Journal of Experimental Psychology:
Human Perception and Performance
2009, Vol. 35, No. 6, 1755–1769


0096-1523/09/$12.00 DOI: 10.1037/a0016798

# How You Move Is What You See: Action Planning Biases Selection in Visual Search

Agnieszka Wykowska and Anna Schubö
Ludwig Maximilian University

Bernhard Hommel
Leiden University

Three experiments investigated the impact of planning and preparing a manual grasping or pointing movement on feature detection in a visual search task. The authors hypothesized that action planning may prime perceptual dimensions that provide information for the open parameters of that action. Indeed, preparing for grasping facilitated detection of size targets while preparing for pointing facilitated detection of luminance targets. Following the Theory of Event Coding (Hommel, Müsseler, Aschersleben, & Prinz, 2001b), the authors suggest that perceptual dimensions may be intentionally weighted with respect to an intended action. More interesting, the action-related influences were observed only when participants searched for a predefined target. This implies that action-related weighting is not independent from task-relevance weighting. To account for our findings, the authors suggest an integrative model of visual search that incorporates input from action-planning processes.

*Keywords:* action-related biases on perception, action planning, visual selection

Human perception is not a passive, bottom-up process. Which of the stimuli reaching our senses will be processed further depends on many various factors. Stimuli that are extremely salient in the environment will, most probably, capture our attention and will be selected. At the same time, our cognitive system is tuned to currently relevant, important information, suggesting that selection emerges from the interaction of bottom-up and top-down processes. Various theories and models have been postulated to describe and to account for selection mechanisms and large amounts of empirical data have been collected to test them (e.g., Bundesen, 1990; Desimone & Duncan, 1995; Eriksen & Yeh, 1985; Müller, Heller, & Ziegler, 1995; Posner, 1980; Wolfe, 1994; and many others). Authors have also stressed that the action context of perceptual events might influence perceptual processing (e.g., Craighero, Fadiga, Rizzolatti, & Umiltà, 1999; Deubel & Schneider, 1996; Fagioli, Hommel, & Schubotz, 2007; Hommel, Müsseler, Aschersleben, & Prinz, 2001b; Humphreys & Riddoch, 2001; Müsseler & Hommel, 1997; Rizzolatti, Riggio, & Sheliga, 1994). As we argue, preparing for a particular type of action prepares an agent to process particular types of information. To be more precise, we claim that preparing to act weights higher those perceptual dimensions that are relevant for the control of the respective action (Fagioli et al., 2007). In the present study, we tested this approach in typical visual search tasks with targets that were either specified in advance or were to be detected based on their salience. We also investigated whether and how action-related weighting interacts with other sources of weighting, for example, weighting induced by the task relevance of the given perceptual dimension or weighting with respect to dimension variability across trials (bottom-up weighting).

## Weighting Mechanisms in Visual Processing

Many authors have agreed that task requirements and behavioral relevance influence the processing of visual features (e.g., Bacon & Egeth, 1994; Egeth, Virzi, & Garbart, 1984; Wolfe, Butcher, Lee, & Hyle, 2003; Wolfe, Horowitz, Kenner, Hyle, & Vasan, 2004). To account for this impact several theories propose a biasing or weighting mechanism (e.g., Bundesen, 1990; Found & Müller, 1996; Müller et al., 1995; Müller, Reimann, & Krummenacher, 2003; Wolfe, 1994). The cognitive system is assumed to assign weights to information that is particularly relevant so that stimuli that vary on highly weighted dimensions are prioritized and have a higher chance of winning the competition for selection. Evidence for a weighting mechanisms has been provided by behavioral studies (e.g., Egeth et al., 1984; Wolfe et al., 2003; Wolfe et al., 2004) and neurophysiological observations (e.g., Chelazzi, Duncan, Miller, & Desimone, 1998; Luck, Chelazzi, Hillyard, & Desimone, 1997; Moran & Desimone, 1985; Reynolds, Chelazzi, & Desimone, 1999). In some of the above-mentioned studies, weighting was induced via task instruction (e.g., Bacon & Egeth, 1994; Wolfe et al., 2004) or cueing (e.g., Luck et al., 1997; Moran & Desimone, 1985; Müller et al., 2003; Reynolds et al., 1999). According to the dimensional weighting account of Müller et al. (1995), the visual field is represented in separate, dimension-specific "maps," such as color, orientation, and so forth. Saliency signals are transmitted from these maps to a master map of saliency, which computes the weighted sum of dimension-specific signals. Top-down processes can thus bias the outcome of this computation by weighting task-related or otherwise interesting dimensions

Agnieszka Wykowska and Anna Schubö, Department of Experimental Psychology, Ludwig Maximilian University; Bernhard Hommel, Institute of Psychology, Leiden University.

This research was supported by the Deutsche Forschungsgemeinschaft (Project FOR 480, SCHU 1330/2-1 to A. S.). We thank Anne-Lene Kurz for her help in data collection.

Correspondence concerning this article should be addressed to Agnieszka Wykowska, Department of Psychology, Ludwig Maximilian University, Leopoldstr. 13, D–80802 Munich, Germany. E-mail: wykowska@psy.uni-muenchen.de

more heavily. If, for instance, the target-defining dimension in a visual search task is known in advance, participants can increase the weights of that dimension ahead of target presentation, so that features on the corresponding dimension can be processed more efficiently.

However, there is evidence suggesting that weighting can also be induced in a bottom-up manner. In a series of experiments in which participants searched for a pop-out item, Müller and colleagues (Found & Müller, 1996; Müller et al., 1995) observed better performance if the target-defining dimension was the same as in the previous trial as compared to when it was different. The authors suggested that the system may automatically increase the weights of the presently relevant dimension, so that switching to another dimension results in a performance drop.

## Interactions Between Perception and Action

Part of the function of perceptual processes is to identify contextual trigger conditions, that is, conditions under which particular actions are to be carried out. Psychological experiments often focus on this trigger function by using stimuli that are arbitrarily mapped onto responses, such as when left and right key presses are signaled by, for example, green and red dots on a computer monitor. However, everyday actions are often rather different (cf., Kelso & Kay, 1987). Controlling the grasping of a cup of coffee requires more than the sight of a coffee cup: Processing the location of the cup is necessary to steer the hand toward it (Jeannerod's, 1984, transport component) and processing its shape is necessary to program the hand for the eventual grasp (the grasping component proper). In other words, perception is often needed to detect and process information that is suited to control relevant parameters of action programs.

A number of authors have considered the possibility that visual selection and action are interdependent. For instance, Allport's (1987) selection-for-action approach claims that attentional selection takes place only because of limitations at the effector system; the Premotor Theory (Rizzolatti et al., 1994) postulates that attentional selection is mediated by pragmatic maps shared by perceptual and motor systems; and Deubel and Schneider (e.g., Deubel & Schneider, 1996; Deubel, Schneider, & Paprotta, 1996) assumed a strong coupling of selection-for-perception and selection-for-action.

In the following, we argue that action planning makes ample use of the bidirectional links that exist between perceptual and action systems (Hommel et al., 2001b; the Theory of Event Coding). We claim that these links are actually used in both directions, in such a way that action controls perception no less than perception controls action. It is obvious that action planning is informed and controlled by perceptual processes that provide information about the objects we act on and the changes of our environment that we intend to achieve. Perhaps less obvious is the need for perceptual processes to be constrained and guided by action planning. Successful acting requires the focusing and selection of action-relevant information from the abundance of input, so to adapt the action to the environmental conditions. In other words, setting up a particular action program should include controlling perceptual systems to focus on those perceptual dimensions that are likely to provide action-relevant information. If attentional control is exerted by weighting, this implies that weighting processes can originate in action planning processes. That is, setting up a particular action plan may increase the weights for perceptual dimensions that are relevant for that action—"intentional weighting" in the sense of Hommel et al. (2001b).

## Intentional Weighting: Linking Perception to Action

Craighero et al. (1999) found evidence for what might be interpreted as such a weighting mechanism. In a series of studies, the authors demonstrated that latencies of a grasping movement towards a particular object were dependent on whether the orientation of a visually presented go-signal was congruent with the to-be grasped object. Their results showed that the congruent go-signals decreased latencies of the movement towards a left- or right-oriented bar. Also in cases when the grasping movement was supposed to be prepared but subsequently withheld and substituted by a response with a foot pedal, response times were dependent on the congruency factor. Therefore, the authors concluded that preparing for a movement (grasping, in the case of their studies) influenced visual detection (of the go-signal) dependent on whether the visually presented stimulus shared characteristics of the to-be grasped object or was incongruent with it.

Furthermore, Humphreys & Riddoch (2001) provided evidence that visual selection can be guided by representations of the action a given target affords. They investigated a patient suffering from unilateral neglect who was impaired in finding objects defined by their perceptual features. When the patient searched for a visual target (a cup, for instance) that was defined by either its name, its color, or by an associated action (e.g., "something to drink from"), his performance was much better in the action condition than if the target was defined by color or name. According to Humphreys and Riddoch, this observation supported their idea that perception and action are linked by a pragmatic processing route, which in this case would allow for the construction of an action-related search template that visual input could be matched against.

Evidence for action-related weighting of perceptual processing was also obtained by Bekkering & Neggers (2002), who demonstrated movement-related influences on visual search. The task was to detect a target defined by a conjunction of orientation and color features. Subsequent to detection, observers were asked to either grasp the target or point to it. The results showed that fewer orientation errors were committed when participants prepared for grasping as compared to pointing. The authors argued that activating the representation of a particular movement enhances the processing of task-relevant features.

Although the observations of Bekkering and Neggers (2002) support the general idea that the selection of perceptual targets interacts with the selection of action targets, they do not require the assumption that preparing for a particular type of action sets the weights for a whole dimension. However, more recent evidence suggests that this is what actually happens. Fagioli et al. (2007) presented participants with sequences of stimuli. In these sequences, one dimension varied in a predictable fashion (e.g., by alternating size: large-small-large-small . . .; or systematically shifting location from bottom-left to top-right), and participants were to detect oddballs, that is, stimuli deviating from the respective "rule." Before each trial, a movement cue signaled the preparation of grasping or pointing action to be carried out after the presentation of the visual sequence. Results showed that preparing for pointing facilitated the detection of location oddballs while preparing for grasping facilitated the detection of size oddballs. We consider that as evidence for intentional weighting in the sense of Hommel et al. (2001b).

