All main effects were highly significant (ps $< .001$), and, as with the RT data, there were two 3-way interactions (the Response Set × Cue Condition × Preparation Interval interaction, $F(1,43) = 10.12$, $p < .01$, and the Cue Condition × Preparation Interval × Stimulus Position interaction, $F(3,129) = 24.87$, $p < .001$), that indicated similar pattern of results as found with the RT data depicted in Figs. 13 and 14 (see Table 4).

9.3. Discussion

Cues in the standard response-cuing paradigm typically reduce the number of possible responses (usually from 4 to 2). In the present experiment, however, in


Preparation Interval 60

Preparation Interval 1000

Fig. 14. Mean reaction time in Experiment 4 as a function of cue condition, preparation interval, and stimulus position. Nos. 1–4 denote left-to-right positions, respectively.

Table 4
Error rates (%) as a function of preparation condition, preparation interval, and stimulus response in Experiment 4

Preparation interval (ms)	Preparation condition							
	Left–right				Inner–outer			
	1	2	3	4	1	2	3	4
60	1.4	16.8	16.1	1.0	1.2	2.4	2.3	0.8
1000	1.9	3.7	2.7	1.1	1.7	1.3	1.2	1.0

Note. Nos. 1–4 denote left-to-right stimulus–response positions.

separate block of trials, there were always only two possible responses, so the present paradigm eliminated contributions from response grouping processes. The most important result was that the usual left–right cue advantage turned into a disadvantage, that is, performance was better with inner–outer cues than with left–right cues, especially for the short preparation interval. This outcome has two important implications. First, it strengthens the claim that perceptual grouping processes mediate performance in the response-cuing task. If, as the Grouping Model claims, left–right cues constitute stronger perceptual subgroups than inner–outer cues, then left–right cues should show slower within-group discriminations than inner–outer cues. This is what the results indicate. In addition, the fact that this effect was strongly evident with the short preparation interval of 60 ms, and had nearly vanished with the longer preparation interval of 1000 ms, corroborates the idea that perceptual subgroup making costs time, and, moreover, that left–right and inner–outer cues may evoke different mechanisms of subgroup making, namely a fast process of subgroup selection and a slower process of subgroup creation, respectively.

Second, the reversal of the left–right advantage in this experiment suggests that the typical pattern of differential response-cuing effects are indeed mediated by processes concerned with between-subgroup discrimination (i.e., selective subgroup making) rather than with the subsequent processes of within-group discrimination (i.e., final response selection). This claim is further supported by the finding that with the longer preparation interval of 1000 ms there was a distinct Kornblum effect, that is, an advantage for the between-hands response set that materialized regardless of cue condition. Interestingly, this effect was also demonstrated in Experiment 1 (Index-Middle Fingers response set), where it emerged with the longest preparation interval of 3 s. The finding that in the present experiment the Kornblum effect was already present with only 1 s of preparation interval is probably related to the use of a fixed two-element response set that guarantees a "finely tuned" or "well established" motor set. The comparable importance of a finely tuned perceptual set for the emergence of a Kornblum effect is demonstrated by its absence when the left–right cue is shortly presented. Hence, for the Kornblum effect to materialize both the stimulus and response sets should be finely tuned and in correspondence.

10. Experiment 5: Adjacent versus overlapped hand placement

Contrary to the widely held view that the left–right advantage is independent of the specific fingers assigned to the response locations (e.g., Proctor, Reeve, & van Zandt, 1992), the Grouping Model would predict that overlapping the hands (that is, with the fingers from each hand alternated) should greatly affect—yes, even eliminate—the left–right advantage typically found with the adjacent hand placement. This is so because crossing the fingers disrupts the natural match between the perceptually salient left–right distinction and the anatomically (i.e., hand) based left–right distinction. In other words, with the hands overlapped, the perceptual left–right distinction can not easily be transferred onto the anatomically based (i.e., hand-based) left–right distinction. But how then to reconcile this prediction with the seemingly robust finding that, with an overlapped placement of hands, the largest precuing benefit is still for the left–right cues even though fingers of different hands are assigned to these cues (e.g., Reeve & Proctor, 1984, Experiment 3)?

The answer to this question contains two parts. First, as noted in the introduction, there is a clear hint in Reeve and Proctor's data that, in fact, there might be a differential time course for the adjacent and overlapped hand placement conditions in generating left–right precuing benefits. If true, this would cast serious doubt on the standard conclusion that effector identity does not play a role in the pattern of precuing benefits. One goal of Experiment 5, therefore, was to address this issue directly by examining the time course of the left–right precuing benefits for the adjacent and overlapped hand placement conditions.

Second, it is possible that Reeve and Proctor's critical result with the hand placement manipulation is restricted to, and thus an artifact of, two procedural factors: Namely, the task instructions provided to participants regarding the possibilities of preparation, and the presentation mode of the preparation intervals. Adam and van Veggel (1992) investigated these two procedural factors and found them to be of utmost importance for the pattern of precuing benefits. They noted that Reeve and Proctor in most—if not all—of their experiments did not explicitly tell their subjects that precue information could always be used to prepare responses. Furthermore, Adam and van Veggel (1992) drew attention to the natural, strong grouping of the left–right cues. On the basis of these two observations, Adam and van Veggel argued that when participants are not explicitly instructed to prepare *all possible* pairs of responses, participants might adopt active preparation strategies in the salient left–right cue condition only, but not—or to a lesser extent—in the inner–outer and alternating cue conditions. According to this logic, the left–right advantage is not so much the result from participants being unable or less able to prepare fingers on different hands, but rather from participants being not or insufficiently aware of the preparation possibilities in the less natural finger pairings.[5]

Moreover, they noted that Reeve and Proctor typically used the factor preparation interval as a variable that varied randomly within a block of trials, thereby precluding participants to anticipate the duration of the upcoming preparation interval. Adam and van Veggel argued that this procedure may have led participants to prepare the obvious pair of responses on all trials, but the less obvious pairs only on those trials that employed the longer preparation intervals. This possibility was consistent with the observation that the inner–outer and alternating cues showed a preparation benefit only with the longer preparation intervals of 1.5 and 3 s, and not with the shorter intervals of 375 and 750 ms, where the left–right cues, on the other hand, did show a substantial precuing benefit (Reeve & Proctor, 1984, Experiment 1).

