Scale Changes Provide an Alternative Cue For the Discrimination of Heading, But Not Object Motion

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Statistical Analysis C
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Manuscript Preparation E
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Funds Collection G

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Background: Understanding the dynamics of our surrounding environments is a task usually attributed to the detection of motion based on changes in luminance across space. Yet a number of other cues, both dynamic and static, have been shown to provide useful information about how we are moving and how objects around us move. One such cue, based on changes in spatial frequency, or scale, over time has been shown to be useful in conveying motion in depth even in the absence of a coherent, motion-defined flow field (optic flow).

Material/Methods: 16 right handed healthy observers (ages 18–28) participated in the behavioral experiments described in this study. Using analytical behavioral methods we investigate the functional specificity of this cue by measuring the ability of observers to perform tasks of heading (direction of self-motion) and 3D trajectory discrimination on the basis of scale changes and optic flow.

Results: Statistical analyses of performance on the test-experiments in comparison to the control experiments suggests that while scale changes may be involved in the detection of heading, they are not correctly integrated with translational motion and, thus, do not provide a correct discrimination of 3D object trajectories.

Conclusions: These results have the important implication for the type of visual guided navigation that can be done by an observer blind to optic flow. Scale change is an important alternative cue for self-motion.

MeSH Keywords: **Motion • Optic Flow • Vision Tests**

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Background

While moving through one's surroundings, a wide variety of visual cues are available which provide the information needed to deduce both how we are moving, and how objects around us move. Primary among these are computations regarding changes in the position of features across the retina, that is, visual motion. Changes in the position and orientation of an observer's head and gaze produce a distinct pattern of motion across the retina, termed optic flow, which has been extensively linked to the perception of self-motion (e.g., [1–4]). Since objects occupy only one portion of the visual field, trajectory discrimination has typically been associated with processes that use changes in object boundaries, such as displacement across the retina or looming. These aspects of motion perception have been linked to the discrimination of 3D object trajectories [5,6] or arrival times [7,8]. For both self-motion and object trajectory discrimination, visual motion provides a powerful cue for determining the dynamic changes in the environment. However, there are situations in which motion information is degraded or difficult to extract from the scene, and in these cases, as well as for neurological patients with impaired motion detection, observers demonstrate a remarkable perceptual ability to infer information about their dynamic environment based on other sources of information.

For example, it has been shown that in the absence of motion, subjects can still detect heading on the basis binocular disparity [9]or heading, from retinal optic flow. Here we show that retinal optic flow is sufficient, but not necessary, for determining heading. By using a purely cyclopean stimulus (random dot cinematogram, landmarks [10–13], whether these cues are static or moving in the scene. Furthermore, stereoscopic cues can make heading estimates more robust to noise [14] because it radiates outward from the direction of heading. However, it is not directly accessible from the retinal flow. Nevertheless, humans can perceive their direction of heading from the compound retinal flow without need for extra-retinal signals that indicate the rotation. Two classes of models have been proposed to explain the visual decomposition of the retinal flow into its constituent parts. One type relies on local operations to remove the rotational part of the flow field. The other type explicitly determines the direction and magnitude of the rotation from the global retinal flow, for subsequent removal. According to the former model, nearby points are most reliable for estimating one's heading. In the latter type of model the quality of the heading estimate depends on the accuracy with which the ego-rotation is determined and is therefore most reliable when based on the most distant points. We report that subjects underestimate the eccentricity of heading, relative to the fixated point in the ground plane, when the visible range of the ground plane is reduced. Moreover we find that in perception of heading, humans can tolerate more noise than the optimal observer (in the least squares sense, and can enhance the perception of self-motion [15]. More recently, Schrater et al. [16] demonstrated that in addition to determining motion in depth from the divergence (i.e., expansion) of the optic flow field, observers could use changes in the size of image features, which they formalized as changes in spatial frequency, or *scale-changes*. Scale changes can by though of as a dynamic version of blur. Blur, the defocusing of certain features based on the distance between a part of the scene and the observer's fixation point, provides only a relatively weak depth cue when presented statically [17]. However, *changes* in blur over time may provide a more informative cue of motion in depth. Schrater et al. showed that when asked to match the speed of stimuli containing scale changes, but devoid of any motion, to an expanding random dot stimulus, there was a perceptual correlation between the rate of change of spatial frequency and the speed of the expanding dots. Their results provided the first demonstration that changes in spatial frequency alone are sufficient to create the percept of motion-in-depth. Following on this study, we were interested to determine whether scale changes and optic flow are processed by independent mechanisms [18]. We used an adaptation paradigm to show that adapting to scale changes had no effect on the ability of observers to detect optic flow, and adapting to optic flow had no effect on the detection of scale changes. The lack of cross-adaptation effects implies that the detection of scale changes and optic flow do not share a common substrate.