## Rationale of the Experiments

Although Fagioli et al. (2007) found evidence for action-related intentional weighting of visual processing, it is not yet known whether and how such a mechanism is related to other sources of weighting, for example, induced by task-relevance or dimension repetition. If action-induced intentional weighting would influence early processing stages, and if it would do so by modulating top-down weighting processes (i.e., top-down, dimension weighting), one would expect action-induced effects in attentional tasks that rely on top-down mechanisms. Accordingly, we manipulated conditions that are known to either induce or prevent the employment of top-down strategies and expected that action-related effects are more likely in the former than the latter. Moreover, to further characterize the expected action-induced dimensional weighting effects we were interested to see whether they would interact with a more bottom-up type of weighting mechanism observed as intertrial dimension repetition effects (Found & Müller, 1996; Maljkovic & Nakayama, 1994; Müller et al., 1995).

Our study was designed to investigate the effects of action-related weighting of perceptual dimensions in a classical visual search task, that is, in a task that is known to tap into early stages of visual processing—where most attentional theories would not expect any direct impact of action planning.

Our first experiment tested whether action-related effects would be observed in a visual search task for a pop-out item. In particular, we tested whether targets with action-relevant characteristics would be easier (i.e., faster and more accurate) to select than targets with action-irrelevant pop-out characteristics. Even though the findings of previous studies are encouraging with respect to the possible impact of action control on visual attention, these studies used rather atypical tasks and designs, which raises the question whether evidence for such an impact can also be demonstrated in a more classical attentional task that is more directly related to available theories of visual attention.

Unlike Bekkering and Neggers (2002) and other previous studies, we were interested in weighting mechanisms that operate at the level of simple feature detection but not on objects defined by conjunctions of features. This linked our investigation to the study by Fagioli et al. (2007), but unlike these authors we were interested in the process of selection in space (as required in a visual search task) rather than selection in time (as required in an oddball paradigm with a sequence of stimuli).

In particular, we asked participants to prepare for a pointing or grasping movement and keep it prepared while trying to detect a target circle that differed from surrounding distracters by its greater luminance or smaller size. Because we were interested in the impact of action preparation on selection of particular perceptual dimensions, we chose two movement types and two dimensions that could be combined to two congruent and two incongruent action-dimension pairs.

We assumed that size should be relevant for grasping movements (see e.g., Jeannerod, 1984; Milner & Goodale, 1995; Tucker & Ellis, 2001). Preparing for a grasping movement requires the specification of size-related parameters to control grip aperture, which we think calls for the privileged processing of size information, whereas information from action-irrelevant perceptual dimensions, such as luminance, can be ignored. Accordingly, if preparing a grasp really primes the processing of size information, search targets defined by size should benefit from preparation of a grasping movement. This renders size-defined targets and grasping movement a congruent pair that should produce better search performance than an incongruent pair (as in the case of luminance targets and grasping movement). As for the pointing movement, localization of a to-be pointed object is of crucial importance. Accordingly, we expected that location is a relevant parameter for pointing movements, suggesting that planning such a movement biases attention towards location information. In contrast, the size of an object should be less relevant for pointing than localization is. It would have been an obvious choice to manipulate the spatial congruence between the planned pointing movement and the search target (similar to Deubel et al., 1996), but that would have created a number of confounds in terms of spatial compatibility and overt attention that we wanted to avoid. Accordingly, and based on results showing that luminance targets enable efficient localization of an object with a pointing-movement response (e.g., Anderson & Yamagishi, 2000; Gegenfurtner, 2004; Graves, 1996), we considered luminance as relevant dimension for pointing. Another reason for this consideration was the fact that luminance contrasts are, most probably, processed in the magno-cellular system (as discussed in Anderson & Yamagishi, 2000) and are therefore closely linked to the dorsal stream responsible for localization (Ungerleider & Mishkin, 1982). Hence, a second congruent pair was created by combining luminance-defined search targets with pointing movement. Accordingly, our second hypothesis was that preparing a pointing movement should be beneficial for detecting luminance-defined as compared to size-defined targets.

In Experiment 1, the target dimension was blocked and defined prior to each block, so that participants always knew the dimension of the upcoming pop-out target. This provided participants with two possible search strategies. One would be using dimensional weighting: Knowing that targets would always differ from the distracters in terms of size participants could increase the weights for the size dimension and thereby facilitate target-distracter discrimination (Bundesen, 1990; Duncan & Humphreys, 1989). It is this top-down weighting process that we assume is targeted by biases originating from action planning, so that we expected that action-induced biases would be particularly visible the more participants would choose a top-down search strategy that allows weighting particular dimensions with respect to task relevance. However, given that the target would always be popping out anyway, the task would not enforce a top-down strategy (even though we considered this strategy as more likely in Experiment 1). Instead, participants could select the target solely based on bottom-up information about a presence of a singleton that pops out from the surrounding distracters. Indeed, there is evidence that, depending on an experimental design and instructions, people sometimes prefer to search for a predefined, expected target, and sometimes to base their selection on any saliency signal that is triggered by events in the visual field—the so-called "singleton-detection" mode (for discussion, see e.g., Bacon & Egeth, 1994). Given that such saliency signals are unlikely to be labeled according to the perceptual dimension of the perceptual oddball, saliency-based performance is unlikely to be affected by top-down weighting. Accordingly, we expected that action-induced attentional biases would be better visible the more people would prefer a search strategy based on explicit weighting (given that we were unable to tell to which degree they did, we went on to manipulate search strategies in Experiments 2 and 3).

In Experiment 2, the target dimensions were randomly intermixed, so that both size and luminance target displays could be presented within a block of trials. Moreover, participants were instructed to detect any singleton that would pop out from the distracter elements. We considered that these manipulations would encourage the "singleton-detection" strategy based on the detecting of bottom-up saliency signals and discourage a strategy based on top-down weighting with respect to task relevance. According to our considerations, this should work against action-induced attentional biases even though the trials were physically comparable to those in Experiment 1. Varying the target-defining dimensions from trial to trial permitted us to investigate dimensional repetition effects. As shown by Müller and colleagues (e.g., Müller et al., 1995), repeating the perceptual dimension results in better performance compared to a situation when the target dimension is switched across subsequent trials. As this effect has been attributed to an increase of the weights of the currently target-defining dimension in a bottom-up manner, we were interested to see whether it would interact with what we consider action-induced weighting. Experiment 3 replicated Experiment 2 but participants were asked to detect one of the popping-out stimuli (e.g., size) and reject the other as irrelevant (luminance in that case). This was to discourage the singleton detection mode that Experiment 2 was likely to have induced, and to induce a strategy based on top-down dimensional weighting instead.

## General Method

### *Stimuli and Apparatus*

Stimuli were presented on a 17-inch computer screen with a 60 Hz refresh rate (Iiyama MA 201D, Vision Master 511, Iiyama Corporation, Japan) placed at a distance of 100 cm from an observer. The experiment was run on a Siemens Celsius 420 computer (Siemens, Germany) with a Celeron 466 MHz processor.

The search display always contained 28 items (grey circles of 1.7° of visual angle; 15 cd/m$^2$ of luminance) positioned on three imaginary circles with a diameter of 6.8°, 4.8°, and 2.8° (cf. Figure 1). The target could appear on one of four positions on the middle circle of 4.8° diameter at the upper left/right or lower left/right from the middle point. The target was defined either by luminance (lighter grey: 58 cd/m$^2$) or by size (smaller circle: 1.1° cm of visual angle).[1]

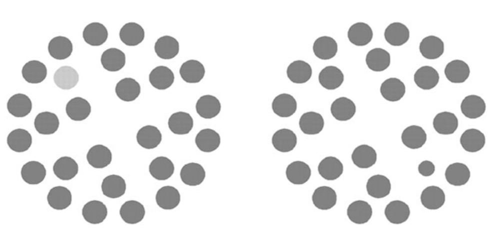

*Figure 1.* Example of search displays. Two displays each containing a singleton: a luminance singleton (left) and size singleton (right). Targets could appear in four possible positions on the middle imaginary circle.

Below the computer screen, at a distance of 80 cm from the participants' seat, the movement execution device (MED, Figure 2) was positioned. Midpoint of the device was situated at 40 cm below and 20 cm distance forward of the midpoint of the computer screen. The MED was especially designed for the purpose of this experiment to allow participants to perform grasping and pointing movements on the same objects.[2] It consisted of a 43 cm × 54 cm × 13 cm box containing eight holes positioned on an imaginary circle of 22.2° of visual angle. Round plastic items that could vary in luminance and size each covered a LED that could be attached and detached from the box. For the purpose of these experiments, we used the following combination of the circular items: four grey (0.6 cd/m$^2$), medium-sized (3.7° of visual angle) items; two grey items that differed in size being smaller (2°) and larger (5.4°) than the standard elements; and finally two items that differed in luminance being darker (0.17 cd/m$^2$) and lighter (2.1 cd/m$^2$) than the standard elements. When those elements were lit, their luminance values were equal to: 5 cd/m$^2$ for the darkest item, 45 cd/m$^2$ for the medium item and 99 cd/m$^2$ for the lightest item. The luminance values were measured with Minolta Chroma meter CS–100 (Minolta, Japan).

Participants were seated in a dimly lit, electrically shielded, and sound attenuated chamber with response keys embedded in a response pad (ERTS ExKey, BeriSoft Corporation, Frankfurt/M., Germany) positioned below their dominant hand. Grasping/pointing action was performed with their other hand on the MED. The device was connected to the experimental computer via an LPT port and was controlled by the computer receiving signals at which moment that particular LED (out of the eight attached LEDs) should light up and for how long it would remain lit. The computer screen was positioned 1 m from the participants' eyes.