When Adam and van Veggel (1992) manipulated these procedural factors they found that when participants are explicitly instructed to prepare all possible finger pairings, and when they know in advance how long the preparation interval is (because of a blocked presentation mode), the relative advantage of the left–right cues over the inner–outer cues is greatly reduced (by about 60%). This is so because under these task constraints the inner–outer cues produce significant RT benefits also with the shorter preparation intervals. Hence, Adam and van Veggel (1992) concluded that response preparation has an important strategic component: Participants preferably engage in preparation activities when procedural constraints make it apparent, convenient, and/or important to do so. This conclusion accords with observations made by other researchers (Miller, 1985; Reeve & Proctor, 1984, Experiment 2; Requin, 1980; Sanders, 1983).

---

[5] Studies on left–right dominance corroborate the idea that participants spontaneously instruct and prepare themselves in terms of left–right responses (e.g., Hommel, 1996; Nicoletti & Umiltà, 1984).

Thus, Adam and van Veggel (1992) argued that when one wants to create optimal, and uniform preparation conditions, explicit preparation instructions in combination with blocked preparation intervals should be used. Unfortunately, Reeve and Proctor's experiment that manipulated hand placement did not conform to these constraints: Participants were not explicitly told to prepare all possible finger pairings nor were the preparation intervals grouped together in separate blocks of trials. Hence, it is possible that Reeve and Proctor's conclusion—that the left–right advantage is independent of finger placement—is only valid for their specific task constraints. Thus, we considered it important to determine whether Reeve and Proctor's conclusion would generalize to task conditions that would allow optimal preparation strategies in all cue conditions.

In Experiment 5, we asked whether the typical pattern of precuing effects would still be independent of hand placement when subjects were explicitly instructed to prepare for all precues and when the different preparation intervals were presented in separate blocks of trials. This experiment thus examines the combined effects of the hand placement manipulation of Reeve and Proctor (1984) and the "optimal" preparation procedures of Adam and van Veggel (1992) on precuing efficiency. In contrast to the translation account favored by Proctor and Reeve, the Grouping account would allow for a significant mediating influence of hand placement on the time course and pattern of differential precuing benefits. In particular, it would predict a strong negative influence of the overlapped hand placement condition on the precuing efficiency of the left–right cues. This is so, because the overlapped hand placement condition greatly reduces the good grouping of the two leftmost and two rightmost elements in the response buffer, while leaving the inner–outer and alternating groupings relatively intact. Consequently, we expected the left–right advantage to disappear, and perhaps even to turn into a disadvantage. In addition, we expected a slower time-course of left–right precuing benefits for the overlapped hand placement condition than for the adjacent hand placement condition.

10.1. Method

10.1.1. Participants

Forty students, 18 male and 22 female, with a mean age of 21.4 years (range 18–26) participated in the experiment.

10.1.2. Apparatus and stimuli

The stimuli were the same as in Experiment 1.

10.1.3. Procedure

There were two hand placements. Half the participants performed with the adjacent hand placement, where the hands were placed adjacent to each other so that the middle and index fingers of the left hand and the index and middle fingers of the right hand were to depress the *V*, *B*, *N*, and *M* keys, respectively (adjacent keys located in the middle of the bottom row of the keyboard). The other half of the participants performed with an overlapped hand placement. There were two versions of the overlapped hand placement condition. For half of the participants ($n = 10$), the fingers were overlapped and alternated, so that the placement of fingers from left to right was right index finger, left middle finger, right middle finger, and left index finger (this was identical to the overlapped hand placement condition used by Reeve & Proctor, 1984, Experiment 3). For the other half of the participants ($n = 10$) only the index fingers were overlapped, so that the placement of fingers from left to right was left middle finger, right index finger, left index finger, and right middle finger.[6] In each of these two overlapped hand placement conditions, half of the participants performed with their left hand (finger) on top, whereas the other half performed with their right hand (finger) on top. The four fingers in the overlapped hand placement condition depressed the same four keys used in the adjacent hand placement condition.

There were five preparation intervals (60, 250, 500, 1000, and 2000 ms) and four cue conditions (uncued, left–right, inner–outer, alternating). Participants received a series of 140 trials for each of the five preparation intervals. Within a block of 140 trials there were 20 trials for the uncued condition (5 for each of the 4 stimulus positions), 40 trials for the left–right condition (10 for each of the 4 stimulus positions), 40 trials for the inner–outer condition (also 10 for each of the 4 stimulus positions), and 40 trials for the alternating condition (also 10 for each of the 4 stimulus positions) The order of these preparation conditions within a block of 140 trials was random. Order of preparation interval was counterbalanced. Twenty-five practice trials preceded each block of 140 test trials. Subjects were informed regarding the nature of the task and were explicitly told and encouraged to take advantage of all the cues.

10.1.4. Analysis

The RTs (0.29%) were removed because they were considered outliers. Mean correct RTs and proportions of errors were calculated for each subject as a function of hand placement, preparation condition, preparation interval, and stimulus–response position. An ANOVA was performed on mean RTs and percentage errors with hand placement (adjacent and overlapped) as between-subject variable, and with preparation condition (uncued, left–right, inner–outer, alternating), preparation interval (60, 250, 500, 1000, and 2000), and stimulus–response position (1–4, from left to right) as within-subject variables.

---

[6] We included the "overlapped index fingers" condition, because this condition seemed to be biomechanically less awkward than the "overlapped index and middle fingers" condition used by Reeve and Proctor (1984). This issue is important because Miller (1985) argued that the Reeve and Proctor's results concerning the overlapped hand placement condition are difficult to compare with those of the adjacent placement condition because the overall RTs were much larger with the overlapped than the adjacent hand placements (751 versus 529 ms). Thus we wanted to examine whether the pattern of differential precuing benefits would be dependent on the relative difficulties of executing responses. However, an initial analysis of our data indicated that this was not true: the two overlapped hand placement conditions showed almost identical mean RTs in all the four main cuing conditions (i.e., uncued, left–right, inner–outer, and alternating). Hence, in the further analysis and reporting of data we did not differentiate between these two sub-conditions.

10.2. Results

10.2.1. Reaction time

All main effects were significant (all Fs > 7.5, all ps $< .001$). There were several significant interactions involving the factor hand placement. The significant Hand Placement × Preparation Condition interaction, $F(3, 114) = 11.79$, $p < .001$, indicated that the adjacent hand placement condition produced the usual pattern of differential precuing benefits (i.e., fastest RTs for the left–right cue, intermediate RTs for the inner–outer cue, and slowest RTs for the alternating cue), whereas the overlapped hand placement condition produced a different pattern, namely fastest RTs for the inner–outer cue, intermediate for the left–right cue, and slowest for the alternating cue (see Fig. 15). In other words, the usual advantage for the left–right condition with the hands adjacent reversed to an advantage for the inner–outer condition with the hands overlapped.