This dissociation of motion and scale change processing mechanisms raises the question of whether there also exists a functional segregation, that is, whether optic flow and scale change support different functional tasks. In this study, we compare the ability of observers to use scale changes, relative to complex (e.g., expanding) motion patterns in tasks of heading (estimation of the direction of self-motion), and trajectory (estimation of an object's direction of motion relative to the observer) discrimination. Our results suggest that scale changes can be used to compute self-motion perception, but do not contribute to the discrimination of 3D object trajectories.

Material and Methods

Participants

A total of 16 right handed subjects participated (ages 18–28, 11 in Experiment 1, 7 in Experiment 2, with two participating in both experiments; 10 male, 6 female). All subjects had normal or corrected to normal vision, and gave written informed consent approved by the Boston University Institutional Review Board.

Apparatus

Stimuli were generated on a Mac Pro in Matlab using PsychToolbox [19,20] and custom software. Stimuli were

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presented on a 20" Apple CRT, calibrated using a Minolta LS-100 luminance meter. Subjects viewed the stimulus from a distance of 60cm, with head position stabilized by a chin and forehead rest.

Scale change stimuli

We describe two main experiments and a control task based on the same set of underlying scale change and motion (optic flow) stimuli. In both experiments, scale change and motion stimuli were created by iteratively filtering white noise images (see [18] for additional details on stimulus generation). The procedure was based on first creating a 20×20°, full-cue "looming" stimulus by zooming in on a filtered white noise image, producing a movie which contained both changes in spatial frequency (scale change, SC) and an expanding pattern of motion (optic flow, OF). The looming sequences were then used as spatial frequency filters to generate a set of stimuli containing the same change in spatial frequency, but no pattern motion (expansion) by filtering a set of random, uncorrelated white noise images by each frame of the looming stimulus (the scale change stimulus). To create a motion only stimulus, we filtered every frame of the looming stimulus with a fixed, bandpass filter, producing a movie that contained the same expanding pattern of motion as the original looming stimulus, but with no changes in spatial frequency. We repeated this procedure using looming stimuli with a range of simulated rates of expansion to produce scale change and optic flow stimuli at a variety of speeds (with speed denoted by the simulated approach velocity of the observer of 1.0 to 5.0 m/s), and repeated to produce 20 unique stimuli for each stimulus type and velocity. These stimuli provided the basis for examining the ability of observers to determine heading and 3D trajectory based on each cue independently.

