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## Visual search for a motion singleton among coherently moving distractors

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**Abstract** In the current study, we tested whether search for a visual motion singleton presented among several coherently moving distractors can be more efficient than search for a motion stimulus presented with a single distractor. Under a variety of conditions, multiple spatially distributed and coherently moving distractors facilitated search for a uniquely moving target relative to a single-motion-distractor condition (Experiments 1, 3, and 4). Color coherencies among static distractors were not equally effective (Experiments 1 and 2). These results confirm that humans are highly sensitive to antagonistically directed motion signals in backgrounds compared with spatially more confined regions of visual images.

### Introduction

Imagine you are driving a car in traffic. As you look and head down the road you see a large part of the visual image move in a uniform direction, namely your direction. Visual motion patterns of this kind are said to be coherent. The motion signal is similar among different locations by one, several, or all of the motion features (e.g., direction, velocity, estimated origin, acceleration, or other higher-order temporal/spatial invariants). Gibson (1966) called the corresponding motion patterns “optic flow”. However, there can also be alternative motion signals in the image that are spatially more confined. For instance, still in traffic, while you approach a cycle in front of you, its motion differs from that of the image background in at least its velocity.

We frequently have to tell apart the different motion signals of the background and a spatially more confined region within an image. Envisage, for instance, that you want to get ahead of the cycle. To prevent collision you want to keep an eye on it. Fortunately, this might be an easy task. You just need to track a “motion singleton”. In general, a singleton is an object that differs from a multiplicity of coherent objects in the image (cf. Bacon & Egeth, 1994). Correspondingly, a motion singleton differs by one, several, or all of its motion features, for example, direction or velocity, from the coherent motion within the image. In the traffic example, to track the cycle, you need not determine its exact motion features. It is sufficient that you keep looking at the singleton, the one region of the image where the difference between motion signals is largest (or where coherence of the motion signal is lowest). Evidence suggests that a motion singleton can indeed “pop out” from the background (e.g., Pollmann, Weidner, Müller, & von Cramon, 2000). We wanted to confirm that a motion singleton benefits processing in a visual search task.

In visual search, participants look for a predefined target among irrelevant distractors. Efficiency can be estimated as the time it takes to find a target or as the mean accuracy of reporting a target (e.g., Duncan & Humphreys, 1989; Eriksen, 1953; Külpe, 1904; Treisman & Gelade, 1980; for a review see Wolfe, 2003). As a rule, search time tends to increase with an increasing number of distractors (“positive [slope] search functions”). This holds true in conditions in which target presence cannot be verified by attending to all stimuli at once. As a consequence, participants have to serially scan through several more confined regions within the image to find the target (or to decide that it is not there). Positive search functions are observed in many situations in which the target to be searched for is defined by a conjunction of features, such as a particular shape and a specific color (e.g., Treisman & Gelade, 1980).

Sometimes, however, search time increments with increasing numbers of distractors are negligible (“flat [slope] search functions”). This indicates that search is

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relatively efficient or parallel among different locations. Search functions are flat, for instance, if the target is defined by a well-discriminated single feature (e.g., a particular shape) or if one of the conjunction features searched-for can be used to efficiently segregate the image, for example, lighting direction or motion direction (e.g., Enns & Rensink, 1990; McLeod, Driver, Dienes, & Crisp, 1991; Nakayama & Silverman, 1986).

Singleton search is also very efficient or parallel (cf. Bacon & Egeth, 1994). One reason for this is that search time tends to decrease as a function of an increasing physical difference between the target and the distractors and an increasing physical similarity among the distractors (cf. Duncan & Humphreys, 1989; Nothdurft, 1991; Theeuwes, 1994a; Wolfe, 1998). Note that with a singleton target image characteristics meet both of these criteria. But also, to find a singleton, you do not have to detail the exact features of the target in advance. You just look for a large physical difference. Thus, when you do not exactly know what you are looking for, it makes sense to search for singletons. This is of course not the case in most psychological experiments, where participants know exactly what to look for. However, in an experiment where one of the target features searched-for is hard to discriminate from (or very similar to) a feature of the distractors—even if it is a single feature that you are looking for—singleton search might cut down on processing time. This might be one origin of an evident preference to search for a singleton in psychological investigations where single-feature search would be equally suited to find the target (Bacon & Egeth, 1994; Lamy & Egeth, 2003; Theeuwes, 1992, 1994a).

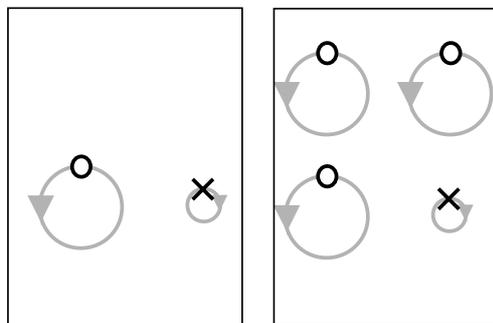
In the current study, we used an adapted search task to test this assumption. Can search for a motion singleton cut down on processing time compared with an appropriate control condition where motion features have to be discriminated to find the target? In the main experiments, each trial contained one and only one stimulus of a motion direction that was searched for. Hence, target motion was never coherent with the motion of the distractors. It always differed from that of the distractors in direction, velocity, and distance covered. However, distractor motion either was coherent or it was not coherent. In the coherent-motion condition, with multiple distractors moving in the same way, the target was a motion singleton but the distractors were not. In contrast, in a control condition with a single motion distractor, there was of course no coherence among the distractors, and both target and distractor were motion singletons (or both were nonsingletons).<sup>1</sup> Both target and distractor provided motion signals that differed from one another (and from the static back-

ground). Therefore, in the coherent-motion condition, locating a motion signal difference within an otherwise coherent motion signal suffices to find the target, whereas with a single motion distractor a more detailed discrimination of the concurrent different motion signals would be necessary. Hence, if search for a motion singleton can cut down on processing time, search for targets might be more efficient with several coherently moving distractors than with a single moving distractor.

## Experiment 1

In Experiment 1, we tested whether coherently moving distractors facilitate target search relative to a single moving distractor. In the *motion block*, each participant searched for a target defined by a particular feature conjunction of identity (or shape) and motion, either for a clockwise moving *X* or a clockwise moving *O* (varying between participants). One stimulus that moved in the direction searched-for was shown in one of four positions on an imaginary grid, together with either a single opposite-moving distractor (*single motion distractor condition*) moving around one of the remaining void grid positions, or together with three opposite-moving distractors (*coherent motion condition*), one per each of the remaining void grid positions (see Fig. 1).