Note, however, that this overall advantage for the inner–outer condition with the hands overlapped emerged mainly because of a disadvantage of the left–right cue with this hand placement. That is, the overall precuing benefit for the left–right cue dropped from 62 ms with the adjacent hand placement to 36 ms with the overlapped hand placement. In contrast, the overall precuing benefit for the inner–outer cue was relatively independent of hand placement, namely 52 and 51 ms for the adjacent and overlapped placement conditions, respectively. The same is true for the alternating cue condition which showed an overall precuing benefit of 34 and 30 ms for the adjacent and overlapped hand placement conditions, respectively.

This differential pattern of cuing effects for the adjacent and overlapped hand placements varied as a function of preparation interval, as evidenced by a significant

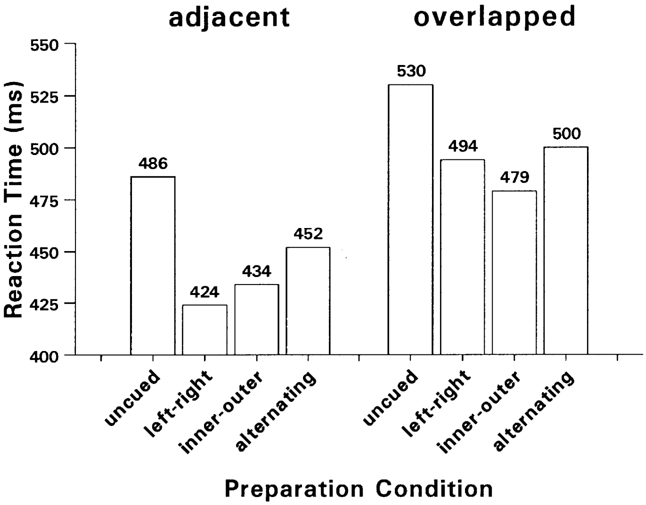


Fig. 15. Mean reaction time in Experiment 5 as a function of preparation condition for the adjacent and overlapped hand placements.

three-way interaction of preparation interval, hand placement, and preparation condition, $F(12, 456) = 2.44$, $p < .01$ (see Fig. 16). With the adjacent hand placement, the advantage of the left–right cues over the inner–outer cues was mainly restricted to the shorter preparation intervals of 60 and 250 ms, whereas with the overlapped hand placement the advantage of the inner–outer cues over the left–right cues occurred only with the longer preparation intervals (i.e., 500 ms and longer).

Hand placement also interacted with stimulus–response position, $F(3, 114) = 4.66$, $p < .01$, indicating a more shallow inverted-U curve as a function of stimulus–response position for the adjacent (437, 457, 475, and 427 ms, respectively) than for the overlapped hand placement condition (473, 534, 528, and 470 ms, respectively). This two-way interaction was further qualified by a three-way interaction involving the factor preparation condition, $F(9, 342) = 7.28$, $p < .001$. This interaction, which is graphically depicted in Fig. 17, indicates that the advantage of the left–right cue with the hands adjacent was restricted to the two inner positions, whereas the advantage of the inner–outer condition (over the left–right cue) with the hands overlapped was restricted to the third stimulus–response position.

Fig. 18 shows the time course of the left–right precuing benefit for the two hand placement conditions. As evidenced by a significant two-way interaction between preparation interval and hand placement, $F(4, 152) = 3.59$, $p < .01$, the left–right precuing benefit accrues much faster with the hands adjacent than with the hands overlapped. This outcome substantiates our observation of a similar pattern present in Proctor and Reeve's data (Reeve & Proctor, 1984, 1988).

10.2.2. Errors

Overall error rate was 5.5%. There was a main effect of hand placement, $F(1, 38) = 12.17$, $p < .001$ indicating more errors with the hands overlapped than

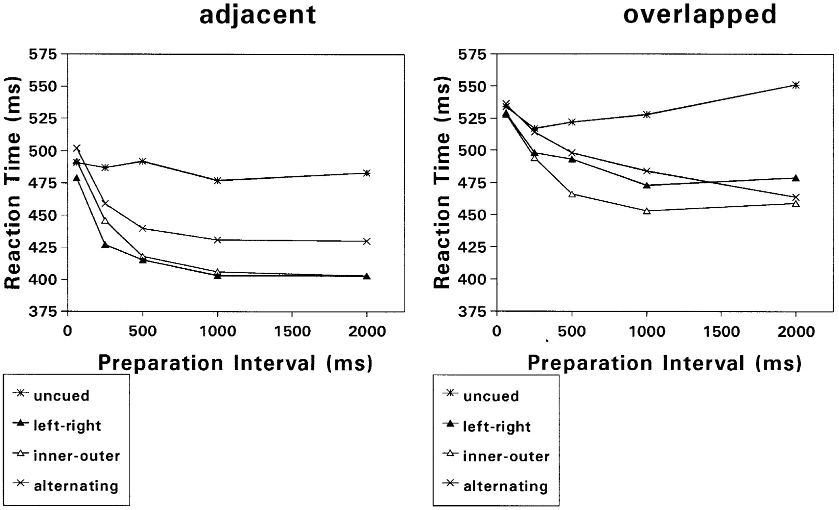


Fig. 16. Mean reaction time in Experiment 5 as a function of preparation condition and preparation interval for the adjacent and overlapped hand placements.

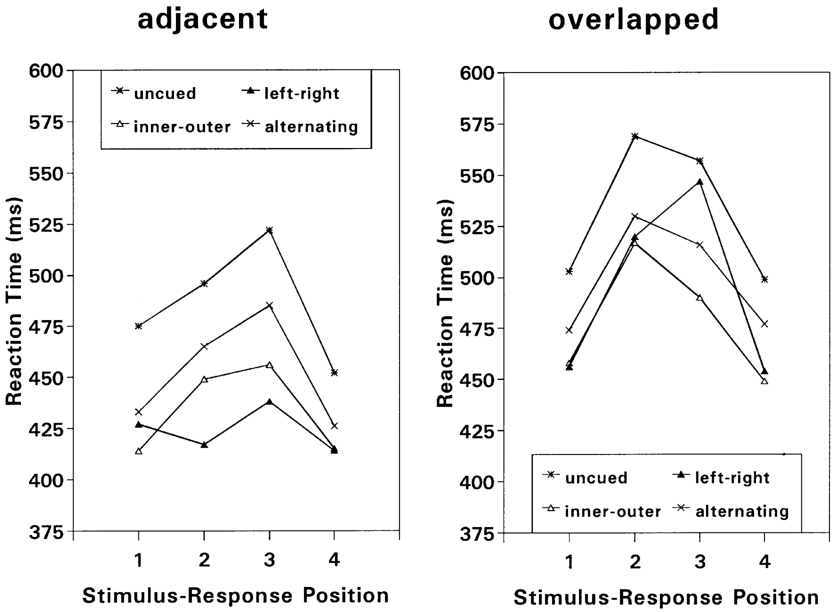


Fig. 17. Mean reaction time in Experiment 5 as a function of preparation condition and stimulus–response position for the adjacent and overlapped hand placements. Nos. 1–4 denote left-to-right positions, respectively.