Experiment 1: Heading discrimination

The heading stimulus consisted of a row of five 4×20° vertical "panels", displayed alongside each other, so that the full display was 20×20° (Figure 1). Panels were chosen from stimuli generated with different approach velocities, so that the speed changed from panel-to-panel across the display. At the start of each trial, one of the five panels was chosen as the heading direction; this panel was assigned the minimum speed (an approach velocity of 1.0 m/s). The velocity of each other panel was then chosen to be proportionally higher, such that the speed of panel *i* depended on the distance to the heading panel (panel *h*) as $v_i=v_h+d_{i,h}*g$, where $d_{i,h}$ is the distance between the panels, and g is the gradient (the increase in speed per distance). In order to align the motion pattern with the speed gradient, the panel chosen as the heading direction was always drawn from the center of the underlying OF or SC stimulus, since this contained the FOE (Focus of Expansion). Panels to the left of this were drawn from the left portion of the underlying OF or SC stimuli, and panels to the right came from the right side of the OF/SC stimuli. This ensured that in the optic flow condition, the FOE aligned with the panel chosen as the heading direction, and the pattern of motion always moved radially outward from this point. Although the same algorithm was used in the scale change condition, it is important to note that there was no FOE or pattern motion present in this case. The resulting perception from this procedure was that of walking down a hallway at a certain angle: the heading direction point was perceived to be far away and approaching slowly, while on space on either side of this approach rapidly.

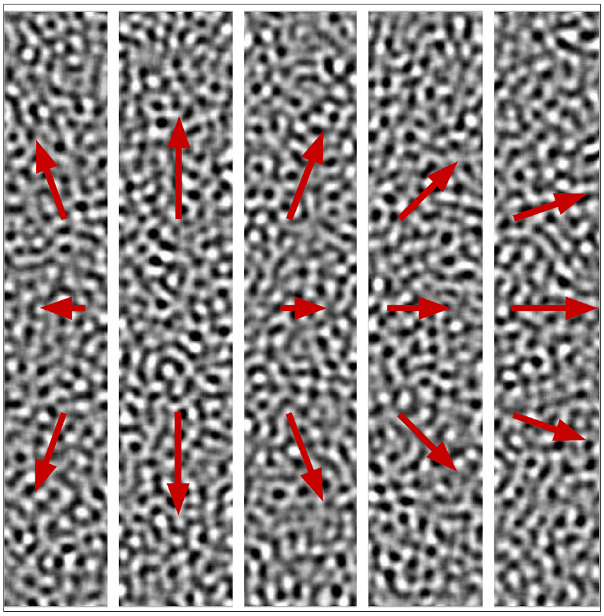

Figure 1. Schematic illustration of the heading stimulus. Each panel has a different simulated approach velocity, such that the direction of heading is perceived to be towards the panel with the minimum rate of approach. The arrows indicate the direction of motion for the optic flow condition. The heading direction for the stimulus shown is towards the second panel from the left, which coincides with the FOE in the optic flow condition.

When preparing and evaluating the stimuli, we discovered an artifact in the scale change stimuli in which the amount of temporal frequency content varied with approach velocity, creating the perception of a change in speed. These speeds were the result of spurious correlations, not any pattern motion, but could nevertheless in theory be used to identify differences across the heading display even if subjects could not detect the change in scale changes themselves. To control for this, we created a third class of stimuli, referred to as *speed-only*. The speed stimulus was created by filtering a set of random, uncorrelated white noise images using the same bandpass filter as was applied to the OF stimuli. This created a stimulus that

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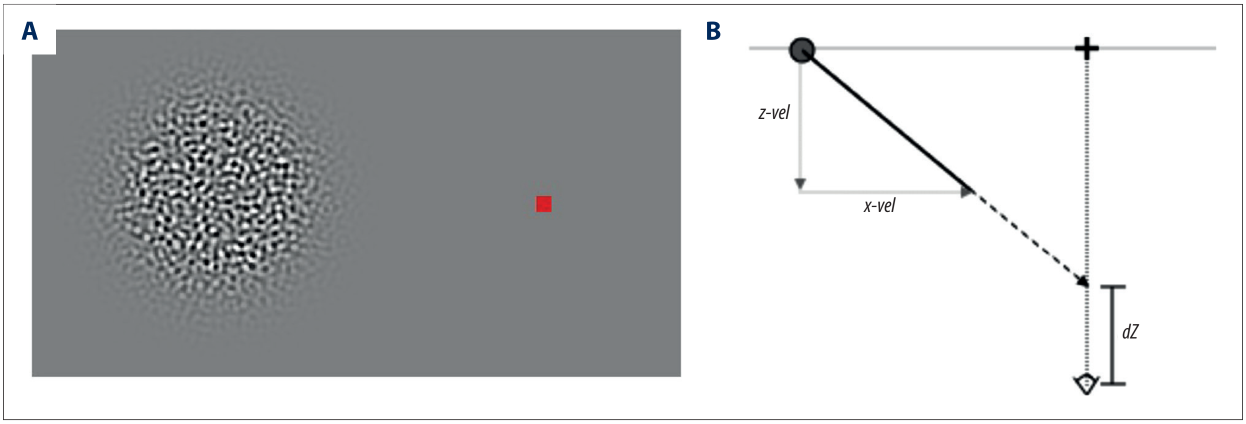