[1] To investigate whether search was efficient in our experiments and could be performed by "early" visual selection processes, a control experiment was conducted in which the number of elements in the search displays was varied between 8, 12, 24, and 28 elements. Sixteen participants were asked to detect either size or luminance targets (in separate blocks). No movement task was required. Elements were arranged on a single imaginary circle (eight-item condition), two imaginary circles (12 or 24 items) or three imaginary circles (28 items). In 80% of target-present trials, targets appeared on the middle eight-item circle of constant eccentricity, only these trials were analyzed. In the remaining trials targets appeared on any of the other positions so that participants would not limit their search to the middle circle. The search display was presented for 100 ms; all other experimental parameters were identical to Experiment 1. Search slopes were estimated by linear regression analysis. Results showed that search was efficient (Wolfe, 1998; Wolfe et al., 2003) both for luminance targets (search slope: 0.02 ms/item for target present trials; mean RTs ranging from 303 ms to 308 ms) and for size targets (search slope: 0.4 ms/item for target present trials; mean RTs ranging from 304 ms to 315 ms). Search was slower for blank trials (see e.g., Found & Müller, 1996; Wolfe, 1994) but also in the range of efficient search (with a slope of 1 ms/item in the luminance blocks, mean RTs ranging from 311 ms to 328 ms and with a slope of 1.3 ms/item in the size blocks; mean RTs ranging from 311 ms to 333 ms).

[2] MED was designed by Agnieszka Wykowska and Anna Schubö. It was constructed by Aleksander Dziadecki, University of Science and Technology, Kraków, Poland.

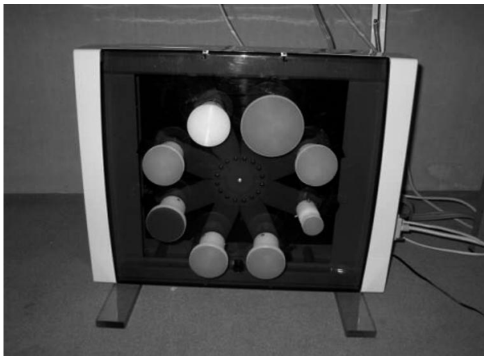

*Figure 2.* Movement execution device (MED) on which observers performed the required movement type (grasping or pointing) on completion of the detection task. Grasping consisted in grasping and pulling one of the plastic circles sticking out of the box (the one that was lit) and pointing required a pointing movement towards the lit circle without touching it.

## Procedure

All participants took part in two sessions consisting of one practice session and a subsequent experimental session with at least 1 and maximum 2 days delay. The aim of the practice session was to train the movement execution so that the whole experimental task would be easier to perform. In the practice session, participants performed four blocks of only one type of movement (pointing or grasping) and two blocks of both types of movements randomly intermixed (64 trials per each block). Participants were trained to perform the movement with both hands. For the first four blocks of the practice session, no information was displayed on the computer screen. For the two last blocks in which both types of movement were required, participants were informed about the movement (grasping or pointing) that had to be executed on a trial-by-trial basis by a cue that consisted in a picture of a particular movement type (cf. Figure 3). Before the practice session, all participants' visual acuity was tested with a Rodenstock R12 vision tester, stimuli nr.112 (Rodenstock, München, Germany). The experiment was conducted with the understanding and consent of each participant.

# Experiment 1

Experiment 1 investigated whether preparing a grasping or pointing movement would affect visual search performance at all. As already explained, we expected that the target-defining dimension (i.e., the dimension on which the visual search target differed from the distracters) would interact with the type of movement prepared. In particular, we expected that preparing a grasp would be congruent with, and thus facilitate, detecting a size-defined target as compared to a luminance-defined target and that preparing a pointing movement would be congruent with, and thus facilitate, detecting a luminance-defined as compared to a size-defined target. Given that we blocked the target-defining dimension, we expected that most participants would prefer search strategy based on a top-down weighting of the task-relevant dimension. As this strategy should be sensitive to action-induced biases, we expected conditions to be good for interactions between prepared action and target dimension to occur.

## Method

*Participants.* Twelve paid volunteers (6 men) aged from 18 to 30 years (*M* age: 25) took part. One participant was left-handed, and all had normal or corrected-to-normal vision. All participants were experienced with other visual search experiments, but they were naïve with respect to the purpose of this particular experiment.

*Procedure.* The experimental session consisted of four blocks, 128 trials each. At the beginning of the experimental session, participants performed a practice block in which they practiced the detection task (one block for luminance and one for size) together with the movement preparation and subsequent execution. In the experimental blocks, the two target types (size and luminance) remained constant for half of the blocks, with their order balanced across participants. The movement task was intermixed within blocks, and participants were presented with a picture cue concerning the movement type they were to execute.

Each trial of a block began with a fixation cross displayed for 500 ms. Subsequently, the movement cue appeared for 1,500 ms. Participants were instructed to prepare for the movement but not execute it until a signal from the MED would appear. The cue was followed by the search display presented for 100 ms. A blank screen followed the search display and remained on the computer screen for 2,500 ms while the participants were to perform the detection task pressing one of the keys for target present trials and the other one for target absent. Key assignment (left or right key response for target presence) was counterbalanced across participants. The blank screen was followed by a signal from the MED, which consisted in one of the LEDs lighting for 300 ms. Only at this point were observers instructed to execute the prepared movement, that is, to either point or grasp the item that was lit. After 1,500 ms, subsequent to LED light offset, a new trial began. The trial sequence is depicted in Figure 4, left panel.

Correctness of movement execution was registered by the experimenter seated in the same chamber as the participants. Participants were asked to be as fast as possible at the same time trying to be accurate with the detection task. With movement execution, they were asked to be as accurate as possible but speed was not stressed. They were instructed in detail about their task before the experiment started.

*Data analysis.* Prior to analysis, mean reaction times (RTs) and standard deviations (*SD*) were computed for each participant

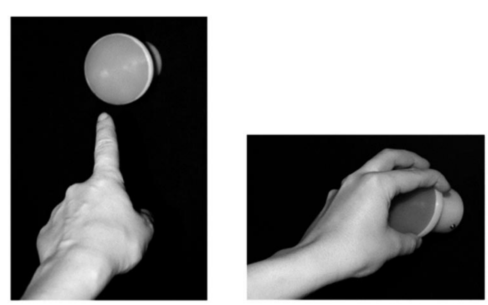

*Figure 3.* Movement cues. A pointing movement cue (left) or a grasping movement cue (right) was presented prior to the search display. The cues informed about the movement type that had to be prepared but not executed until the completion of the detection task.

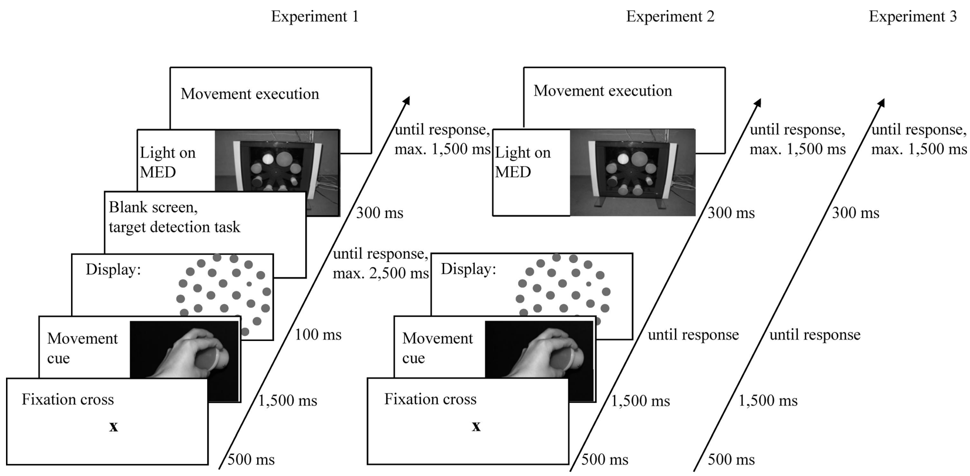


*Figure 4.* Trial sequences in Experiment 1 (left), Experiment 2 (middle), and Experiment 3 (right). A trial started with a fixation cross (500 ms) followed by a movement cue (1,500 ms). With the presentation of the movement cue, participants were instructed to prepare the cued movement but not execute it prior to completion of the detection task. Subsequent to presentation of the movement cue, the search display was presented. It remained on the screen for 100 ms (Experiment 1) or until response (Experiment 2 and 3). Subsequent to response in the detection task, one of the lights on MED was lit and observers were asked to execute the movement type they have been preparing. With the execution of the movement, the trial ended. MED = Movement execution device.

and each experimental block. Incorrect movement trials, trials with no responses, as well as outliers in the search task (±3 *SD* from the overall mean of RTs for each participant and each block separately) were excluded from further analyses. From the remaining data, individual mean RTs and errors in the detection task were submitted to analysis of variance (ANOVA) with: task-relevant dimension (luminance vs. size), movement type (point vs. grasp), trial type (target absent vs. target present trials) as within-subject factors. Wherever appropriate, specific subgroup differences were tested with paired-sample *t* tests.

## *Results*

*RTs.* The 2 × 2 × 2 ANOVA showed a main effect of task-relevant dimension, $F(1, 11) = 19.74$, $p < .005$, $\eta_p^2 = .642$, indicating slower RTs for size detection ($M = 573$ ms, $SEM = 28$) compared to luminance detection ($M = 502$ ms, $SEM = 18$). There was also a main effect of trial type, $F(1, 11) = 10.11$, $p < .01$, $\eta_p^2 = .479$, showing longer RTs for target absent trials ($M = 558$ ms, $SEM = 25$) compared to target present trials ($M = 517$ ms, $SEM = 21$).

The analysis showed also a significant interaction between task-relevant dimension and movement type, $F(1, 11) = 5.99$, $p < .05$, $\eta_p^2 = .353$ (cf. Figure 5) and, in addition, an interaction between trial type and task-relevant dimension factors, $F(1, 11) = 25.6$, $p < .001$, $\eta_p^2 = .700$.

To compare mean RTs in grasping and pointing conditions in luminance and size detection separately, additional one-tailed *t* tests were conducted. The *t* tests showed that when luminance was the task-relevant dimension, the difference between RTs in grasping compared to pointing condition was significant, $t(11) = 2.2$, $p < .05$, showing faster reactions to luminance targets when preparing for pointing compared to grasping (cf. Figure 5, left panel). When size was the task-relevant dimension, the *t* tests showed also a significant difference between the grasping and the pointing condition $t(11) = 1.8$, $p < .05$. In this condition, reactions in size detection were faster in grasping condition compared to pointing (cf. Figure 5, right panel). Summarized results of the interacting movement type and task-relevant dimension factors are given in Table 1.