In conjunction search tasks, reaction times (RT) to the target and the error rate tend to increase with the number of the distractors. Therefore, search performance might be expected to deteriorate, or at least not to significantly improve in the coherent-motion condition relative to a single-motion-distractor condition (cf. Treisman & Gelade, 1980). However, if a difference signal between the local motion of the target and



**Fig. 1** Schematic illustration (not to scale) of a single-motion trial (*left*) and a coherent-motion trial (*right*) in Experiment 1. (The no-distractor condition and the conditions of the color block are not depicted.) The *gray circles* and the *arrowheads* were not shown during the experiment. They represent the stimulus motion paths and the motion directions respectively. In each trial of the motion block, a single letter (*X* or *O*) stimulus moved in a direction that was searched for. Letters are shown in their respective motion path start positions. For further information refer to the Methods section of Experiment 1

<sup>1</sup>It could be argued that, under these conditions, neither the target nor the distractor qualifies as a singleton because both of these stimuli are not presented among homogenous nonsingletons. However, functionally the outcome would be very similar. There would be no advantage for the processing of the target relative to that of the distractors due to the singleton status of the former compared with the latter.

the global/coherent motion of the distractors can be used to search for the target as a motion singleton, a detailed search for a motion-identity conjunction target might only be required in the single-distractor condition. Thus, search might be facilitated (faster or less error-prone) in the coherent-motion condition relative to a single-motion-distractor condition.

Also, we tested whether search facilitation in a coherent condition is motion-specific. Increasing the coherence or the similarity between the distractors to-be-ignored yields search performance advantages with a variety of features (cf. Duncan & Humphreys, 1989). Bravo and Nakayama (1992), for example, observed decreasing search times with increasing numbers of similarly colored, static distractors. Furthermore, static stimuli were used in most singleton search studies (e.g., Bacon & Egeth, 1994; Lamy & Egeth, 2003). To test for an influence of coherence among static stimuli, we used a color block. In the color block, participants searched for a static *color-identity target*. Concomitantly with a single stimulus of the color searched for, one static color distractor with an alternative color was shown (*single-color-distractor condition*) or three static color distractors with an alternative color were shown (*coherent-color condition*). Search improvements mediated by a feature-unspecific mechanism should show up in the color block too (cf. Bravo & Nakayama, 1992; Wolfe, 1998). However, a motion-specific facilitation should not show up, since it can only be observed in the motion block.

To test whether coherent distractors can be completely ignored, we compared search performance with a no-distractor condition. In the no-distractor condition, a stimulus of the searched motion direction (motion block) or a static stimulus of the searched color (color block) was shown without a distractor. This single stimulus equally likely did have (target-present trials) or did not have the searched identity (target-absent trials). If coherent distractors are completely ignored and not processed, search performance should be about the same in coherent-distractor and in no-distractor conditions. However, we assume that the coherently moving distractors are processed to cut down on motion-discrimination time because locating a strong physical difference within the motion signal suffices to find the target and a detailed discrimination of the concurrent motion signals becomes superfluous. A processing of the coherent distractors should show up as less efficient search in a coherent-distractor condition than in a no-distractor condition.

All hypotheses were tested in conditions that avoided a single-feature search strategy. To this end, only *incongruent* conditions were used in which the stimuli of both identities (i.e., *X* and *O*) were presented in each trial of both distractor conditions (cf. Eriksen & Schultz, 1979). Thus, single-feature search for identity in a *congruent* subset of the distractor trials, in which all stimuli would have had the same identity, was prevented.

## Method

### Participants

Sixteen students (11 women, 5 men) with a mean age of 28 years participated in Experiment 1. Here and in later experiments, most of the participants were students at Bielefeld University, had normal or fully-corrected vision, and were paid for their participation.

### Apparatus

The experiment was controlled by a computer that also served for data registration. Stimuli were presented on a 15-inch color monitor. A serial mouse was used to register responses. Participants pressed the left or right mouse button with the index finger of the corresponding hand, and latencies were measured from the beginning of the target to the nearest millisecond. The participants sat in a dimly lit room, 65 cm in front of the screen, with their line of gaze vision kept straight ahead by a head rest.

### Stimuli and procedure

Examples of trials are schematically depicted in Fig. 1. Targets and distractors were the letters *X* and *O* (width  $0.25^\circ \times$  height  $0.39^\circ$ ) presented on a dark background. Participants searched for a feature-conjunction target at one of four equidistant ( $2^\circ$ ) positions on an imaginary  $2 \times 2$  position grid, presented either alone (*no-distractor condition*), concomitantly with a single distractor (*single-motion-distractor* and *single-color-distractor conditions*), or together with three distractors (*coherent-motion* and *coherent-color conditions*), one distractor in each void grid position. The experiment consisted of two blocks. In the *motion block*, participants searched for a red *motion-identity target*. This target moved clockwise and was either an *X* or an *O* (balanced among participants). Red distractors moved in the opposite direction (i.e., counter-clockwise). In the *color block*, participants searched for a static *color-identity target*. Participants searched for a red *X*, a red *O*, a green *X*, or a green *O* (balanced across participants). If targets were red, distractors were green, and vice versa.

In each trial of the motion block, one stimulus moved in the searched direction (i.e., clockwise). This stimulus equally likely did have the identity searched for (say, *X*) or did not have it (e.g., an *O* in cases when *X* was the target). Moving distractors always had the *alternative* identity compared with the stimulus that moved in the direction of search. Motion path diameters were  $1^\circ$  for the stimuli that moved in the searched direction but  $1.5^\circ$  for the distractors to render the target and distractor non-overlapping in some of the later conditions (see Experiment 3 below). All stimuli (target and distractors) moved in phase within 800 ms on full circular paths and

**Table 1** Reaction time (RT) in ms, error rate in percent as a function of block condition (motion block vs. color block), distractor condition, and target condition (present vs. absent) in Experiment 1. *CD* coherent distractors, *SD* single distractor, *ND* no distractor

Block	Target	CD		SD		ND	
		RT	Error rate	RT	Error rate	RT	Error rate
Motion	Present	613	10.7	640	23.3*	505*	3.7*
	Absent	624	12.3	721*	18.1	525*	3.9*
Color	Present	472	6.1	452*	4.3	416*	3.3
	Absent	499	6.9	471*	5.1	442*	3.8

\*Significantly different from the corresponding CD condition, at least at an alpha level of .05

started at the point of highest elevation on their respective motion paths. For example, if a clockwise moving *X* was searched for, *target-present conditions* comprised:

- trials with only a clockwise circling *X* (*no-distractor condition*),
- trials with a clockwise circling *X* and one counter-clockwise circling *O* in one of the three remaining void grid positions (*single-motion-distractor condition*),
- trials with a clockwise circling *X* and three counter-clockwise circling *O*s (*coherent-motion condition*), one in each of the remaining void grid positions, in equal amounts.