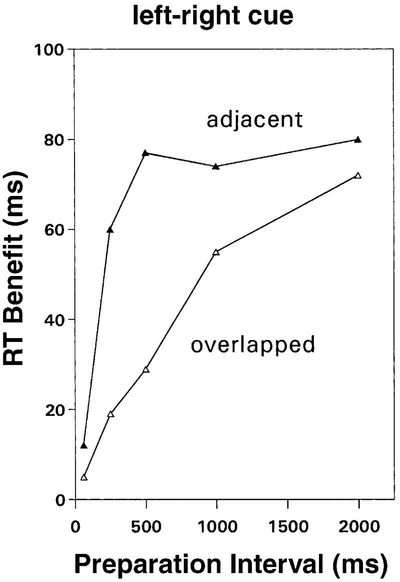


Fig. 18. Mean reaction time benefit for the left–right cue as a function of preparation interval for the adjacent and overlapped hand placement conditions.

with the hands adjacent (i.e., 6.9 vs. 4.0%, respectively). There was also a main effect of preparation interval, $F(4, 152) = 3.96$, $p < .01$, indicating that the three shortest preparation intervals produced more errors than the two longest (i.e., 5.7, 6.0, 6.4, 4.5, and 4.8% of errors for preparation intervals of 60, 250, 500, 1000, and 2000 ms, respectively). The main effect of stimulus–response position, $F(3, 114) = 33.13$, $p < .001$, indicated substantially more errors for the two inner than for the two outer positions (i.e., 4.0, 7.3, 7.5, and 2.9% for left-to-right positions, respectively).

Finally, there was a significant Hand Placement × Preparation Condition × Stimulus–Response Position interaction, $F(9, 342) = 2.07$, $p < .05$. This interaction indicated that with the hands adjacent the error pattern closely resembled the RT pattern in that the left–right cue produced the fewest errors (2.6%), followed by the inner–outer cue (3.7%), the alternating cue (4.3%), and the uncued condition (5.4%). These differences were mainly apparent for the two inner stimulus–response positions. With the hands overlapped there was a different pattern. Here, the inner–outer cue produced the fewest errors (6.5%) followed by the left–right cue (7.0%) and the alternating cue (7.7%). The uncued condition produced an intermediate number of errors (6.8%). Again, the differences between these conditions were most apparent for the two inner stimulus–response positions (see Table 5).

10.3. Discussion

Experiment 5 demonstrated that with optimal preparation opportunities and with the hands overlapped, the usual advantage of the left–right cues switches to an advantage for the inner–outer cues. This outcome is not in accordance with the results of other studies reporting that the left–right advantage is independent of the position of the hands/fingers (e.g., Proctor & Reeve, 1988; Reeve & Proctor, 1984). The crucial difference between these previous reports and the present experiment is that the present experiment explicitly instructed participants to prepare all possible pairs of responses, and, moreover, used a blocked presentation mode of preparation interval. The present experiment shows that with preparation opportunities equalized and

Table 5
Error rates (%) as a function of hand placement, stimulus–response position, and preparation condition in Experiment 5

S–R position	Hand placement							
	Adjacent				Overlapped			
	Uncued	Left–right	Inner–outer	Alternating	Uncued	Left–right	Inner–outer	Alternating
1	3.2	2.0	1.8	2.6	7.2	4.6	4.4	5.5
2	9.6	2.8	5.0	5.6	7.4	9.2	8.1	10.4
3	8.2	4.2	6.2	7.8	7.6	9.2	7.7	9.6
4	0.8	1.4	1.8	1.2	4.8	3.1	4.7	5.1

Note. S–R, stimulus–response.

optimized for all cue conditions, hand placement does in fact modulate the pattern of differential precuing benefits. This novel and important finding is inconsistent with a pure spatial coding account of response-cuing effects (e.g., Reeve & Proctor, 1984). Instead it provides strong support for the Grouping Model, according to which grouping operations in the motor buffer are mediated by spatial and motoric (i.e., anatomical) factors.

11. General discussion

In this paper we examined the mechanisms responsible for the pattern of differential precuing benefits that is commonly observed in the response-cuing paradigm. In particular, we examined the precuing advantage for left–right cues that is evident with short preparation intervals and with the hands adjacent. In contrast to most previous approaches which argued for one specific locus, the present approach considered influences from perceptual and motoric factors. The Grouping Model we propose attributes the left–right advantage to a combination of factors. In particular, it is based on the following principles: (1) stimuli and responses are represented by functionally distinct cognitive structures that often use multiple and hierarchical coding schemes; (2) coding functions in visual and motor buffers are strongly affected by low-level grouping factors that, respectively, may depend on stimulus-driven factors (e.g., Gestalt principles) and on response-related factors (e.g., interresponse dependencies); (3) these grouping factors mediate the outcome and efficiency of subgroup making; (4) response-precuing benefits are, to a large extent, a function of the efficiency of the processes that make subgroups, and, to a modest extent, a function of the efficiency of the subsequent processes concerned with within-subgroup discrimination; (5) there are two modes of subgroup making: fast, automatic selection and slow, effortful creation; and (6) efficiency of within-subgroup discrimination is inversely related to subgroup strength. According to this model, left–right cues are particularly effective in reducing uncertainty because they activate potent, unambiguous chunks of information that allow fast, automatic activation of a subset of responses.

11.1. The grouping assumption

The Grouping Model argues that response-cuing effects in general and the left–right advantage in particular are mostly a function of low-level grouping operations that specify stimulus and response subgroups. In Experiment 1 we showed that the organization of the response set is an important determinant of the left–right advantage. In Experiments 2 and 3 we orthogonally manipulated stimulus and response grouping factors, and showed that both factors, in complex interaction, determine the pattern of response-precuing effects. The results supported the idea that visual grouping factors drive the process of subgroup making, with motoric factors providing important constraints. In Experiment 4 we showed that processes of within-subgroup discrimination are not responsible for the pattern of differential precuing benefits and moreover that processes of within-subgroup discrimination are inversely related to subgroup strength. In the fifth and last experiment we tested a vital prediction of the Grouping Model concerning the effect of an adjacent versus overlapped hand placement response organization on the left–right advantage. Contrary to previous reports and theorizing, results showed a left–right advantage for the adjacent hand placement and an inner–outer advantage for the overlapped hand placement. This novel and important finding demonstrates the relevance of motoric grouping factors in shaping precuing performance.