Furthermore, separate *t* tests were conducted to compare RTs to target present and target absent trials for each task-relevant dimension (luminance vs. size) separately. When size was the task-relevant dimension, RTs were significantly longer for target absent trials (vs. target present), $t(11) = 4.6$, $p < .005$, although this difference did not reach significance for luminance, $p > .26$.

*Error rates.* Overall mean error rates were below 5%. The 2 × 2 × 2 ANOVA showed a main effect of task-relevant dimension, $F(1, 11) = 6.94$, $p < .05$, $\eta_p^2 = .387$, showing larger error rates for size ($M = 6.2$ %, $SEM = 1.5$) compared to luminance detection task ($M = 2.9\%$, $SEM = 0.5$). No other effects reached the level of significance.

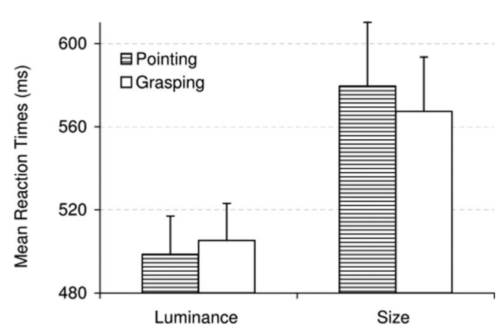


*Figure 5.* Effects of task-relevant dimension and movement type in Experiment 1. Mean reaction times to luminance as task-relevant dimension and size as task-relevant dimension while participants prepared a pointing movement (filled bars) or a grasping movement (empty bars).

Table 1
*Mean RTs and SEMs to Task-Relevant Dimensions as a Function of Movement Type (Pointing vs. Grasping) in Experiment 1*

| Task-relevant dimension | *M* RTs | | *SEM* | |
|---|---|---|---|---|
| | Pointing | Grasping | Pointing | Grasping |
| Luminance | 498 | 505 | 18 | 18 |
| Size | 580 | 567 | 31 | 26 |

*Note*. RT data are given in milliseconds. RTs = reaction times; SEM = mean standard error.

### *Discussion*

Experiment 1 investigated whether the preparation of a grasping or pointing action would bias attentional selection in a visual search task in such a way that targets popping out on action-related perceptual dimensions would be easier to detect. The obtained results fully support this hypothesis in showing that detecting size-defined targets benefited from the preparation of a grasping movement whereas detecting luminance-defined targets benefited from the preparation of a pointing movement. Even though our search task is likely to tap into rather early visual processes, they are systematically affected by concurrent action planning. The obtained interactions are particularly interesting from a dual-task performance point of view. Whereas higher level cognitive processes like mental rotation or memory retrieval are known to share capacity with response selection (for an overview, see Jolicœur, Tombu, Oriet, & Stevanovski, 2002; Pashler, 1984), the detection of visual targets is considered to be largely independent from action planning (Johnston, McCann, & Remington, 1995; Pashler, 1989). Even though the design of our study does not allow us to measure possible dual-task costs, the interaction between prepared action and target-defining dimension clearly demonstrates that action planning and visual attention communicate in specific ways.

Our remaining observations are of less theoretical interest, at least in the present context. Apart from slower responses to absent than present targets, a common phenomenon in visual search tasks (Chun & Wolfe, 1996), we found that RTs were slower when size was the task-relevant dimension. This effect is likely to reflect a search asymmetry as has been found for other dimensions (e.g., Treisman & Gormican, 1988). The same interpretation is likely to hold for the interaction between trial type and task-relevant dimension, showing that the difference between target absent and target present trials was pronounced if searching for size but insignificant if searching for luminance.

## Experiment 2

Experiment 1 was successful in demonstrating that action planning can influence selection of perceptual dimensions that are needed to specify relevant action parameters. As we suggested earlier, action-control processes may bias visual attention by increasing the weights of action-relevant dimension maps, so to facilitate the processing of coded stimuli. Experiment 1 was thought to suggest (but not to enforce) a search strategy that relies on top-down dimension weighting, so to make possible biases from action planning visible. If so, preventing participants from adopting this strategy and tempting them to use the "singleton detection" that is thought to rely on saliency signals solely (see Bacon & Egeth, 1994) should work against action-induced biasing. In Experiment 2, we tested this prediction by making a singleton-detection strategy particularly plausible. We did so by randomly varying the target dimensions and asked participants to respond to any singleton independent of its dimension. That is, size singletons and luminance singletons as well as target-absent trials could all appear within the same block, and any type of singleton required a target-present response.

### *Method*

*Participants.* Eleven paid volunteers (7 men) aged from 20 to 35 years (*M* age: 24.4) took part. Two participants were left-handed, and all had normal or corrected-to-normal vision. All participants were experienced with other visual search experiments, but they were naïve with respect to the purpose of this particular experiment. None of the participants took part in Experiment 1.

*Materials, procedure, and data analysis.* Stimuli and apparatus were as described in the General Method section. Experiment 2 differed from Experiment 1 only with respect to the trial sequence (see Figure 4, middle panel). In contrast to Experiment 1, both task-relevant dimension and movement type varied randomly across trials. Participants were to respond to any pop-out target in the search array and to simply decide whether a target had been presented or not. The detection display was presented until response.[3] Participants performed one practice block followed by two experimental blocks, 256 trials each. The data was analyzed using a 2 × 3 ANOVA design with movement type (point vs. grasp) and display type (blank vs. luminance vs. size) as within-subject factors. Due to the intermixed design, there was no proper factor of task-relevant dimension in Experiment 2 as singletons of both dimensions were to be selected as targets. The display type factor (luminance vs. size vs. blank) therefore combined two factors of Experiment 1, namely: task-relevant dimension (both size and luminance were relevant) and trial type (singleton present vs. blank). To test the movement-related effects with respect to implicit dimensional weighting, a subsequent analysis was conducted for target trials only with display type (luminance vs. size), movement type (point vs. grasp) and dimension repetition (same dimension vs. different dimension) as within-subject factors.

[3] Presentation time of the display was increased (relative to Experiment 1) because a pilot study with the same parameters as in Experiment 1 yielded an error rate of over 30%. Such an effect might be due to the fact that participants were to perform two tasks: to detect a target by responding with their dominant hand while preparing to perform a particular movement type with their other hand. In such a situation when the target is not blocked and unpredictable on each trial (Experiment 2), it might be more difficult to detect it compared to when the target is blocked; therefore, participants know in advance that if there will be a target, it will be of a particular dimension (Experiment 1). That does not imply that a singleton search (Experiment 2) is more difficult than search for a particular feature dimension (Experiment 1). In Experiment 1, the target could have been, presumably, detected both based on its saliency signals (singleton search) and based on search for a particular, predefined dimension.

### Results

*RTs.* The 2 × 3 ANOVA indicated a main effect of display type, $F(2, 20) = 15.04$, $p < .005$, $\eta_p^2 = .601$, showing the slowest responses in blank trials ($M = 591$ ms, $SEM = 19$), intermediate responses in size trials ($M = 558$ ms, $SEM = 22$), and fastest responses in luminance trials ($M = 535$ ms, $SEM = 22$). No other main or interaction effect reached significance: Movement Type × Display Type, $F(2, 20) < 1$, $p = .61$, $\eta_p^2 = .048$.

Subsequent analysis conducted for target trials only with the factors display type (luminance vs. size), movement type (point vs. grasp), and dimension repetition (repeated dimension vs. different dimension) indicated a main effect of display type, $F(1, 10) = 13.9$, $p < .005$, $\eta_p^2 = .583$, and a main effect of repetition, $F(1, 10) = 8.2$, $p < .05$, $\eta_p^2 = .451$, showing faster RTs in the repeated dimension condition ($M = 529$ ms, $SEM = 24$) compared to the different dimension condition ($M = 554$ ms, $SEM = 21$). Again the interaction between display type and movement type did not reach the level of significance, $F(2, 20) = 1.7$, $p = .21$, $\eta_p^2 = .147$. A further analysis conducted only for the repeated-singleton condition with the factors display type (luminance vs. size) and movement type (point vs. grasp) also did not reveal a significant interaction between target type and movement type, $F(1, 10) = 1$, $p = .33$, $\eta_p^2 = .094$.

To investigate whether the effects we obtained would depend on the relative RT level, we conducted further analyses of Vincentized RT distributions (Ratcliff, 1979): Each participant's correct RTs (raw data) were rank ordered according to response speed. The ranked RTs were then divided into five equal bins and, subsequently, divided into the experimental conditions. The 3 × 2 × 5 ANOVA with the factors display type (luminance vs. size vs. blank), movement type (point vs. grasp) and bin (shortest through longest RTs) showed only a main effect of bin, $F(4, 36) = 320$, $p < .001$, $\eta_p^2 = .973$, which was produced by the data subdivision. No significant interaction between bin and other factors was obtained. In addition, no effects of movement type for any of the bins separately were observed.

*Error rates.* Overall error rates were below 3%. In the 2 × 3 ANOVA with the factors movement type (point vs. grasp) and display type (blank vs. luminance vs. size), no effects reached the level of significance. Also the 2 × 2 × 2 ANOVA for target trials only with the factors display type (luminance vs. size), movement type (point vs. grasp), and dimension repetition (repeated dimension vs. different dimension), revealed no significant effects or interactions.

### Discussion

In Experiment 2, we took measures to prevent participants from adopting a top-down search strategy and tried to induce a singleton-detection mode that relies only on detection of saliency signals. If this could be achieved, we reasoned, action-related biases could still be generated but they would no longer be considered by the "official search policy," as it were. Accordingly, action-induced biases would no longer be able to impact visual attention; we should work against the interaction between planned action and target-defining dimension observed in Experiment 1. Consistent with this hypothesis, this interaction was eliminated in Experiment 2, suggesting that the adopted search strategy left no room for any impact of action planning. One might argue that this was not a consequence of the strategy as such, and of the type of information considered, but rather a side effect of the possibly more efficient processing, which might have been too fast for biases to show up in the RTs. We checked for this possibility by looking into the RT distribution, considering that the bias may only be visible in the longer (i.e., slower) tail of the distribution representing the trials with less efficient processing. However, action-induced effects were not obtained in any RT bin, apart from the fact that mean RTs were even slower than in Experiment 1, which provides no support for an account in terms of efficiency or relative processing speed.