Color blocks were created analogously. In each trial of the color block, one static stimulus had the color searched for (e.g., red). This stimulus equally likely did have the identity searched for (say, *X*) or did not have it (e.g., an *O* in cases when *X* was the target). In the color block, static distractors always had the alternative identity compared with the stimulus with the color searched for. For example, if a red *X* was searched for, target-present conditions comprised:

- trials with only a red *X* (*no-distractor condition*),
- trials with a red *X* and one green *O* (*single-color-distractor condition*),
- trials with a red *X* and three green *O*s (*coherent color condition*), in equal amounts.

In both blocks, participants had to press the left key to signal the presence of the motion-letter or color-letter conjunction target searched-for and the right key to signal its absence (or vice versa, between participants). If there was an incorrect response, the sentence *Falsche Taste! (Wrong key!)* appeared, and if there was a response slower than 1,000 ms, the sentence *Schneller reagieren! (Respond faster!)* was presented, both for 700 ms at the center of the screen.

Location and identity of the color or motion stimulus searched-for varied unpredictably from trial to trial. Singleton location and distractor location were uncorrelated. Different distractor conditions (no-distractor, single-distractor, and coherent-distractor conditions) were equally likely. The different conditions were intermixed in a random order. Each participant went

through both blocks. The order of the blocks (motion block first vs. color block first) was balanced across participants. In each block, after 72 practice trials, there were 216 data acquisition trials (with short breaks every 72 trials).

## Results

See Table 1 for the results. Out of all responses, 1.3% were discarded because they were faster than 100 ms or slower than 1,250 ms. In the motion block, performance was facilitated by the coherently moving distractors. In the target-absent condition, the mean correct search time was lower in the coherent-motion condition than in the single-motion-distractor condition: 624 vs. 721 ms,  $t(15)=5.158$ ,  $p < .01$ .<sup>2</sup> In the target-present/coherent-motion condition, the mean correct search time was nonsignificantly lower than in the target-present/single-motion-distractor condition: 613 vs. 640 ms,  $t(15)=1.641$ . Furthermore, in the target-present/coherent-motion condition, the arcsine transformed error rate was significantly lower than in the target-present/single-motion-distractor condition: 10.7 vs. 23.3%,  $t(15)=6.272$ ,  $p < .01$ . In the target-absent condition, a similar facilitation, although nonsignificant, was obtained: coherent-motion condition 12.3%, single-motion-distractor condition 18.1%,  $t(15)=1.972$ .

In contrast, coherently colored distractors did not facilitate target search. Search times increased slightly. In the target-present/coherent-color condition, mean correct RT was higher than in the target-present/single-color-distractor condition: 472 vs. 452 ms,  $t(15)=4.98$ ,  $p < .01$ . A similar RT pattern was obtained in the target-absent condition: coherent-color condition 499 ms, single-color-distractor condition 471 ms,  $t(15)=6.261$ ,  $p < .01$ . The arcsine transformed error rate was nonsignificantly higher in the target-present/coherent-color condition than in the target-present/single-color-distractor condition: 6.1 vs. 4.3%,  $t(15)=0.803$ . The same trend was observed in the target-absent condition: coherent-color condition 6.9%, single-color-distractor condition 5.1%,  $t(15)=1.111$ . In both blocks, search was more efficient in the no-distractor condition than in

<sup>2</sup>Alpha levels of the *t*-tests were Bonferroni-adjusted (Hays, 1988), except where noted otherwise.

the coherent-distractors condition: all  $t(15) > 3.7$ ,  $p < .01$  (for means see Table 1).

## Discussion

Several results of Experiment 1 were in line with the notion that the participants' search for a motion singleton facilitated performance. Facilitation was obtained in the coherent-motion conditions (reflected in search speed for target-absent conditions and in search accuracy for target-present conditions). Furthermore, the moving distractors underwent some processing: Search was less efficient in the coherent-motion condition relative to the no-distractor condition. Coherently moving distractors were not completely ignored.

However, in Experiment 1, the motion-coherent distractors also had an alternative but coherent identity compared with the target. Therefore, participants could have theoretically redefined their search strategies in one of two ways:

- a) They could have searched for the distractors rather than for the targets, or
- b) they could have searched for a shape singleton rather than for a motion singleton.

With respect to possibility (a), for example, instead of searching for a clockwise moving  $X$  (as required), participants could have searched for the concomitant counter-clockwise moving distractors  $O$ . As a consequence, in the coherent-motion condition, participants would have responded to three stimuli (to the distractors) rather than to only one target. This search strategy might account for facilitated search in the coherent-motion condition: Responses to redundant stimuli can be faster than responses to a single stimulus (e.g., Fournier & Eriksen, 1990; Theeuwes, 1994b).

At least three arguments speak against this explanation. First, to search for the distractors was not a beneficial strategy in the majority (two-thirds) of the trials. In the single-motion-distractor condition (one-third of all trials), to search for a single distractor would not have been easier than search for a single target. In the no-distractor condition (another third of the trials), it was impossible to search for a distractor. In the no-distractor condition, participants had to use the instructed search criteria to find the target. Second, the evidence is against this redefinition account. Performance should have been least efficient in the no-distractor condition because of the selective necessity to return to the instructed search criteria. Yet, the opposite data pattern resulted: Search was most efficient in the no-distractor condition. Finally, search for redundant distractors would have been possible in the color block too. Yet search was not facilitated by the coherently colored, static distractors. There is a caveat to this final argument that is elaborated at the end of

the present discussion, but to tentatively conclude: It seems unlikely that participants redefined their search criteria to be met by the coherently moving distractors, but a straightforward control is provided in Experiments 3 and 4.

With respect to possibility (b), to find the target, participants might have searched for a shape singleton (the one odd shape among the other similar shapes) in the coherent-motion condition and in the no-distractor condition. In these conditions, participants may have searched for a shape singleton and may only then have identified the shape of that singleton. In the motion block of Experiment 1, the only condition where shape singleton searching was insufficient to find the target was the single-motion-distractor condition. In that condition, both stimuli were shape singletons (or neither of them was a shape singleton).<sup>3</sup> Therefore, in the single-motion-distractor condition, participants had to discriminate between the motion and the shape features of the target and the distractor. Thus, what appears to be search facilitation for a motion singleton among coherently moving distractors might (partly) reflect a more efficient search for a shape singleton.