Figure 2. Schematic of the trajectory discrimination task. (**A**) Stimulus containing a textured object and fixation mark. The object was produced by using a scale change or optic flow movie, and applying a 2D Gaussian spatial filter so that it faded gradually into the background and had no hard edge. (**B**) Stimulus schematic showing the combination of x- and z-velocities for 3D object trajectory. The x-velocity (translation) component of the trajectory was produced by shifting the image position towards fixation, while the z-velocity (depth) component was conveyed by the optic flow or scale change texture content. The integration of these components produced a 3D trajectory designed pass in front of or behind the observer. Positive values of ΔZ indicate an object passing behind the observer, while negative values refer to an object passing in front of the observer (as shown).

had no pattern motion (since every frame was independently chosen white noise), nor any change in scale (since the same filter was used on every frame). We measured the distribution of local speeds to characterize the speed distribution of each stimulus, and selected those whose profiles match the SC stimuli most closely. The resulting stimuli were then used in the same heading experiment to determine whether the distribution of local speeds alone could account for performance in the SC condition.

Stimuli were displayed for 500ms and subjects were asked to identify which of the 5 panels they were moving towards (5 alternative forced choice task). Data was collected in constant stimulus blocks, with 100 trials per a block of a single stimulus type (optic flow, scale change, or speed only). Each block contained 20 trials of simulated heading toward each of the five panels presented in a randomized sequence. Observers were given two blocks of each stimulus type, presented in a pseudorandom sequence. Performance was measured as proportion correct averaged across heading direction (panel) for each speed and stimulus type.

Experiment 2: Object motion trajectory discrimination

The trajectory stimulus contained a small, textured image moving towards the observer. The image, drawn from the same set of OF and SC stimuli as the ones used in Experiment 1, was presented within a 2D Gaussian envelope (to remove sharp edges at the margins of the stimulus, Figure 2A). In order to create a stimulus moving along a 3D trajectory, we used the OF or SC content of the images to convey a change in depth, and manipulated the eccentricity of the stimulus to produce translational motion. The combination of these two effects was a textured object moving along a 3D trajectory (as illustrated in Figure 2B).

The depth component of the trajectory ("*z*") was simulated either by optic flow or scale changes, based on the stimulus generation procedure described above. Importantly, the size of the image was held constant, so there was no looming or angular expansion present in the overall shape or boundary of the object, but rather the motion-in-depth was conveyed exclusively through the motion or scale changes of the object's texture. The translational (frontoparallel) component of the trajectory ("*x*") was produced by initially placing stimuli along the vertical midline at a horizontal eccentricity of 7.5° and shifting them towards fixation during the trial. When coupled, the depth and translational changes produced apparent motion along a 3D trajectory. The velocities of the translational and depth components were chosen to create a trajectory that caused the object to pass in front of or behind the observer by 0.1, 0.2 or 0.3 m ("ΔZ", Figure 2)

Since there was no absolute frame of reference for the texture changes, we did not know how subjects would integrate the translational and depth components. This was in part because the designation of meters and m/sec depended on the simulated depth used when generating the stimuli (which was not known to subjects). Thus, we could not know *a priori* how subjects would combine these cues into a 3D trajectory. To correct for this, we first tested how the depth velocity was perceived relative to the translational velocity (i.e., what rate of approach was necessary to produce a trajectory moving directly towards the observer).