Another purpose of Experiment 2 was to see whether bottom-up dimensional weighting induced by dimension-specific intertrial effects would occur in the hypothesized absence of action-related intentional weighting. We did observe intertrial repetition effects: Responses were significantly faster in repeated-dimension than in different-dimension trials, which replicate earlier observations (see, e.g., Found & Müller, 1996; Maljkovic & Nakayama, 1994; Müller et al., 1995). More interesting, however, this effect did not interact with movement type and/or display type, which might be taken to suggest a functionally different origin. In Experiment 3, we created conditions that we considered likely to yield reliable action-induced biases and tested whether intertrial repetition effects would still be independent of the action-induced weighting effects.

## Experiment 3

Experiment 2 confirmed our hypothesis that creating conditions that suggest adopting a bottom-up driven search strategy eliminates the impact of action preparation on visual selection. In Experiment 3, we went in the opposite direction and created conditions that suggested a top-down search strategy, which we considered suitable to make action-induced biases visible. Accordingly, we expected the same kind of interaction between action planning and visual search as we obtained in Experiment 1—even though design-wise Experiment 3 maintained the task characteristics of Experiment 2 as far as possible. Combining the design of Experiment 2 with conditions that we considered likely to create sizeable action-induced biases had another advantage: We were now able to test whether bottom-up dimensional weighting visible through intertrial dimension repetition/switch effects would still be observed and, if so, if it would be modulated by action-induced weighting.

Again, two types of singletons (luminance and size) were presented within the same block, only that this time participants detected singletons on one dimension while ignoring singletons on the other dimension. Hence, the displays containing size or luminance singletons varied across trials, but the target-defining dimension was kept constant within a block. This entailed that observers could not detect a target based solely on saliency but had to search for a specific, task-relevant target dimension. According to our line of reasoning, this would encourage a top-down strategy based on the explicit weighting of the task-relevant dimension map, which again should allow action-induced biases to influence the weighting and, thus, modulate selection.

## Method

*Participants.* Seventeen paid volunteers (9 men) aged from 20 to 36 years (*M* age: 26.3) took part. One participant was left-handed, and all had normal or corrected-to-normal vision. All participants were experienced with other visual search experiments, but they were naïve with respect to the purpose of this particular experiment. None of the participants took part in Experiment 1 or Experiment 2. One participant had to be excluded from analysis due to extremely long RTs ($M = 948$ ms) and a large overall standard deviation ($SD = 364$).

*Procedure.* Procedure and trial sequence remained the same as in Experiment 2 (cf. Figure 4, right panel) except for instructions in the experimental session. As in Experiment 2, singletons of two types (i.e., size and luminance) varied randomly across trials. In one of the sessions, the target was defined as a smaller size item and participants were asked to respond with the target-related key when a size target would appear, and with the alternative key otherwise (i.e., for irrelevant luminance singletons and blank trials). In the other session, the target was defined by lighter grey.

Participants performed eight blocks of 64 trials each in two sessions. There was one practice block at the beginning of the first session and another practice block at the beginning of the second session. The order of target-defining dimensions (luminance vs. size) was counterbalanced across participants. The data were analyzed using a 2 × 2 × 3 ANOVA design with task-relevant dimension (luminance vs. size), movement type (point vs. grasp), and trial type (target vs. irrelevant singleton vs. blank) as within-subject factors. To test the movement-related effects with respect to implicit dimensional weighting, a subsequent analysis was conducted only for singleton-present trials with task-relevant dimension (luminance vs. size), movement type (point vs. grasp), trial type (target vs. irrelevant singleton), and dimension repetition (repeated dimension vs. different dimension) as within-subject factors. The rest of the procedure of data analysis remained the same as in Experiment 1 and 2.

## Results

*RTs.* The 2 × 2 × 3 ANOVA showed a main effect of task-relevant dimension, $F(1, 15) = 15.99$, $p < .01$, $\eta_p^2 = .516$; indicating slower RTs for size ($M = 601$ ms, $SEM = 22$) than for luminance ($M = 546$ ms, $SEM = 20$). The main effect of trial type, $F(2, 30) = 5.41$, $p < .05$, $\eta_p^2 = .265$, was due to slower responses to target absent trials ($M = 583$ ms, $SEM = 20$) and irrelevant singleton trials ($M = 581$ ms, $SEM = 21$) compared to target present trials ($M = 556$ ms, $SEM = 21$).

The three-way interaction of task-relevant dimension, movement type, and trial type was reliable, $F(2, 30) = 5.31$, $p < .05$, $\eta_p^2 = .262$ (see Figure 6). Because both luminance and size singletons could play the role of either targets or irrelevant singletons (luminance singletons in the conditions where size was task relevant and size singletons in the condition where luminance was task relevant), subsequent separate analyses with the factors: task-relevant dimension (luminance vs. size) and movement type (point vs. grasp) were conducted for target trials and irrelevant singleton trials.

In the case of target trials (see Figure 6a), the task-relevant dimension interacted with movement type, $F(1, 15) = 4.5$, $p = .05$, $\eta_p^2 = .233$; showing that in the luminance task condition, participants reacted faster when they were preparing for a pointing movement ($M = 540$ ms, $SEM = 23$) relative to the grasping movement ($M = 552$ ms, $SEM = 23$, see Figure 6a, left panel) whereas in the size task condition, participants were slightly faster when preparing for grasping ($M = 564$ ms, $SEM = 21$) compared to pointing ($M = 569$ ms, $SEM = 21$, see Figure 6a, right panel). Further one-tailed *t* tests showed that the difference was significant in the luminance condition, $t(15) = 2.1$, $p < .05$, but did not reach the level of significance for the size condition, $t(15) = 1.08$, $p = .147$.

In the case of irrelevant singleton trials (see Figure 6b), the interaction between task-relevant dimension and movement type was marginally significant, $F(1, 15) = 4.1$, $p = .058$, $\eta_p^2 = .219$; showing that in the luminance task condition, participants reacted faster when they were preparing for a grasping movement ($M = 542$ ms, $SEM = 19$) relative to the pointing movement ($M = 556$ ms, $SEM = 20$, see Figure 6b, left panel) whereas in the size task condition, there was no difference in RTs with respect to the type of movement prepared (pointing movement: $M = 612$ ms, $SEM = 25$; $M = 613$ ms, $SEM = 23$, see Figure 6b, right panel). Further one-tailed *t* tests showed that the difference was significant in the

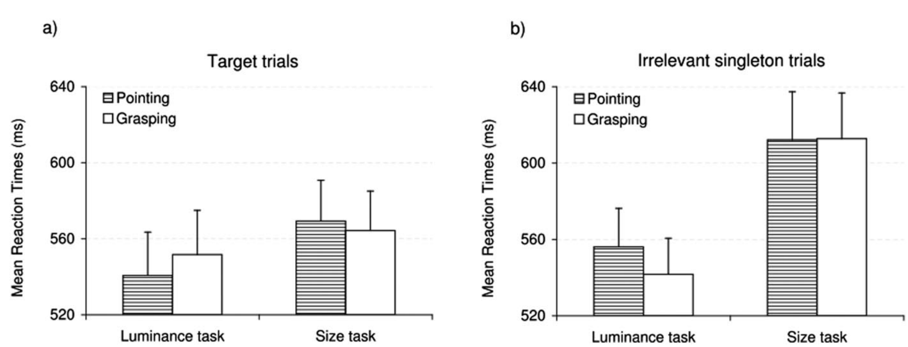


*Figure 6.* Effects of task-relevant dimension, movement type, and trial type in Experiment 3, target trials (6a) and irrelevant singleton trials (6b). Mean reaction times to luminance as task-relevant dimension and size as task-relevant dimension as a function of movement type: pointing (filled bars) versus grasping (empty bars). In Figure 6b, the panel representing size as task-relevant dimension depict trials containing irrelevant luminance singletons and the bars representing luminance as task-relevant dimension depict trials containing irrelevant size singletons.

luminance condition, $t(15) = 2.1$, $p < .05$, but not in the size condition.

The analysis conducted for blank trials showed only a significant effect of task-relevant dimension, $F(1, 15) = 28$, $p < .001$, $\eta_p^2 = .655$, revealing faster RTs in the luminance condition ($M$ = 541 ms, $SEM$ = 19) relative to the size condition ($M$ = 624 ms, $SEM$ = 24). No other effects reached the level of significance. For a summary of the Task-Relevant Dimension × Trial Type × Movement Type Effects, see Table 2.

In addition to the effects of interest, an interaction between task-relevant dimension and trial type was significant, $F(2, 30) = 22.53$, $p < .001$, $\eta_p^2 = .600$ (see Figure 7). To get a grip on this effect, we analyzed the data from the two tasks separately. For size dimension, the trial-type effect was significant, $F(2, 30) = 15.8$, $p < .001$, $\eta_p^2 = .511$ (see Figure 7, right panel). A planned comparison showed that target trials were responded to faster than irrelevant singleton trials, $F(1, 15) = 14.1$, $p < .005$, $\eta_p^2 = .487$ (see Figure 7, right panel, empty bar), although there was no difference between irrelevant singleton trials and blank trials (see Figure 7, right panel, striped and checked bar, respectively). For the luminance dimension, the trial-type effect did not reach the level of significance, $F(2, 30) = .285$, $p = .662$, $\eta_p^2 = .019$ (see Figure 7, left panel). Planned comparisons showed also no significant differences.

Further analysis on target-present trials only, conducted to reveal movement-related effects with respect to implicit dimension weighting, showed no interaction between dimension repetition and movement type, $F(2, 30) = 0.9$, $p = .34$, $\eta_p^2 = .057$, and no interaction between dimension repetition, movement type and task-relevant dimension, $F(2, 30) = 0.07$, $p = .78$, $\eta_p^2 = .005$.