Note that, once again, search for a shape singleton was possible in the color block too. Yet, search was not facilitated in the color block (but see the final two paragraphs of the present discussion). Moreover, even if the participants searched for a shape singleton in the motion block, this does not mean that motion coherence was without effect. First of all, performance advantages of the target being a shape singleton and being a motion singleton may have co-occurred. There is a redundancy gain, for instance, when a target is easily discriminated among all the distractors within two dimensions (say, color and shape) rather than only one dimension (say, color; cf. Krummenacher, Müller, & Heller, 2002a, 2002b). Furthermore, to fetch information contained in a moving visual stimulus (e.g., about its shape or even its location), stimulus motion needs to be processed because visuospatial attention (required to process the stimulus features) has to catch up with the moving stimulus (cf. Aschersleben & Müsseler, 1999; Müsseler & Aschersleben, 1998; Müsseler, Stork, & Kerzel, 2002; von Mühlhausen & Müller, 2001). Thus, the preconditions for an effect of the motion singleton were met. In Experiment 1, in line with the assumption that motion is processed before shape information can be derived from the target, search time in the no-distractor condition was increased in the motion block relative to the color block (see Table 1). The possibility that search for a shape singleton in the coherent-motion

<sup>3</sup>It could be argued that, under these conditions, neither the target nor the distractor qualifies as a singleton because both of these stimuli are not presented among homogenous nonsingletons. However, functionally the outcome would be very similar. There would be no advantage for the processing of the target relative to that of the distractors due to the singleton status of the former compared with the latter.

condition accounts for our results is directly tested in Experiments 3 and 4.

Some of the above arguments are based on a comparison of the performance between the motion block and the color block. However, this comparison might be unfair. Performance differences between motion and color block might reflect a successful *top-down feature search* in the case of a color-identity target, but a failure of top-down feature search in the case of a motion-identity target. It is important to note that many previous studies demonstrated a very efficient top-down guidance of search for a particular, well-discriminated color (cf. Ansorge & Heumann, 2003, 2004; Folk & Remington, 1998; Green & Anderson, 1956). In Experiment 1, this assumption was supported by a lower mean RT in the color block than in the motion block. This difference suggests that discrimination between a static color-identity target and the dissimilar color distractors can be very easy. Moreover, coherence-facilitated search might be restricted to situations of bottom-up or stimulus-driven searching, for instance, because top-down search for a particular feature fails (cf. Theeuwes & Burger, 1998; Wolfe, 1994). Therefore, top-down search for a well-discriminated target color might have predominated in the color block, whereas bottom-up influences of target-distractor feature contrasts by additional coherent distractors may have been selectively pertinent in the motion blocks, in which the discrimination between motion directions was more difficult. In Experiment 2, we tested whether color coherence facilitates target search once successful top-down search for the color target becomes less likely because color discrimination between target and distractors is more difficult.

## Experiment 2

In Experiment 2, we tested whether color-coherent distractors facilitate search when top-down feature search for target color is more difficult. Target-distractor color discrimination was easy in the color block of Experiment 1. This might have compromised facilitation by color coherence. Successful top-down feature search may have prevented bottom-up influences of increased target-distractor feature contrasts by the coherent color distractors (cf. Wolfe, 1998). Evidence for facilitation by

color coherence among the distractors might show up where target and distractor colors are less well discriminated so that top-down color search for the target does not account for most of the variance.

## Method

### Participants

Twelve students (7 women, 5 men) with a mean age of 27 years participated in Experiment 2.

### Apparatus, stimuli, and procedure

Targets were red and distractors were orange. Otherwise, the procedure was identical to that of the color block of Experiment 1.

## Results and discussion

See Table 2 for the results. Out of all responses, 0.5% were discarded by the latency criterion of Experiment 1. Target search was not facilitated by the static, coherently colored distractors relative to a single-color-distractor condition. Mean correct RT was significantly higher in the target-present/coherent-color condition than in the target-present/single-color-distractor condition: 595 vs. 568 ms,  $t(11)=2.414$ ,  $p < .05$ . In the target-absent condition, a similar trend was observed, but it was not significant: coherent-color condition 651 ms, single-color-distractor condition 643 ms,  $t(11)=1.045$ . The arcsine transformed error rate was the same in the target-present/coherent-color condition as in the target-present/single-color-distractor condition (9.1 vs. 9.1%). This was also true for the target-absent condition: coherent-color condition 10.7%, single-color-distractor condition 9.9%,  $t(11)=0.385$ .

Search for the color-identity target was more difficult (search times and error rates were higher) than in Experiment 1, e.g., RT:  $F(1, 26)=26.105$ ,  $p < .001$ . Therefore, task difficulty does not account for the performance difference between color and motion blocks. In conclusion, color coherence among static distractors does not facilitate target search as readily as motion coherence among moving distractors. This observation supported the assumption that a motion-

**Table 2** Reaction time in ms, error rate in percent as a function of distractor condition and target condition (present vs. absent) in Experiment 2

Target	CD		SD		ND	
	RT	Error rate	RT	Error rate	RT	Error rate
Present	595	9.1	568*	9.1	495*	5.2
Absent	651	10.7	643	9.9	541*	4.1

\*Significantly different from the corresponding CD condition, at least at an alpha level of .05

specific effect was responsible for the search facilitation in the coherent motion conditions of Experiment 1.

### Experiment 3

In Experiment 3, we tested whether search for a shape singleton or search for the redundant motion distractors is responsible for lower search times in the coherent-motion conditions. Above, we noted that participants in Experiment 1 theoretically could have searched for a shape singleton selectively in the coherent-motion condition. Also, although unlikely in the light both of the results and of the procedures of Experiment 1, participants might have searched and responded to the three redundant distractors rather than to a single target. Experiment 3 controls for these reservations. Participants gave choice responses to a motion-identity target (e.g., pressing a left key for an *X* moving in a clockwise direction, and a right key for an *O* moving in a clockwise direction), and *distractor and target identities were uncorrelated*. Distractors equally likely did have the same identity as the concomitant target (*congruent condition*) or did have an alternative identity to the target (*incongruent condition*). Under these conditions, shape-singleton search is not possible in the congruent conditions. Likewise, the same correct responses cannot be given to the identities of the redundant distractors in the congruent and in the incongruent condition. Therefore, if the participants' search for a shape singleton facilitated search performance in the coherent-motion condition, facilitation should be selectively observed in incongruent single-motion-distractor conditions relative to incongruent coherent-motion conditions. Search facilitation should not be observed in the congruent conditions. The same predictions hold true if the participants' search for the motion distractors (rather than for the target) was responsible for search facilitation. In contrast, if coherently moving distractors permit search for a motion singleton, coherently moving distractors should facilitate search in both congruent and incongruent conditions.

Also, in Experiment 3, we prevented costs incurred by strategy changes between the different distractor conditions to asymmetrically increase search times in the single-motion-distractor condition. In Experiment 1, different distractor conditions were intermixed. If participants used singleton search (which was an optimal search mode in the coherent-motion conditions) as a default, and only changed to motion-identity conjunction search when this was inevitable (i.e., in a single-motion-distractor trial), shift costs incurred by a strategy change selectively contributed to search times in the single-motion-distractor conditions. These contributions are ruled out if a particular distractor condition and, thus, its most suitable search strategy, is the same throughout a block. Therefore, in Experiment 3, different distractor conditions were realized in separate blocks, which was known by the participants.