11.2. The automatic vs. effortful processing assumption

According to the Grouping Model, two qualitatively different processes mediate response-precuing effects. If a cue indicates a strong perceptual and corresponding response group, a fast, automatic selection of the cued responses occurs. If, on the other hand, the indicates stimuli belonging to poorly defined or to different groups, then a slower, effortful (top-down) process is needed to select the relevant responses. The data obtained with the short and longer preparation intervals in this paper are consistent with this claim In a separate paper (see Adam et al., 2002), using converging operations, we report additional evidence to substantiate the distinction between these two qualitatively different processes (see also Neely, 1977; Posner & Snyder, 1975; Schneider & Shiffrin, 1977).

11.3. The locus of response-cuing effects

"To prepare for future events implies an expectation of these events: an internal representation of what is going to happen" (Requin et al., 1991, p. 358). According to the grouping Model, the functional significance of cue encoding processes is to create a new, selective internal representation of the stimulus display, which in turn may lead to a redefinition or resetting of the response buffer containing the appropriate action codes. In this sense, early (perceptual) cue encoding processes may benefit late (post-perceptual) response selection processes by restricting the number of possible action codes in the response buffer. According to this interpretation the dichotomy between perceptual and motoric processes becomes blurred and probably less relevant (see also Hommel, Müsseler, Aschersleben, & Prinz, 2001; Lynch, 1980; Requin et al., 1991). Importantly, our conclusion that precuing effects arise at multiple loci in the information processing system is consistent with recent neurophysiological evidence indicating that advance information may benefit both motoric and nonmotoric processes (Adam et al., in press; Leuthold et al., 1996). In particular, Adam et al. (in press) reported the results of a functional magnetic resonance imaging (fMRI) study of the neuronal activation patterns associated with response-cuing. Their results revealed a large-scale distributed network of neural areas involved in response-cuing, including specific areas in the parietal cortex (which are assumed to derive multiple representations of perceptual space), the frontal cortex (including the premotor and supplementary motor cortex) and the basal ganglia.

11.4. Relation to other views

The only serious alternative theoretical framework that has been developed to account for response-cuing effects is the salient-features coding principle advanced by Proctor and Reeve (1986, 1988; Proctor et al., 1992). This account assumes that the stimulus and response sets are coded in terms of the salient features of each, with response selection occurring most rapidly when the salient features of the respective sets correspond. According to this approach, precuing effects (and more generally also stimulus–response compatibility effects) reflect the efficiency of stimulus–response translation processes mediating between stimulus and response codes. According to Proctor and Reeve, the pattern of differential precuing benefits in the response-cuing task "suggests a hierarchy of translation difficulty for the respective precued locations, which in turn suggests a hierarchy of salience of the features used for the representations that translate between stimuli and responses" (Proctor & Reeve, 1988, p. 188). Thus the salient-features account explains the pattern of differential precuing effects in term of a hierarchy of salience for spatial locations (Reeve & Proctor, 1990).

Besides the potential problem of circularity in defining saliency (but see Proctor et al. (1992) for a discussion of how this problem can be reduced), the results of the present Experiment 5 are at odds with a key prediction of the salient-features coding account, namely that the precued stimulus–response locations are the primary determinants of precuing efficiency, with the specific fingers assigned to the locations being of little or no consequence. The data of Experiment 5 that used an overlapped hand placement refute this claim as they show a strong influence of motoric grouping factors on precuing efficiency. Similarly, the data of Experiments 1, 2, and 3 show a powerful influence of the anatomical hand distinction on precuing efficiency, demonstrating that precuing effects may depend critically on the relation between the visual world and the physical apparatus (effectors) of the perceiver. Moreover, the salient-features coding approach lacks a processing component that is prominent in several modern dual-route conceptions of response selection (e.g., De Jong, Liang, & Lauber, 1994; Eimer, Hommel, & Prinz, 1995; Kornblum et al., 1990). According to this latter approach, response selection can occur by either: (a) a slow, indirect, translation route that applies a translation rule and draws upon central resources, or (b) a direct, automatic response-activation route that exploits natural and coherent stimulus–response associations. Note that the Grouping Model endorses this notion by distinguishing between fast, automatic subgroup selection and slow, controlled subgroup making. The theoretical issues surrounding this essential ingredient in the Grouping Model, however, are deferred for another paper (see Adam et al., 2002).

11.5. Limitations of the grouping model

What makes a good group? The concept of "good grouping" (i.e., relative relatedness or associative strength) as defined in the tradition of Gestalt psychology (e.g., Koffka, 1935; Rock & Palmer, 1990) refers to such properties as proximity, symmetry, regularity, common fate, and simplicity. Unfortunately, application of these principles to assume some but not other groupings is sometimes difficult to justify in advance. This is a weakness because predictive power depends on an a priori method of describing the strength of grouping across a wide variety of stimulus and response sets. This limitation, however, can be overcome by developing formal, computational models of grouping strength that allow precise, quantitative predictions (for formal models of grouping by proximity see, for example, Logan, 1996; van Oeffelen & Vos, 1982, 1983). Furthermore, assumptions about good grouping are open to independent tests. For instance, the strong grouping of left and right perceptual subgroups is bolstered by independent evidence showing that humans spontaneously and naturally divide the visual space into right-side and left-side parts (e.g., Mapp & Ono, 1999; Nicoletti & Umiltà, 1989).The stronger grouping of fingers on one hand as opposed to fingers on different hands is substantiated by the well-known fact that cerebral control of hand and finger movements is almost completely localized in the contralateral frontal lobe (e.g., Gazzaniga, 1970).

Another limitation of the Grouping Model is that it is silent about possible interactions between the two factors that determine grouping in the response buffer—the spatial position of the responses and the anatomical connections between the effectors that are assigned to the response locations. This limitation can be overcome by future research that aims to dissociate these two factors.