At the same time, a significant interaction between the task-relevant dimension and singleton repetition, $F(1, 15) = 7.6$, $p < .05$, $\eta_p^2 = .336$, was obtained. In trials with size targets, but not luminance targets, the main effect of singleton repetition was significant, $F(1, 15) = 6.04$, $p < .05$, $\eta_p^2 = .301$. However, the factor of singleton repetition did not interact with the factor of movement type.

Table 2
*Mean RTs and SEMs to Task-Relevant Dimensions as a Function of Movement Type (Pointing vs. Grasping) for Target Trials (Two Upper Rows) and Irrelevant Singleton Trials (Two Lower Rows) in Experiment 3*

| Task-relevant dimension | *M* RTs Pointing | *M* RTs Grasping | *SEM* Pointing | *SEM* Grasping |
|---|---|---|---|---|
| Target trials | | | | |
| Luminance | 541 | 552 | 23 | 23 |
| Size | 569 | 564 | 21 | 21 |
| Irrelevant singleton trials | | | | |
| Luminance (size singletons) | 556 | 542 | 20 | 19 |
| Size (luminance singletons)[a] | 612 | 613 | 25 | 24 |
| Blank trials | | | | |
| Luminance task | 544 | 539 | 19 | 20 |
| Size task | 619 | 630 | 26 | 23 |

*Note*. Reaction time data are given in milliseconds. RTs = reaction times; SEM = mean standard error.
[a] Irrelevant singleton trials denote those trials in which size singletons were presented in the condition in which luminance was the task-relevant dimension and trials with luminance singletons when size was the task-relevant dimension.

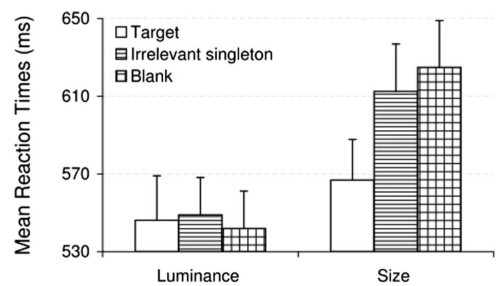


*Figure 7.* Effects of task-relevant dimension and trial type in Experiment 3. Mean reaction times to luminance as task-relevant dimension and size as task-relevant dimension as a function of trial type (target trials [empty bars] vs. irrelevant singleton trials [horizontally striped bars] vs. blank trials [checked bars]). The striped bar in the luminance task condition represents trials containing irrelevant size singletons and the striped bar in size task condition represents trials containing irrelevant luminance singletons.

*Error rates.* Overall error rates were below 1%, which did not allow for a meaningful analysis.

### Analysis Across Experiments 1 Through 3

A final analysis compared the data across all three experiments for target-present trials. An ANOVA with the within-subjects factors of target type (luminance vs. size) and movement type (point vs. grasp) as well as a between-subject factor of experiment (Experiment 1 vs. Experiment 2 vs. Experiment 3) revealed a main effect of target type, $F(1, 36) = 15$, $p < .001$, $\eta_p^2 = .298$, indicating longer RTs for size targets ($M$ = 555 ms, $SEM$ = 13) relative to luminance targets ($M$ = 525 ms, $SEM$ = 13) in all three experiments. The analysis revealed also a marginally significant three-way interaction of experiment, movement type, and target type, $F(2, 36) = 2.95$, $p = .06$, $\eta_p^2 = .141$. Planned comparisons indicated that the interaction of movement type and target type, $F(1, 26) = 8.64$, $p = .01$, $\eta_p^2 = .250$, showed the same pattern for Experiment 1 and 3, $p > .97$ but differed when Experiment 1 and 3 were averaged and compared to Experiment 2, $F(1, 36) = 5.87$, $p < .05$ (see Figure 8). This finding suggests that action planning influenced visual search in a similar way in Experiment 1 and 3 but did not show modulatory effects in Experiment 2.

### Discussion

Experiment 3 tested whether action-related effects in a version of the task used in Experiment 2 would reappear under conditions that encourage top-down weighting of the task-relevant feature dimension. Indeed, detecting luminance targets was easier when preparing for a pointing movement while detecting size targets tended to be easier when preparing to grasp. Even irrelevant singletons could be rejected faster when a congruent action was prepared, a further suggestion that preparing a particular movement type automatically increases the weights on congruent perceptual dimensions. That is, Experiment 3 confirmed the assumption that selection in visual search is biased by action planning.

The result showed that differences between pointing and grasping conditions were significant in the luminance task condition,

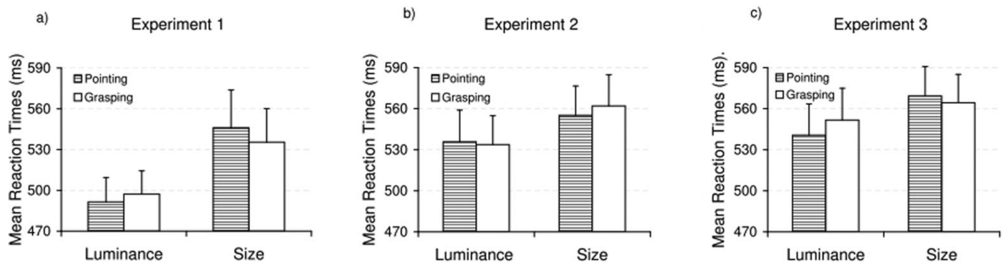


*Figure 8.* Effects of movement type and target type across the three experiments for target-present trials only. Mean reaction times to size targets and luminance targets as a function of movement type: point (filled bars) vs. grasp (empty bars) in Experiment 1 (8a), Experiment 2 (8b) and Experiment 3 (8c).

that is, for luminance targets but not for size targets (Figure 6a) and for irrelevant size items but not irrelevant luminance items (Figure 6b). This might be due to the fact that the size task condition was more difficult in general (RTs for all display types were longer in this condition, c.f. right panel of Figure 7), which might have attenuated the action-related impact on size detection and the rejection of irrelevant luminance singletons.

More interesting, even though this time we did observe a reliable action-induced bias, it showed a pattern dissociable from the effects of dimension repetition. Although both dimension repetition and movement type interacted with singleton type, dimension repetition effects were observed for trials with size but not luminance targets whereas movement-related biases were more pronounced for luminance targets than size targets. This supports our claim that action-related effects are of different origin than inter-trial dimension repetition effects and is consistent with the interpretation that these effects reflect the operation of top-down and bottom-up processes, respectively.

In addition to the effects of major theoretical interest, we obtained a main effect of trial type showing that blank trials and irrelevant singleton trials slowed down responding as compared to target present trials. As argued above, the difference between blank and target present trials, which showed the same pattern as in Experiments 1 and 2, is often observed in visual search studies. The difference between irrelevant singleton trials and target present trials might be due to that irrelevant items induce a strong saliency signal that has to be overridden by the task-relevance control classifying the saliency signal as irrelevant. In other words, the bottom-up signal calls for a positive response, which top-down control has to inhibit. However, the significant interaction of trial type and task-relevant dimension showed that the difference between target present and blank trials was mainly stemming from the condition in which size was the task-relevant dimension (see Figure 7, right panel) but not when luminance was task-relevant (Figure 7, left panel). Such an interaction, as discussed above, might reflect another effect of search asymmetry. As the difference between target trials and irrelevant singleton trials was only observed for luminance items (in size task) and as in all three experiments RTs were generally shorter if luminance was the task-relevant dimension, luminance singletons might have been more salient and thus more difficult to reject.

To summarize, results of Experiment 3 confirm that the same setup that eliminated action-induced biases in Experiment 2 can produce such biases if only top-down weighting of a task-relevant dimension is encouraged. At the same time, Experiment 3 provided evidence, in line with results of Experiment 2, that action-induced weighting is independent from the weighting induced by dimension repetition.

## General Discussion

Three experiments tested whether planning an action biases visual search toward dimensions that deliver important information for controlling that action. Our findings implicate that even those tasks that are commonly taken to tap rather early interactions of perception and attention, such as efficient visual search (cf. footnote 1), are sensitive to action control processes. Our results showed that planning a grasping or a pointing movement facilitated the detection of targets and rejection of irrelevant singletons (as in Experiment 3) on action-congruent feature dimensions even at early stages of processing under conditions in which movement and visual search were logically independent and entirely unrelated. Considering that action-induced biases are no less likely to occur under conditions in which action-planning and search processes belong to the same task, as in standard visual search tasks, it seems possible that much of our present knowledge about attentional operations in visual search is specific to the actions used to indicate them—commonly spatially defined button pressing, a type of action that seems to prime the processing of stimulus location (Hommel, 2007).

It seems clear that preparing for a particular type of action primes processing of action-related information. This supports the idea that action planning primes perceptual dimensions that are likely to provide information that is useful for the control of the planned action. Well-practiced actions are commonly driven by two types of information: feed-forward information about the invariant characteristics of the action, which can be retrieved from long-term memory and used to prepare the action off-line, and online information that specifies open parameters and adapts the action to the current environment (Glover, 2004; Hommel, Müsseler, Aschersleben, & Prinz, 2001a; Schmidt, 1975). Considering the present findings, together with those of Fagioli et al. (2007), it makes sense to believe that off-line action preparation has not only the function of specifying and implementing invariant action properties but also to prepare the perceptual system to deliver information that is suited to specify the still open parameters. With regard to grasping, these parameters are likely to comprise of object size (as suggested by the present study as well as by Fagioli et al., 2007), and with regard to pointing, they are likely to comprise of luminance (as suggested by the present study) and location (as suggested by Fagioli et al., 2007).