## Method

### Participants

Twenty-four participants (17 women, 7 men) with a mean age of 26 years participated in Experiment 3.

### Apparatus, stimuli, and procedure

Two-choice responses to alternative motion-identity targets were required. Half of the participants responded to an *X* moving on a predefined path (clockwise or counter-clockwise, between participants) by pressing the right key, and to an *O* moving in the same direction by pressing the left key. The other half of the participants had a reversed stimulus-response (S-R) mapping. Target and distractor identities within a trial were equally likely to be the same (*congruent condition*, i.e., both stimuli were *O*s or both were *X*s) or not (*incongruent condition*, i.e., *X* was the target and *O* was the distractor, or *O* was the target and *X* was the distractor). Three distractor conditions were realized. A target was presented concomitantly either with a *valid single-motion distractor* moving around the same position as the target, or with an *invalid single-motion distractor* in one of the three other void grid positions, or with three *coherently moving distractors*, one in each void grid position. The different distractor conditions were realized in separate blocks. Different block sequences and target-response mappings were balanced across participants. Each block consisted of 48 practice trials and 192 data acquisition trials with short rests every 48 trials. Otherwise, the procedure was similar to that of the motion block of Experiment 1.

## Results

See Table 3 for the results. Out of all responses, 1.2% were discarded by the latency criterion of Experiment 1. Once again, coherently moving distractors facilitated search in most of the conditions. In congruent trials, mean correct RT was lower in the coherent-motion condition than in the invalid single-motion-distractor condition, 503 vs. 543 ms,  $t(23)=3.795$ ,  $p < .01$ , and, although nonsignificantly, in the valid single-motion-distractor condition, 518 ms,  $t(23)=1.537$ . Also, in incongruent trials, RT was lower in the coherent-motion condition than in the invalid single-motion-distractor condition, 581 vs. 741 ms,  $t(23)=7.804$ ,  $p < .001$ , and in the valid single-motion-distractor condition, 647 ms,  $t(23)=2.291$ ,  $p < .05$ . Correspondingly, in congruent trials, the error rate was lower in the coherent-motion condition than in the invalid single-motion-distractor condition, 4.7 vs. 9.6%,  $t(23)=6.905$ ,  $p < .01$ , and it was about the same as in the valid single-motion-distractor condition, 5%,  $t(23)=0.869$ . In the incongruent trials, the error rate was significantly lower in

**Table 3** Reaction time in ms, error rate in percent as a function of distractor condition and congruence (congruent vs. incongruent) in Experiment 3. *CM* coherent motion, *vSD* valid single motion distractor, *iSD* invalid single motion distractor

Target	CM		vSD		iSD	
	RT	Error rate	RT	Error rate	RT	Error rate
Congruent	503	4.7	518	5.0	543*	9.6*
Incongruent	581	11.5	647*	14.5	741*	23.6*

\*Significantly different from the corresponding CM condition, at least at an alpha level of .05

the coherent motion condition than in the invalid single-motion-distractor condition, 11.5 vs. 23.6%,  $t(23) = 6.426$ ,  $p < .01$ , and it tended to be lower than in the valid single-motion-distractor condition, 14.5%,  $t(23) = 1.514$ .

## Discussion

The results were in line with the assumption that search for a motion singleton facilitates target search. In the congruent condition of Experiment 3, search was faster in the coherent-motion condition than in the invalid single-motion-distractor condition. However, it was impossible to search for a shape singleton or to search for the redundant motion distractors rather than for the target. Note that the different distractor conditions were realized in separate blocks. Thus, shift costs incurred by search strategy changes did not selectively increase search times in the single-motion-distractor conditions.

This search facilitation was larger in invalid conditions (where the target and the single distractor were in different positions) than in valid conditions (where the target and the single distractor were in about the same position). It was most likely that a lower spatial uncertainty about the target location in the valid condition than in the invalid condition reduced search times in the former condition (cf. Folk, Remington, & Wright, 1994). As a consequence, there was already less processing time to be further reduced by the facilitating effect of motion coherence in the valid conditions. In summary, the data are in line with the assumption that participants selectively searched for a motion singleton to find the target (and thus were able to cut down on the motion discrimination time) in the coherent-motion conditions.

Still, it can be argued that only in the coherent motion condition, participants switched between two very efficient search strategies for nonmotion features: A shape-singleton search strategy in the incongruent condition and a single-feature search strategy for shape in the congruent condition. (According to this line of reasoning, in the congruent coherent-motion condition, a discrimination of motion was unnecessary. A single-feature search for coherent shape was sufficient.) In contrast, in the single-motion-distractor condition, a conjunction search for targets defined by shape *and* motion was enforced.

We consider this alternative account to be very unlikely because single-feature search for coherent shape was possible in all congruent conditions, whether with a single motion distractor or with several motion distractors. Yet search was faster with congruent coherently moving distractors than with a single congruent motion distractor. (Also, as will be remembered from Experiment 1, a higher search time in no-distractor conditions of the motion block than of the color block suggested that motion has to be processed to derive shape information from the moving stimuli.) But to make sure that facilitation is indeed a consequence of motion coherence, we put our hypothesis to a final test.

## Experiment 4

In Experiment 4, we tested whether coherently moving distractors facilitate performance because they permit search for a motion singleton or whether in the coherent-motion condition of the previous experiment, participants switched between two very efficient alternative search strategies for nonmotion features: To search for a shape singleton in the incongruent condition and to search for a single static feature (shape) in the congruent condition. To this end, we took two measures. First, we used a color-conjunction task (cf. Wolfe et al., 1990) to map the responses to the alternative identities of the motion stimulus searched for. Participants had to press a right key in response to a clockwise moving red-vertical/green-horizontal cross and a left key in response to a clockwise moving green-vertical/red-horizontal cross, or vice versa (between participants). As in Experiment 3, the identities of target and distractor(s) were uncorrelated. Half of the trials were congruent: Target and distractors had the same color-color conjunction. The other half of the trials were incongruent: Distractors had the alternative color-color conjunction compared with that of the target. Thus, to search for a *singleton defined by only one static feature* is not a viable strategy in any of the conditions. If a strategy to search for a static feature singleton (such as a shape singleton) is responsible for facilitated search in the coherent-motion condition relative to the single-motion distractor condition, no facilitation should be observed. However, if, as we believe, coherently moving distractors permit search for a motion-singleton target, once again, coherently

moving distractors were expected to facilitate target search in both congruent and incongruent conditions.