11.6. Benefits of the grouping model

The Grouping Model is timely and important because it extends the power of organizational characteristics—well established in the domain of perceptual processing—into the realm of response organization. Moreover, the Grouping Model extends the theory of controlled vs. automatic information processing—well established in the domains of visual search, word recognition, attention, stimulus–response compatibility, and dual-task performance—into the province of action control. Even though the Grouping Model is still in its qualitative development phase, it is able to make ordinal predictions concerning several key effects, including the strong influence of perceptual and motoric factors on precuing efficiency and the dominating influence of vision when input and output factors are in conflict. Concerning the influence of motoric effects, note that the Grouping Model correctly predicted an effect of the hand placement manipulation on the pattern of differential precuing benefits, a fact at variance with the salient features coding account and furthermore a fact that has gone unchallenged for nearly twenty years. Finally, the Grouping Model is consistent with and adds to the growing literature showing that perception and action are intimately related, with action constraining perception, and perception constraining action (e.g., Cohen & Shoup, 1997; Lippa & Adam, 2001; Tipper et al., 1992). Of course, although the present experiments increased the plausibility of the Grouping Model as a general, qualitative account of how visuomotor preparation might work in the response-cuing paradigm, ongoing theoretical and empirical developments are needed to allow more precise, quantitative predictions.

11.7. Conclusion

The basic idea of the Grouping Model is that successful performance in the response-cuing task requires a process of subgroup making that defines and isolates a subset of relevant information in the perceptual-motor workspace. According to the Grouping Model, precue information dynamically reorganizes the perceptual-motor workspace by aligning the primed responses with the primed stimuli. The present results indicate that these input–output functions are strongly affected by low-level grouping factors, which mediate the unit and efficiency of selection. If the cue indicates stimulus–response elements that belong to the same, finely tuned, visual and motoric subgroups, fast subgroup selection is possible. If, on the other hand, the cue indicates elements that belong to different groups or to weak groups, a slower process is needed to create finely tuned subgroups.

References

Adam, J. J. (1992). The spatial proximity hypothesis of the hand advantage in spatial precuing tasks. *Human Movement Science, 11*, 641–652.

Adam, J. J. (1994). Manipulating the spatial arrangement of stimuli in a precuing task. *Acta Psychologica, 85*, 183–202.

Adam, J. J., Backes, W., Rijcken, J., Hofman, P., Kuipers, H., & Jolles, J. (in press). Rapid visuomotor preparation in the human brain: A functional MRI study. *Cognitive Brain Research*.

Adam, J. J., Hommel, B., & Umiltà, C. (2002). Preparing for perception and action (II): The role of attention in the response-cuing task. Manuscript in preparation.

Adam, J. J., Keyson, D. V., & Paas, F. G. W. C. (1997). Vibro-tactual choice reaction time in a precuing task. *Human Movement Science, 16*, 549–565.

Adam, J. J., Paas, F. G. W. C., Teeken, J. C., van Loon, E. M., van Boxtel, M. P. J., Houx, P. J., & Jolles, J. (1998). Effects age on performance in a finger precuing task. *Journal of Experimental Psychology: Human Perception and Performance, 24*, 870–883.

Adam, J. J., & van Veggel, L. M. A. (1992). Manipulating procedural variables in a spatial precuing task. *Acta Psychologica, 81*, 97–114.

Adini, Y., & Sagi, D. (1992). Parallel processes within the 'spot-light' of attention. *Spatial Vision, 6*, 61–77.

Alain, C., Buckolz, E., & Taktak, K. (1993). Same-hand and different-hand finger pairings in two-choice reaction time: Presence or absence of response competition. *Journal of Motor Behavior, 25*, 45–51.

Allport, D. A. (1989). Visual attention. In M. I. Posner (Ed.), *Foundations of cognitive science* (Vol. 2, pp. 631–682). Cambridge, MA: MIT Press.

Baylis, G. C., & Driver, J. (1992). Visual parsing and response competition: The effect of grouping factors. *Perception & Psychophysics, 51*, 145–162.

Baylis, G. C., & Driver, J. (1993). Visual attention and objects: Evidence for hierarchical coding of location. *Journal of Experimental Psychology: Human Perception and Performance, 9*, 451–470.

Broadbent, D. E. (1971). *Decision and stress*. London: Academic Press.

Cohen, A., & Shoup, R. (1997). Perceptual dimensional constraints in response selection processes. *Cognitive Psychology, 32*, 128–181.

Corballis, M. C., & Beale, I. L. (1983). *The ambivalent mind*. Chicago, IL: Nelson-Hall.

Craighero, L., Fadiga, L., Rizzolatti, G., & Umiltà, C. (1999). Action for perception: A motor-visual attentional effect. *Journal of Experimental Psychology: Human Perception and Performance, 25*, 1673–1692.

De Jong, R., Liang, C.-C., & Lauber, E. (1994). Conditional and unconditional automaticity: A dual-process model of effects of spatial stimulus-response correspondence. *Journal of Experimental Psychology: Human Perception and Performance, 20*, 731–750.

De Jong, R., Wierda, M., Mulder, G., & Mulder, L. J. M. (1988). Use of partial stimulus information in response processing. *Journal of Experimental Psychology: Human Perception and Performance, 14*, 682–692.

Duncan, J., & Humphreys, G. W. (1989). Visual search and stimulus similarity. *Psychological Review, 96*, 433–458.

Eimer, M., Hommel, B., & Prinz, W. (1995). S–R compatibility and response selection. *Acta Psychologica, 90*, 301–313.

Eriksen, C. W. (1990). Attentional search of the visual field. In D. Brogan (Ed.), *Visual search* (pp. 3–19). London: Taylor & Francis.

Eriksen, C. W., & Rohrbaugh, J. W. (1970). Some factors determining efficiency of selective attention. *American Journal of Psychology, 83*, 330–342.

Farah, M. J., Brunn, J. L., Wong, A. B., Wallace, M. A., & Carpenter, P. A. (1990). Frames of reference for allocating attention to space: Evidence from the neglect syndrome. *Neuropsychologia, 28*, 335–347.

Gazzaniga, M. (1970). *The bisected brain*. New York: Appleton-century-Crofts.

Gehrke, J., & Hommel, B. (1998). The impact of exogenous factors on spatial coding in perception and memory. In C. Freksa, C. Habel, & K. F. Wender (Eds.), *Spatial cognition: An interdisciplinary approach to representing and processing spatial knowledge* (pp. 64–77). Berlin: Springer.

Goldsmith, M. (1998). What's in a location? Comparing object-based and space-based models of feature integration in visual search. *Journal of Experimental Psychology: General, 127*, 189–219.

Harms, L., & Bundesen, C. (1983). Color segregation and selective attention in a nonsearch Task. *Perception & Psychophysics, 33*, 11–19.

Hasbroucq, T., Mouret, I., Seal, J., & Akamatsu, M. (1995). Finger pairings in two-choice reaction time tasks: Does the between-hands advantage reflect response preparation? *Journal of Motor Behavior, 27*, 251–262.