The present findings suggest a much more general effect of action planning on selection than previous demonstrations, which showed that actions aiming at particular objects prime particular feature values of that object (Bekkering & Neggers, 2002; Craighero et al., 1999; Deubel et al., 1996). Rather than (or in addition to) specific feature values, it seems that preparing for an action is priming a whole dimension, thereby enhancing the processing of any feature value falling in that dimension. Hence, dimensions are intentionally weighted (Hommel et al., 2001b), to the degree that they are considered action relevant. The mechanism underlying this weighting process may be the same as the one that has been hypothesized to account for other top-down effects on visual selection. According to the guided search model (Wolfe, 1994; Wolfe et al., 2003) or the dimensional weighting account of Müller and colleagues (e.g., Müller et al., 1995), a visual scene is encoded in dimensional maps from where the signal is transmitted to a master map of activation (cf., Treisman, 1988; Wolfe, 1994). On the master map, weighted dimension-specific saliency signals are summed in parallel. More important for our purposes, it is assumed that whole dimensions are weighted (e.g., color), but not particular feature values (e.g., red), and that weights modulate the impact of the respective dimensions on further processes. Weights can be explicitly assigned in a top-down manner, for example, as a consequence of instruction, but they can also be induced in a more bottom-up fashion as observed through intertrial repetition effects (e.g., Found & Müller, 1996; Geyer, Müller, & Krummenacher, 2007; Maljkovic & Nakayama, 1994; Müller et al., 1995) to the degree that the particular weighting adopted improves performance. In case of the present experiments, perceptual dimensions have also been weighted with respect to action relevance.

More interesting, we found evidence that the action-related bias is not independent from weighting related to task relevance. We distinguished between a top-down selection strategy that is based on the prior specification of the target-relevant dimension and a bottom-up selection strategy based on saliency detection (singleton detection). Experiments 1 and 3 encouraged top-down weighting of particular target dimensions with respect to their task relevance, whereas Experiment 2 encouraged selection based on bottom-up saliency signals. These manipulations also affected action-induced weighting, as action-related effects were observed in Experiments 1 and 3 but not in Experiment 2. This suggests that action-induced weighting affects selection only when task-relevance biases also come into play but not if selection can be based on bottom-up saliency signals only. This parallels comparable observations regarding the potency of top-down weighting reported by Bacon and Egeth (1994), and supports the idea that the mechanism realizing action-induced biases is closely related to the mechanism responsible for task-induced top-down weighting.

In contrast, the double dissociation we obtained for action-induced biases and dimension-repetition effects suggests that the mechanisms underlying these two phenomena are unrelated, which again supports the idea that repetition priming is a type of a bottom-up effect (Found & Müller, 1996; Maljkovic & Nakayama, 1994; Müller et al., 1995; Müller et al., 2003). This dissociation is in line with the findings of Müller et al. (2003), where bottom-up intertrial effects were reduced when the target-defining dimension was validly cued. These results show that bottom-up dimension weighting can be modulated by a top-down weight-setting process. In the context of our study, the intended action may have acted as a top-down cue for the congruent perceptual dimension. When the intended action affected processing of the congruent dimension, the intertrial effects were attenuated. Similar findings on top-down attenuation of bottom-up effects were reported by Folk & Remington (2008). The authors observed that intertrial priming occurred only when participants were in a singleton detection mode but not when their attention set was focused on a specific target feature (feature search mode). Folk and Remington concluded that top-down attentional control settings for a particular feature can override bottom-up intertrial repetition priming.

The dissociation between bottom-up and top-down (also action-related) weighting could also be interpreted within a framework of guided search or the dimensional weighting account. When no information concerning dimension relevance is specified in advance, all dimensions are equally weighted at first. Subsequently, dimensions presented at a given trial are weighted higher as compared to other dimensions and that results in a benefit for repeated dimensions and/or a so-called dimension switch cost (e.g., Found & Müller, 1996; Maljkovic & Nakayama, 1994; Müller et al., 1995). In case of singleton detection mode, such bottom-up weighting might be a default mechanism. Yet, as soon as the task encourages adopting an attentional set (cf. Folk & Remington, 1998; Folk, Remington, & Johnston, 1992) for particular dimensions, top-down weighting becomes prioritized, as a result relevant dimensions are weighted higher than irrelevant ones. Therefore, the benefit of repeated dimension might be reduced if the dimension is irrelevant to the task at hand. If the given dimension is relevant, its weight is set high through top-down processes that might outweigh the dimension switch costs given by bottom-up weighting (c.f., Müller et al., 2003). As a result, the intertrial priming might not be observed when attention is set for a task-relevant dimension. The present results show that once top-down weighting comes into play, bottom-up processes are modulated by action relevance in a similar way as they are modulated by task-relevance.

To account for our findings we propose a combination of Hommel et al.'s (2001b) intentional weighting mechanism with the guided search model (Wolfe, 1994; 1998; Wolfe et al., 2003) and the dimensional weighting account (Found & Müller, 1996; Krummenacher, Müller, & Heller, 2002; Müller et al., 1995; see also Wolfe, 1994; Wolfe et al., 2003), as depicted in Figure 9. We extend former visual search models by postulating a weighting mechanism related to the action intentions of an agent. We assume that the agent sets intentional weights, not necessarily consciously, to those perceptual dimensions that he or she considers relevant, or that were learned to be relevant, for those tasks that are to be performed: the search task and the motor task. Weight setting with respect to task relevance and weight setting with respect to action planning take place in separate modules as weighting results from different (sub)tasks. Nevertheless, their respective impacts converge on a common intentional weight that is capable of modulating signals of the bottom-up processing stream. Although the exact nature of the interrelation between both weighting mechanisms is not clear at the present state, results favor a direct weighting link from task relevance to perceptual dimensions for the actually performed search task (w) and a modulatory influence of the

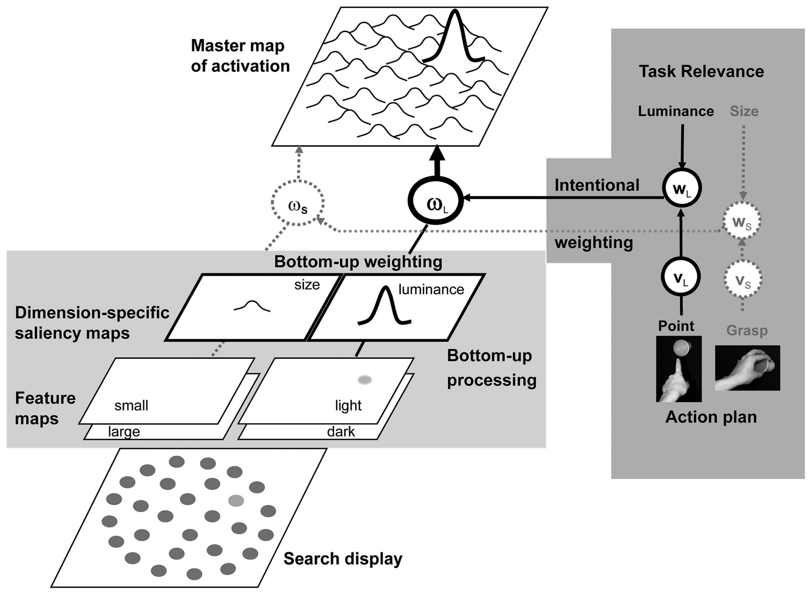


*Figure 9.* Graphical illustration of an action-based model of visual processing postulated to account for the results of the present experiments. Visual information is considered to be processed in dimension-specific modules, salient objects cause increased activation. Before the activation is summoned across all dimensions in a master map, weights (e.g., $\omega_S$ or $\omega_L$) can be assigned to the dimensions. The weights may be set in a top-down manner (e.g., when the observer is instructed to search for a specific task-relevant perceptual dimension (right side, upper part), or in a more bottom-up manner (intertrial dimension repetition/switch effects). Our experiments show that top-down weighting incorporates not only weighting due to task-relevance (e.g., $W_L$ or $W_S$, right side, upper part) but also weighting due to action planning (e.g., $V_L$ or $V_S$, right side, lower part). Both form an intentional weight (dark-grey area on the right) that modulates saliency-based processing (light-grey area on the left). Task-relevance weighting and action-induced weighting, however, do not have equivalent potency: When the task-relevance weighting mechanism does not occur, action-related weighting cannot directly modulate weights at the specific dimensions (ω). Bottom-up processing is thus modulated by a combined common weight (ω) that incorporates intentional weighting (action-related and task-relevance), bottom-up weighting, as well as other possible forms of weighting mechanisms.

action-related weight setting (v). Only if a task-relevance bias occurs will the action-related weighting also influence perceptual processing. In such a case, bottom-up processing will be modulated by the common weight combining task-relevance and action-relevance.

The assumption that weighting by task-relevance and weighting by action planning are based on similar mechanisms and eventually converge on a common weight suggests the speculation that top-down attentional control might originally have derived from action control. As recent findings from neuroimaging studies show, attending to particular visual dimensions activates the human premotor cortex and other action-related areas even under conditions that do not require immediate action (Schubotz & von Cramon, 2001, 2002). Even more interesting, this activation follows a rather systematic pattern (Schubotz & von Cramon, 2003): attending to shape is accompanied by the activation of a fronto-parietal prehension network and attending to location by the activation of cortical areas involved in manual reaching, while attending to temporal aspects activates a network associated with tapping and uttering speech. These observations may reflect an important integrative role of premotor cortex in the anticipation of perceptual events and the control of actions related to these events (Fagioli et al., 2007; Schubotz, 2007). The premotor cortex may integrate actions and their expected consequences into a kind of habitual pragmatic body map (Schubotz & von Cramon, 2001, 2003) that is part of a broader representational system for the "common-coding" of perceptual events and action plans (Hommel, 2004; Hommel et al., 2001b).

The possibility of anticipating the consequences of an action, and the need to control it in such a way to maximize wanted consequences, may have laid the ground for the (phylogenetic and/or ontogenetic) development of selective attention mechanisms. As suggested by Milner and Goodale (1995), offline channels of information processing are likely to have developed phylogenetically later than, and to some degree independently from online channels. This raises the problem of how offline channels, that are capable of setting up planned, anticipatory action, can make use of, and exert control on online processing. Dimensional weighting would be a very useful means to exert some relatively indirect but still effective control. Even though on-line channels would not be top-down limited with respect to what kind of information they process, the degree to which this information is fed into action control is determined by the weights currently assigned to the respective dimension. Once this highly adaptive mechanism has been acquired, it can be used for purposes other than action control, and it may be these purposes that are tapped by most studies on human attention.