Second, we used a control condition in which several distractors moved incoherently. If motion coherence facilitates search, facilitation should be small or absent in an incoherent-motion condition. In an incoherent-motion condition, there is more than one area in the visual display where the motion signals differ, thus making a motion-singleton search strategy less effective.

Furthermore, the number of distractors was varied in four steps to determine whether facilitation by the coherent distractors is an all-or-none process or whether facilitation is proportional to the number of the distractors. In each trial, a target was presented concomitantly with one distractor, three, seven, or 15 distractors. As in Experiment 3, different distractor conditions were realized in separate blocks.

## Method

### Participants

Sixteen participants (10 women, 6 men) with a mean age of 27 years participated in Experiment 4.

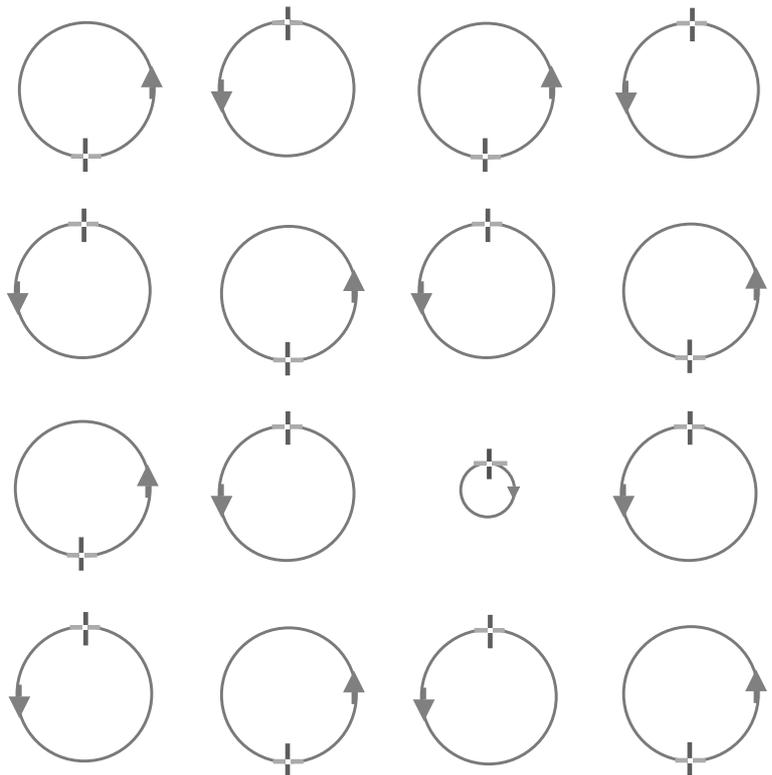
### Apparatus, stimuli, and procedure

These were the same as those of Experiment 3, except as noted. Two-choice responses to the alternative possible

color-color identities of a clockwise moving target were required. Half of the participants had to respond to an isosceles cross with a red vertical leg (length:  $0.8^\circ$ , width:  $0.8^\circ$ ) and a green horizontal leg (the junction of the legs was dark) by pressing the right key, and to a cross with a green vertical leg and a red horizontal leg by pressing the left key. The other half of the participants had a reversed S-R mapping. Stimuli were presented on a  $4 \times 4$  position grid. Each target was presented concomitantly with a *single motion distractor* in one of the three void central grid positions, with *three moving distractors*, one in each of the three void central grid positions, with *seven moving distractors*, one in each of the seven void positions of the two middle rows of the grid, or with *15 moving distractors*, one in each of the 15 void grid positions. Motion distractors moved counter-clockwise, either coherently or incoherently. In the *coherent conditions*, distractor motions were the same as in the preceding experiments. In the *incoherent conditions*, distractor motion-path start positions alternated between adjacent grid locations: Half of the distractors started from the vertex position on their respective motion-path, whereas the other half started from the trough position on their respective motion path. See also Fig. 2.

The presentation time of the stimuli and maximal allowed RT were increased because it was relatively difficult to search for the target in some of the incoherent conditions. Thus, in each trial of both coherent and incoherent conditions, all stimuli moved in-phase within

**Fig. 2** Schematic illustration (not to scale) of an incongruent incoherent-motion trial in Experiment 4. The *gray circles* and the *arrowheads* were not shown during the experiment. They represent the stimulus motion paths and the motion directions respectively. In each trial, one color-color cross moved in a direction that was searched for. Color-color crosses are shown in their respective motion-path start positions. For further information refer to the Methods section in Experiment 4



1,600 ms twice on full circular paths. In cases of a response slower than 3,000 ms, the sentence *Schneller reagieren!* (*Respond faster!*) was presented for 700 ms in the center of the screen.

Coherent and incoherent conditions were realized in separate sessions on different days. Alternative sequences of the different distractor blocks were balanced across participants according to a latin square. In each session, participants worked through 128 trials in each of the three multiple distractor blocks, and 144 trials in the single-motion-distractor block (resulting from an equiprobability of possible target positions, target identities, and distractor identities, in each of the different distractor conditions). Including short rests within and between blocks, and practice at the beginning of each session, the experiment took about 2 h.

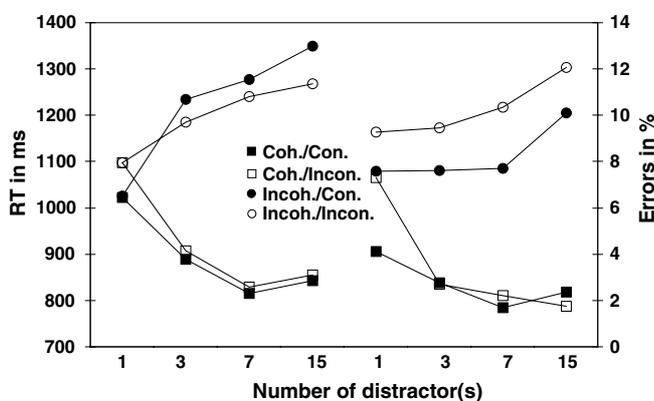
## Results

See Fig. 3 for the results. Out of all responses, 0.6% and 3.5% were discarded in the coherent and in the incoherent conditions respectively, because responses were below 100 ms or above 3 s. An RT ANOVA, with coherence (coherent vs. incoherent), distractor (one distractor vs. three vs. seven vs. 15 distractors), and congruence (congruent vs. incongruent) as variables, led to the following results. There was a significant main effect of coherence,  $F(1, 15) = 61.98$ ,  $p < .001$ . The main effects of distractor and congruence were nonsignificant,  $F < 1$ . Also, significant two-way interactions of Coherence  $\times$  Distractor,  $F(3, 45) = 24.88$ ,  $p < .001$  (Greenhouse-Geisser corrected), Coherence  $\times$  Congruence,  $F(1, 15) = 8.41$ ,  $p < .05$ , and Distractor  $\times$  Congruence,  $F(3, 45) = 7.41$ ,  $p < .01$  (Greenhouse-Geisser corrected), resulted. RT was lower in the coherent (907 ms) than in the incoherent (1,210 ms) conditions. It