Henderson, J. M. (1991). Stimulus discrimination following covert attentional orienting to an exogenous cue. *Journal of Experimental Psychology: Human Perception and Performance, 17*, 91–106.

Hendrikx, A. J. P. (1986). Compatibility of precuing and of S–R mapping in choice reactions. *Acta Psychologica, 62*, 59–88.

Hick, W. E. (1952). On the rate of gain of information. *Quarterly Journal of Experimental Psychology, 4*, 11–26.

Hommel, B. (1993). Inverting the Simon effect by intention: Determinants of direction and extent of effects of irrelevant spatial information. *Psychological Research, 55*, 270–279.

Hommel, B. (1995). Attentional scanning in the selection of central targets from multi-symbol strings. *Visual Cognition, 2*, 119–144.

Hommel, B. (1996). No prevalence of right–left over above-below spatial codes. *Perception & Psychophysics, 58*, 102–110.

Hommel, B. (1997). Toward an action-concept model of stimulus–response compatibility. In B. Hommel & W. Prinz (Eds.), *Theoretical issues in stimulus–response compatibility* (pp. 281–320). Amsterdam: North-Holland.

Hommel, B. (1998). Observing one's own action—and what it leads to. In J. S. Jordan (Ed.), *Systems theory and a priori aspects of perception* (pp. 143–179). Amsterdam: North-Holland.

Hommel, B., Gehrke, J., & Knuf, L. (2000). Hierarchical coding in the perception and memory of spatial layouts. *Psychological Research, 64*, 1–10.

Hommel, B., Müsseler, J., Aschersleben, G., & Prinz, W. (2001). The theory of event coding (TEC): A framework for perception and action planning. *Behavioral and Brain Sciences, 24*, 849–937.

Hyman, R. (1953). Stimulus information as a determinant of reaction time. *Journal of Experimental Psychology, 45*, 188–196.

Kahneman, D., Treisman, A., & Gibbs, B. J. (1992). The reviewing of object files: Object-specific integration of information. *Cognitive Psychology, 24*, 175–219.

Keppel, G. (1982). *Design and analysis*. Englewood cliffs, NJ: Prentice Hall.

Koffka, K. (1935). *Principles of Gestalt psychology*. New York: Harcourt, Brace & World.

Kornblum, S. (1965). Response competition and/or inhibition in two-choice reaction time. *Psychonomic Science, 2*, 55–56.

Kornblum, S., Hasbroucq, T., & Osman, A. (1990). Dimensional overlap: Cognitive basis for stimulus–response compatibility—A model and taxonomy. *Psychological Review, 97*, 253–270.

Kosslyn, S. M. (1994). *Image and brain: The resolution of the imagery debate*. Cambridge, MA: The MIT Press.

Lamberts, K., Tavernier, G., & d'Ydewalle, G. (1992). Effects of multiple reference points in spatial stimulus–response compatibility. *Acta Psychologica, 79*, 115–130.

Leonard, J. A. (1958). Partial advance information in a choice reaction task. *British Journal of Psychology, 49*, 89–96.

Leuthold, H., Sommer, W., & Ulrich, R. (1996). Partial advance information and response preparation: Inferences from the lateralized readiness potential. *Journal of Experimental Psychology: General, 125*, 307–323.

Lippa, Y. (1996). A referential-coding explanation for compatibility effects of physically Orthogonal stimulus and response dimensions. *Quarterly Journal of Experimental Psychology, 49A*, 950–971.

Lippa, Y., & Adam, J. J. (2001). An explanation of orthogonal S–R compatibility effects that vary with hand or response position: The end-state comfort hypothesis. *Perception & Psychophysics, 63*, 156–174.

Logan, G. D. (1995). Linguistic and conceptual control of visual spatial attention. *Cognitive Psychology, 28*, 103–174.

Logan, G. D. (1996). The CODE theory of visual attention: An integration of space-based and object-based attention. *Psychological Review, 103*, 603–649.

Lynch, J. C. (1980). The functional organization of posterior parietal association cortex. *Behavioral and Brain Sciences, 3*, 485–534.

Mack, A., Tang, B., Tuma, R., Kahn, S., & Rock, I. (1992). Perceptual organization and attention. *Cognitive Psychology, 24*, 475–501.

Mapp, A. P., & Ono, H. (1999). Wondering about the wandering cyclopean eye. *Vision Research, 39*, 2381–2386.

McCloskey, M., & Rapp, B. (2000). Attention-referenced visual representations: Evidence from impaired visual localization. *Journal of Experimental Psychology: Human Perception and Performance, 26*, 917–9336.

Merikle, P. M. (1974). Selective backward masking with an unpredictable mask. *Journal of Experimental Psychology, 103*, 589–591.

Mewhort, D. J. K., & Campbell, A. J. (1978). Processing spatial information and the selective-masking effect. *Perception & Psychophysics, 24*, 93–101.

Miller, J. (1982). Discrete versus continuous models of human information processing: In search of partial output. *Journal of Experimental Psychology: Human Perception and Performance, 8*, 273–296.

Miller, J. (1985). A hand advantage in preparation of simple keypress responses: Reply to Reeve and Proctor (1984). *Journal of Experimental Psychology: Human Perception and Performance, 11*, 221–233.

Müsseler, J., & Hommel, B. (1997). Blindness to response-compatible stimuli. *Journal of Experimental Psychology: Human Perception and Performance, 23*, 861–872.

Neely, J. H. (1977). Semantic priming and retrieval from lexical memory: Roles of inhibitionless spreading activation and limited-capacity attention. *Journal of Experimental Psychology: General, 106*, 226–254.

Nicoletti, R., & Umiltà, C. (1984). Right-left prevalence in spatial compatibility. *Perception & Psychophysics, 35*, 333–343.

Nicoletti, R., & Umiltà, C. (1989). Splitting visual space with attention. *Journal of Experimental Psychology: Human Perception and Performance, 15*, 164–169.

Nicoletti, R., Umiltà, C., & Ladavas, E. (1984). Compatibility due to the coding of relative position of effectors. *Acta Psychologica, 57*, 133–143.

Palmer, S. E. (1992). Common region: A new principal of perceptual grouping. *Cognitive Psychology, 24*, 436–447.

Parsons, L. M. (1987). Imagined spatial transformations of one's hands and feet. *Cognitive Psychology, 19*, 178–241.

Posner, M. I. (1980). Orienting of attention. *Quarterly Journal of Experimental Psychology, 32*, 3–25.

Posner, M. I., & Snyder, C. R. R. (1975). Attention and cognitive control. In R. L. Solso (Ed.), *Information processing and cognition: The Loyola symposium*. Hillsdale, NJ: Erlbaum.