In any case, the present study provides strong evidence that even presumably "early" operations of visual attention are more dependent on the type of action accompanying it than hitherto believed. As actions commonly do not play a major role in attentional theorizing and the interpretation of attentional studies, this raises the question of how general and generalizable the available accounts and findings are.

## References


Allport, A. (1987). Selection for action: Some behavioral and neurophysiological considerations of attention and action. In H. Heuer & A. F. Sanders (Eds.), *Perspectives on perception and action* (pp. 395–419). Hillsdale, NJ: Erlbaum.

Anderson, S. J., & Yamagishi, N. (2000). Spatial localization of colour and luminance stimuli in human peripheral vision. *Vision Research, 40,* 759–771.

Bacon, W. F., & Egeth, H. E. (1994). Overriding stimulus-driven attentional capture. *Perception and Psychophysics, 55,* 485–496.

Bekkering, H., & Neggers, S. F. W. (2002). Visual search is modulated by action intentions. *Psychological Science, 13,* 370–374.

Bundesen, C. (1990). A theory of visual attention. *Psychological Review, 97,* 523–547.

Chelazzi, L., Duncan, J., Miller, E. K., & Desimone, R. E. (1998). Responses of neurons in inferior temporal cortex during memory-guided visual search. *Journal of Neurophysiology, 80,* 2918–2940.

Chun, M. M., & Wolfe, J. M. (1996). Just say no: How are visual searches terminated when there is no target present? *Cognitive Psychology, 30,* 39–78.

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

Desimone, R., & Duncan, J. (1995). Neural mechanisms of selective visual attention. *Annual Review of Neuroscience, 18,* 193–222.

Deubel, H., & Schneider, W. X. (1996). Saccade target selection and object recognition: Evidence for a common attentional mechanism. *Vision Research, 36,* 1827–1837.

Deubel, H., Schneider, W. X., & Paprotta, I. (1996). Visual attention and manual aiming: Evidence for obligatory and selective spatial coupling. *Perception, 25*(Suppl.), 13–14.

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

Egeth, H. E., Virzi, R. A., & Garbart, H. (1984). Searching for conjunctively defined targets. *Journal of Experimental Psychology: Human Perception and Performance, 10,* 32–39.

Eriksen, C. W., & Yeh, Y. (1985). Allocation of attention in the visual field. *Journal of Experimental Psychology: Human Perception and Performance, 11,* 583–597.

Fagioli, S., Hommel, B., & Schubotz, R. I. (2007). Intentional control of attention: Action Planning primes action related stimulus dimensions. *Psychological Research, 71,* 22–29.

Folk, Ch. L., & Remington, R. (1998). Selectivity in distraction by irrelevant featural singletons: Evidence for two forms of attentional capture. *Journal of Experimental Psychology: Human Perception and Performance, 24,* 847–858.

Folk, Ch. L., & Remington, R. (2008). Bottom-up priming of top-down attentional control settings. *Visual Cognition, 16,* 215–231.

Folk, Ch. L., Remington, R., & Johnston, J. C. (1992). Involuntary covert orienting is contingent on attentional control settings. *Journal of Experimental Psychology: Human Perception and Performance, 18,* 1030–1044.

Found, A., & Müller, H. J. (1996). Searching for unknown feature targets on more than one dimension: Investigating a "dimension weighting" account. *Perception and Psychophysics, 58,* 88–101.

Gegenfurtner, K. R. (2004). The accuracy of pointing movements to targets defined by color [Abstract]. *Journal of Vision, 4,* 404a.

Geyer, T., Müller, H. J., & Krummenacher, J. (2007). Cross-trial priming of element positions in pop-out visual search is dependent on regular stimulus arrangement. *Journal of Experimental Psychology: Human Perception and Performance, 33,* 788–797.

Glover, S. (2004). Separate visual representations in the planning and control of action. *Behavioral and Brain Sciences, 27,* 3–78.

Graves, R. E. (1996). Luminance and colour effects on localization of briefly flashed visual stimuli. *Visual Neuroscience, 13,* 567–573.

Hommel, B. (2004). Event files: Feature binding in and across perception and action. *Trends in Cognitive Sciences, 8,* 494–500.

Hommel, B. (2007). Feature integration across perception and action: Event files affect response choice. *Psychological Research, 71,* 42–63.

Hommel, B., Müsseler, J., Aschersleben, G., & Prinz, W. (2001a). Codes and their vicissitudes. *Behavioral and Brain Sciences, 24,* 910–937.

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

Humphreys, G. W., & Riddoch, M. J. (2001). Detection by action: Neuropsychological evidence for action-defined templates in search. *Nature Neuroscience, 4,* 84–89.

Jeannerod, M. (1984). The timing of natural prehension movements. *Journal of Motor Behavior, 16,* 235–254.

Johnston, J. C., McCann, R. S., & Remington, R. W. (1995). Chronometric evidence for two types of attention. *Psychological Science, 6,* 365–369.

Jolicœur, P., Tombu, M., Oriet, C., & Stevanovski, B. (2002). From perception to action: Making the connection. In W. Prinz & B. Hommel (Eds.), *Common mechanisms in perception and action: Attention and performance XIX* (pp. 558–586). Oxford, England: Oxford University Press.

Kelso, J. A. S., & Kay, B. (1987). Information and control: A macroscopic basis for perception-action coupling. In. H. Heuer & A. F. Sanders (Eds.), *Tutorials in perception and action.* Hillsdale, NJ: Erlbaum.

Krummenacher, J., Müller, H. J., & Heller, D. (2002). Visual search for dimensionally redundant pop-out targets: Parallel-coactive processing of dimensions is location specific. *Journal of Experimental Psychology: Human Perception and Performance, 28,* 1303–1322.

Luck, S. J., Chelazzi, L., Hillyard, S. A., & Desimone, R. (1997). Mechanisms of spatial selective attention in areas V1, V2, and V4 of macaque visual cortex. *Journal of Neurophysiology, 77,* 24–42.

Maljkovic, V., & Nakayama, K. (1994). Priming of pop-out: I. Role of features. *Memory & Cognition, 22,* 657–672.

Milner, A. D., & Goodale, M. A. (1995). *The visual brain in action.* Oxford, England: Oxford University Press.

Moran, J., & Desimone, R. (1985). Selective attention gates visual processing in the extrastriate cortex. *Science, 229,* 782–784.

Müller, H. J., Heller, D., & Ziegler, J. (1995). Visual search for singleton feature targets within and across feature dimensions. *Perception and Psychophysics, 57,* 1–17.

Müller, H. J., Reimann, B., & Krummenacher, J. (2003). Visual search for singleton feature targets across dimensions: Stimulus- and expectancy-driven effects in dimensional weighting. *Journal of Experimental Psychology: Human Perception and Performance, 29,* 1021–1035.

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

Pashler, H. (1984). Processing stages in overlapping tasks: Evidence for a central bottleneck. *Journal of Experimental Psychology: Human Perception and Performance, 10,* 358–377.

Pashler, H. (1989). Dissociations and dependencies between speed and

accuracy: Evidence for a two-component theory of divided attention in simple tasks. *Cognitive Psychology, 21,* 469–514.
Posner, M. I. (1980). Orienting of attention. *Quarterly Journal of Experimental Psychology, 32,* 3–25.
Ratcliff, R. (1979). Group reaction time distributions and an analysis of distribution statistics. *Psychological Bulletin, 86,* 446–461.
Reynolds, J. H., Chelazzi, L., & Desimone, R. (1999). Competitive mechanism subserve attention in macaque areas V2 and V4. *Journal of Neuroscience, 19,* 1736–1753.
Rizzolatti, G., Riggio, L., & Sheliga, B. M. (1994). Space and selective attention. In C. Umilta & M. Moscovitch (Eds.), *Attention and performance XV: Conscious and nonconscious information processing* (pp. 231–265). Cambridge, MA: MIT Press.
Schmidt, R. A. (1975). A schema theory of discrete motor skill learning. *Psychological Review, 82,* 225–260.
Schubotz, R. I. (2007). Prediction of external events with our motor system: Towards a new framework. *Trends in Cognitive Sciences, 11,* 211–218.
Schubotz, R. I., & von Cramon, D. Y. (2001). Functional organization of the lateral premotor cortex: FMRI reveals different regions activated by anticipation of object properties, location and speed. *Cognitive Brain Research, 11,* 97–112.
Schubotz, R. I., & von Cramon, D. Y. (2002). Predicting perceptual events activates corresponding motor schemes in lateral premotor cortex: An fMRI study. *NeuroImage, 15,* 787–796.
Schubotz, R. I., & von Cramon, D. Y. (2003). Functional-anatomical concepts of human premotor cortex: Evidence from fMRI and PET studies. *NeuroImage, 20,* 120–131.
Treisman, A. (1988). Features and objects: The fourteenth Bartlett memorial lecture. *The Quarterly Journal of Experimental Psychology, 40*A, 201–237.
Treisman, A., & Gormican, S. (1988). Feature analysis in early vision: Evidence from search asymmetries. *Psychological Review, 95,* 15–48.
Tucker, R., & Ellis, M. (2001). The potentiation of grasp types during visual object categorization. *Visual Cognition, 8,* 769–800.
Ungerleider, L. G., & Mishkin, M. (1982). Two cortical visual systems. In D. J. Ingle, M. A. Goodale, & R. J. W. Mansfield (Eds.), *Analysis of visual behavior* (pp. 549–586). Cambridge, MA: MIT Press.
Wolfe, J. M. (1994). Guided search 2.0: A revised model of visual search. *Psychonomic Bulletin and Review, 1,* 202–238.
Wolfe, J. M. (1998). Visual search. In H. Pashler (Ed.), *Attention.* London: University College London Press, 13–73.
Wolfe, J. M., Butcher, S. J., Lee, C., & Hyle, M. (2003). Changing your mind: On the contributions of top-down and bottom-up guidance in visual search for feature singletons. *Journal of Experimental Psychology: Human Perception and Performance, 29,* 483–502.
Wolfe, J. M., Horowitz, T. S., Kenner, N., Hyle, M., & Vasan, N. (2004). How fast can you change your mind? The speed of top-down guidance in visual search. *Vision Research, 44,* 1411–1426.

Received September 12, 2007
Revision received April 9, 2009
Accepted April 13, 2009 ■