is important to note that the Coherence  $\times$  Distractor interaction reflected the selective presence of facilitation in the coherent conditions: RT was lower in the coherent-motion conditions than in the coherent single-motion-distractor condition, all  $t(15) > 2.8$ , all  $ps < .05$ ; in contrast, in incoherent-motion conditions, RT was higher than in the incoherent single-motion-distractor condition, all  $t(15) > 3.8$ , all  $ps < .05$ . (RTs did not significantly differ between the coherent and the incoherent single-motion-distractor conditions,  $t < 1$ .) The Coherence  $\times$  Congruence interaction was due to an average performance advantage in coherent congruent (892 ms) relative to the coherent incongruent (922 ms) conditions,  $t(15) = 2.51$ ,  $p < .05$ , that turned into a nonsignificant cost,  $t(15) = 1.28$ ,  $p = .22$ , in a comparison between incoherent congruent (1,222 ms) and incoherent incongruent (1,198 ms) conditions. The Distractor  $\times$  Congruence interaction was due to a mean performance advantage in congruent single-motion-distractor (1,024 ms) conditions relative to the incongruent single-motion-distractor (1,098 ms) conditions,  $t(15) = 2.47$ ,  $p < .05$ , that turned into a nonsignificant cost for the three distractors (congruent RT = 1,061 ms, incongruent RT = 1,046 ms) and the seven distractors (congruent RT = 1,046 ms, incongruent RT = 1,035 ms) conditions, both  $t(15) < 1$ , and into a significant cost,  $t(15) = 2.38$ ,  $p < .05$ , for the 15 distractors (congruent RT = 1,096 ms, incongruent RT = 1,062 ms) conditions. This “inverted” congruence effect in the multiple-distractor conditions was obvious in the incoherent conditions, but not in the coherent conditions (see Fig. 3 and the Coherence  $\times$  Congruence interaction above), but the Coherence  $\times$  Distractor  $\times$  Congruence interaction failed to become significant,  $F(3, 45) = 2.16$ ,  $p = .11$ . The main effects of distractor and congruence were far from significant, both  $Fs < 1$ .

A corresponding analysis of the arcsine transformed error rates yielded a significant main effect of coherence,  $F(1, 15) = 20.26$ ,  $p < .001$ , and a significant Coherence  $\times$  Distractor interaction,  $F(3, 45) = 9.48$ ,  $p < .001$ . Error rates were lower in coherent (3.2%) than in incoherent conditions (9.3%). The Coherence  $\times$  Distractor interaction mirrored the RT data. The error rate was lower in the coherent-motion conditions than in the coherent single-motion-distractor condition (significantly for seven and 15 coherently moving distractors, both  $t[15] > 2.3$ ,  $ps < .05$ , and nonsignificantly for three coherently moving distractors,  $t[15] = 1.5$ ,  $p = .15$ ); in contrast, in incoherent motion conditions, the error rate was numerically but nonsignificantly higher than in the incoherent single-motion-distractor condition, all  $t(15) < 2.1$ , all  $ps > .057$  (error rates from the coherent and incoherent single-motion-distractor conditions were not significantly different from one another,  $t[15] = 1.3$ ,  $p = .22$ ). The main effects of distractor,  $F < 1$ , and congruence,  $F(1, 15) = 2.29$ ,  $p = .15$ , and the other interactions, all  $ps > .19$ , were nonsignificant.

Individual search slope coefficients were estimated by linear regression of search times on the number of



**Fig. 3** Mean reaction time (RT) in ms (left) and mean error rates in percent (right) as a function of motion coherence (coh.: coherent vs. incoh.: incoherent), target-distractor shape congruence (con.: congruent vs. incon.: incongruent), and the number of distractors (one, three, seven, or 15) in Experiment 4

stimuli of the multiple-distractor conditions.<sup>4</sup> Slope coefficients were subjected to an ANOVA with coherence and congruence as variables. There was only a significant main effect of coherence,  $F(1, 15)=7.7$ ,  $p < .05$ . Search times decreased slightly but nonsignificantly with the number of coherently moving distractors (coherent congruent: slope =  $-2.8$  ms/item, coherent incongruent: slope =  $-3.4$  ms/item, both not significantly different from zero,  $t_s < 1.4$ ), whereas search times increased slightly with an increasing number of incoherently moving distractors (incoherent congruent: slope =  $9.4$  ms/item, significantly different from zero by one-sided  $t[15]=2$ ,  $p < .05$ , incoherent incongruent slope =  $6.4$  ms/item, not significantly different from zero,  $t = 1.6$ ). The main effect of congruence,  $F(1, 15)=2.42$ ,  $p = .14$ , and the Coherence  $\times$  Congruence interaction,  $F < 1$ , were nonsignificant.

## Discussion

The results were in line with the assumption of search facilitation for a motion singleton. Search was facilitated by the coherently moving distractors. It was not facilitated by the incoherently moving distractors. Thus, we ruled out that search for a static singleton (in Experiment 4, a color-color singleton or a color-shape singleton) accounted for any of the facilitation in the coherent-motion conditions. Admittedly, participants may have searched for a color-shape or a color-color singleton (e.g., for the one differently colored vertical) in conditions with multiple distractors, as evidenced by an “inverted” congruence effect (an advantage in incongruent relative to the congruent conditions). However, search for a static singleton (i.e., a singleton defined by static features) plainly cannot account for the facilitation in coherent-motion conditions. Search for a static singleton was a viable strategy in the incoherent-motion condition and yet, in the incoherent-motion condition, search times tended to increase rather than decrease with the number of distractors. Search for a static singleton was also a viable strategy in the incongruent condition but not in the congruent condition, and yet coherently moving congruent distractors facilitated search too. Finally, if anything, evidence for static singleton search (advantages for incongruent relative to congruent conditions) tended to be more firm (in fact, this evidence appeared to be selectively present) with incoherently moving distractors, but search facilitation was definitely restricted to coherent-motion conditions. Furthermore, different distractor conditions were presented in separate blocks, ruling out strategy shifts as being the responsible factor. In summary, the results of Experiment 4 sup-

ported the notion that with a coherent motion signal in the background, a motion singleton might be easily detected and located.

Search slopes suggest that motion coherence of the background facilitated search performance in an all-or-none manner. Search times did not further decrease with increasing numbers of coherently moving distractors. Obviously, to search for a motion singleton and, thus, to cut down on a time-consuming motion discrimination was more successfully prevented in the incoherent-motion conditions. Search slopes were steeper in the incoherent-motion conditions, but still shallow ( $< 10$  ms/item). It should be noted that even in the incoherent conditions, the target had unique motion features. Thus, it appears that in the incoherent-motion conditions, search was still relatively efficient for a differently moving target among different groups of coherently moving distractors (cf. von Mühlenen & Müller, 1999).