Posner, M. I., Snyder, C. R. R., & Davidson, B. J. (1980). Attention and the detection of signals. *Journal of Experimental Psychology: General, 109*, 160–174.

Prinz, W., & Hommel, B. (Eds.). (2002). *Common mechanisms in perception and action: Attention & performance XIX*. Oxford: Oxford University Press.

Prinzmetal, W. (1981). Principles of feature integration in visual perception. *Perception & Psychophysics, 30*, 330–340.

Proctor, R. W., & Reeve, T. G. (1986). Salient-feature coding operations in spatial precuing tasks. *Journal of Experimental Psychology: Human Perception and Performance, 12*, 277–285.

Proctor, R. W., & Reeve, T. G. (1988). The acquisition of task-specific productions and modification of declarative representations in spatial precuing tasks. *Journal of Experimental Psychology: General, 117*, 182–196.

Proctor, R. W., Reeve, T. G., & van Zandt, T. (1992). Salient-features coding in response selection. In G. E. Stelmach & J. Requin (Eds.), *Tutorials in motor behavior II* (pp. 727–741). Amsterdam: North-Holland.

Reeve, T. G., & Proctor, R. W. (1984). On the advance preparation of discrete finger responses. *Journal of Experimental Psychology: Human Perception and Performance, 10*, 541–553.

Reeve, T. G., & Proctor, R. W. (1985). Non-motoric translation processes in the preparation of discrete finger responses: A rebuttal of Miller's (1985) analysis. *Journal of Experimental Psychology: Human Perception and Performance, 11*, 234–240.

Reeve, T. G., & Proctor, R. W. (1990). The salient-features coding principle for spatial- and symbolic-compatibility effects. In R. W. Proctor & T. G. Reeve (Eds.), *Stimulus–response compatibility* (pp. 163–180). Amsterdam: North-Holland.

Reeve, T. G., Proctor, R. W., Weeks, D. J., & Dornier, L. (1992). Salience of stimulus and response features in choice-reaction tasks. *Perception & Psychophysics, 52*, 453–460.

Requin, J. (1980). Toward a psychobiology of preparation for action. In G. E. Stelmach & J. Requin (Eds.), *Tutorials in motor behavior* (pp. 373–398). Amsterdam: North-Holland.

Requin, J., Brener, J., & Ring, C. (1991). Preparation for action. In J. R. Jennings & M. G. H. Coles (Eds.), *Handbook of cognitive psychophysiology: Central and autonomic nervous system approaches* (pp. 357–448). New York: Wiley.

Requin, J., Riehle, A., & Seal, J. (1993). Neural networks for movement preparation. In D. E. Meyer & S. Kornblum (Eds.), *Attention and performance* (Vol. 14, pp. 745–769). Cambridge, MA: MIT Press.

Riggio, L., Gawryszewski, L., & Umiltà, C. (1986). What is crossed in crossed-hand effects. *Acta Psychologica, 62*, 89–100.

Rock, I., Linnett, C. M., Grant, P., & Mack, A. (1992). Perception without attention: Results of a new method. *Cognitive Psychology, 24*, 502–534.

Rock, I., & Palmer, S. (1990). The legacy of Gestalt psychology. *Scientific American* (December), 48–61.

Rock, I., & Victor, J. (1964). Vision and touch: An experimentally created conflict between the two senses. *Science, 143*, 594–596.

Rosenbaum, D. A. (1980). Human movement initiation: Specification of arm, direction, and extent. *Journal of Experimental Psychology: General, 109*, 444–474.

Rosenbaum, D. A. (1983). The movement precuing technique: Assumptions, applications, and extensions. In R. A. Magill (Ed.), *Memory and control of action* (pp. 231–274). Amsterdam: North-Holland.

Roswarski, T. E., & Proctor, R. W. (1996). Multiple spatial codes and temporal overlap in choice-reaction tasks. *Psychological Research, 59*, 196–211.

Sadalla, E. K., Burroughs, W. J., & Staplin, L. J. (1980). Reference points in spatial cognition. *Journal of Experimental Psychology: Human Learning and Memory, 6*, 516–528.

Sanders, A. F. (1983). Towards a model of stress and human performance. *Acta Psychologica, 51*, 223–243.

Schneider, W. X. (1995). VAM: A neuro-cognitive model for visual attention control of segmentation, object recognition, and space-based motor action. *Visual Cognition, 2*, 331–375.

Schneider, W., & Shiffrin, R. M. (1977). Controlled and automatic information processing: I. Detection, search, and attention. *Psychological Review, 84*, 1–66.

Simon, J. R., Hinrichs, J. V., & Craft, J. L. (1970). Auditory S–R compatibility: Reaction time as a function of ear-hand correspondence and ear-response-location correspondence. *Journal of Experimental Psychology, 86*, 97–102.

Sternberg, S. (1969). The discovery of processing stages: Extensions of Donders' method. *Acta Psychologica, 30*, 276–315.

Stoffer, T. H. (1991). Attentional focussing and spatial stimulus–response compatibility. *Psychological Research, 53*, 127–135.

Tipper, S. P., & Behrmann, M. (1996). Object-based not scene-based visual neglect. *Journal of Experimental Psychology: Human Perception and Performance, 22*, 1261–1278.

Tipper, S. P., Lortie, C., & Baylis, G. C. (1992). Selective reaching: Evidence for action-centered attention. *Journal of Experimental Psychology: Human Perception and Performance, 18*, 891–905.

Treisman, A. M. (1988). Features and objects: The fourteenth Bartlett memorial lecture. *Quarterly Journal of Experimental Psychology, 40A*, 201–237.

van der Heijden, A. H. C. (1992). *Selective attention in vision*. London: Routledge & Kegan.

van Oeffelen, M. P., & Vos, P. G. (1982). Configurational effects on the enumeration of dots: Counting by groups. *Memory & Cognition, 10*, 396–404.

van Oeffelen, M. P., & Vos, P. G. (1983). An algorithm for pattern description on the level of relative proximity. *Pattern Recognition, 16*, 341–348.

Vecera, S. P., & Farah, M. J. (1994). Does visual attention select objects or locations? *Journal of Experimental Psychology: General, 123*, 146–160.

Wallace, R. J. (1971). S–R compatibility and the idea of a response code. *Journal of Experimental Psychology, 88*, 354–360.

Wolfe, J. M. (1994). Guided search 2.0. A revised model of visual search. *Psychonomic Bulletin & Review, 1*, 202–238.

Yantis, S. (1992). Multielement visual tracking: Attention and perceptual organization. *Cognitive Psychology, 24*, 295–340.