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## General discussion

In the current study, we investigated search for a motion singleton. A motion singleton is the one stimulus that moves differently from the stimuli that move in a similar way in an image. A motion singleton might be found by locating an area with a relatively high difference between a spatially confined motion signal and an encompassing/global motion signal. Thus, search for a motion singleton might cut down on the time that is required to discriminate a particular motion feature. An ability to rapidly search for a motion singleton is also adaptive. Agents that use visual inputs to steer their actions quite frequently need to locate objects by differences between global motion (e.g., induced by the agent’s own movements) and deviating local motion signals (cf. Braddick, 1993; Gibson, 1966).

In confirmation of the hypothesis that motion singletons cut down on search times for a target with a unique motion, we found that a number of coherently moving distractors facilitated search relative to a single-motion-distractor condition (Experiments 1, 3, and 4). Note that search was facilitated with coherently moving distractors compared with a single motion distractor, even though other putative influences should have affected search times in the opposite direction. First of all, in many situations in which basic features are searched to find the target, search time is at best relatively independent of the number of distractors (e.g., Enns & Rensink, 1990; Wolfe, 1998; for an exception see Bravo & Nakayama, 1992). Quite frequently, search times even increase with the number of distractors, for example, when targets are defined by a conjunction of features, such as a particular color and a particular shape (cf. Treisman & Gelade, 1980; Wolfe, 2003). Therefore, search times should have been lower with a single distractor than with multiple distractors in all of our 0experiments. However, the target was found more

<sup>4</sup>Search times from single-motion-distractor conditions were not included in the regression analysis. To determine whether search time decrements with coherently moving distractors are an all-or-none process, estimates from the multiple distractor conditions alone provide a more appropriate test.

efficiently among several coherently moving distractors than when it was accompanied by a single distractor.

Furthermore, in Experiment 3, single motion distractor positions coincided with target positions in some conditions whereas distractors in the coherent-motion conditions were presented at a distance from the targets. Because target search is often facilitated in the former relative to the latter conditions (e.g., Folk et al., 1994; Jonides, 1981), better performance would be expected in a single-motion-distractor condition than in a coherent-motion condition. However, the opposite pattern was obtained. Note also that we ruled out several factors that could have been responsible for part of our results, such as shape-singleton search and asymmetric shift costs (Experiments 3 and 4). To summarize, whenever participants could have searched for a motion singleton, performance was facilitated, while there is not a single alternative explanation for all instances of facilitated search.

Using several static, coherently colored distractors did not improve search performance (color blocks of Experiments 1 and 2). Instead, search time in coherent-color conditions was slightly but significantly above that in single-color-distractor conditions, regardless of task difficulty. Thus, search for a color singleton did not reduce processing time relative to a single-color-distractor condition. Two major differences between the conditions may be responsible for the differential effects between the motion and the color blocks. First, facilitation by the coherently moving distractors could reflect information processing within a domain-specific mechanism that is selectively tuned to visual motion signals (cf. McLeod et al., 1991). To date, there is a lot of physiological evidence for neural mechanisms dedicated to process motion and coherent motion in the MT (middle temporal) and MST (medial superior temporal) areas of the monkey cortex (e.g., Berezovskii & Born, 2000; Born, 2000; Morrone, Burr, & Vaina, 1995; Tanaka et al., 1986). For instance, Tanaka et al. identified neurons with wide receptive fields that have centers and surrounds that are sensitive to similar motion directions of visual texture elements. These wide-field motion neurons preferably respond to coherent motion among locations as, for example, in optic flow. Other neurons preferably respond to antagonistic motion within centers compared with the surrounds of their receptive fields (Born, 2000; Born & Tootell, 1992). Thus, circuitry within the visual system seems to be tuned to register coherent motion as well as deviations within the coherent motion signals (cf. Braddick, 1993; Duchon & Warren, 2002; Egelhaaf et al., 2002).

In line with the assumption that a motion-specific mechanism is at work in the present Experiments 1, 3, and 4, under very similar conditions, we (Ansorge, Scharlau, & Kälberer, 2003)<sup>5</sup> showed that coherently

moving distractors induced target motion, changing the perceived target motion path (cf. Duncker, 1929),<sup>6</sup> that is, the fully circular path of a clockwise circling target presented among counter-clockwise moving distractors was perceived to be ellipse-shaped. Of course, this is not to say that a phenomenally perceived change of target motion causes or precedes the successful detection of the target. Instead, facilitated search may precede induced motion as an outcome of one underlying mechanism dedicated to processing visual motion. For instance, objective performance in the search task might be an early effect of feed-forward-driven gist perception. In contrast, conscious perception of the details of the image (e.g., perception of induced motion) could be the result of re-entrant processes occurring later (cf. Hochstein & Ahissar, 2002).

However, given that previous research demonstrated similar facilitation by increased distractor coherence in the nonmotion features of static stimuli (e.g., Bravo & Nakayama, 1992; Duncan & Humphreys, 1989), interpreting our data in terms of domain-specific effects is not the only possible, and most parsimonious, account. Differential effects of distractor coherence between motion and color blocks can be due to relatively motion-independent but reliably evoked covariations between the motion and the color blocks. For example, receptive field size involved in the discrimination between target and distractors may have differed between color and motion blocks. Receptive field size seems to be an often neglected but influential variable in visual search (e.g., Rolls, Aggelopoulos, & Zheng, 2003). In particular, the mean size of the receptive fields involved in the search for a motion-identity target among coherently moving distractors is likely to be relatively large. Coherent motion has been shown to be processed by brain structures with receptive fields of up to 70° of visual angle (e.g., Burr, Morrone, & Vaina, 1998). Quite possibly, in the color blocks, the receptive field sizes involved in the detection of a local static color target among coherently colored, static distractors were smaller. As a consequence, overall feature contrasts between the “neighboring” distractors and the target (cf. Wolfe, 1998) might have been derived from larger sample areas (“neighborhoods”) in the motion blocks. Future research is necessary to resolve this issue.

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<sup>5</sup>In fact, our manipulation of heterogeneity in Experiment 4 was inspired by the effects of distractor start positions on perceived induced target motion.

<sup>6</sup>This is not to say that filtering of optic flow and induced motion as described by Duncker (1929) always coincide. Overlapping expanding and frontoparallel flow patterns, for instance, shift the phenomenally perceived focus of expansion of the flow field (Duffy Wurtz, 1993), although the phenomena may be related (Meese, Smith, Harris, 1995).

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