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We found that a scaling factor of 1/20 was necessary to match the simulated and perceived velocities (i.e., a stimulus with a simulated approach velocity of 1 m/s was perceived to move at 50 cm/sec). This scaling factor was applied to the speed of depth motion to determine the object trajectory in both conditions, optic flow and scale changes. Twelve combinations of x- and z-velocity components ($\dot{x}$, $\dot{z}$) were chosen such that responses could not be accurately based on either component individually. In a 2AFC task, subjects indicated whether the object would pass in front of or behind them when crossing their midline.

Subject performance was recorded as the proportion of trials they reported that the object would pass behind them when crossing their midline. This (proportion behind) was equivalent to proportion correct when ΔZ (the distance between the subject and the object at the time of passage) was positive, indicating the object was on a trajectory passing behind the subject, whereas for negative values of ΔZ (an object on course to pass in front of the subject), proportion behind was calculated as 1-proportion correct. This formulation allowed fitting ΔZ *vs.* proportion correct to a two-parameter sigmoid function with parameters indicating the point of subjective equality (PSE) and slope of the curve. This is important because it was not known a priori whether the scaling factor used for depth motion velocities was appropriate for both test conditions. That is, if observers underestimate the true speed of motion-in-depth as conveyed by either optic flow or scale changes, they would be more likely to report the object as passing in front of them, and vice versa. This bias would be captured by a shift of the PSE. However, it would not reflect the sensitivity of the observers to the stimulus cue (optic flow or scale change) itself, which would instead be indicated by the steepness of the psychometric function. By measuring the PSE and slope separately, we can determine the sensitivity of observers to both optic flow and scale changes, independent of the effects of bias due to non-veridical velocity judgments.

Results

Preliminary Experiment 1 (PE1): Detection of optic flow and scale changes

First we quantified the detectability of the optic flow and scale change stimuli (Figure 3) described in the methods section. Observers' sensitivity was greater to optic flow, such that scale changes had to be approximately moving two orders of magnitude faster to be equally detectable. This was consistent with our previous findings for these stimuli, in which the two tasks were comparable in difficulty only after adding substantial amounts of noise to the optic flow stimuli [18]. Since the detectability of two classes of stimuli was so different, we could not use differences in detection rates between optic flow and scale changes stimuli alone to determine whether one or the other was used when determining direction of heading or trajectory discrimination (since differences would be expected based on the detection of the motion or scale change cues themselves). Instead, for each experiment below we consider statistical comparisons to control data to determine whether subjects are indeed using each cue.

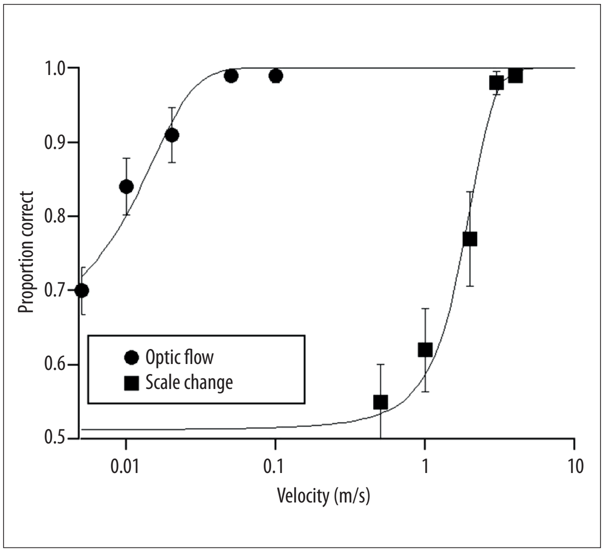

Figure 3. Comparison of detection of optic flow (circles) and scale changes (squares). X axis shows the approached velocity simulate when generating stimuli and y axis shows proportion correct. Performance was measured as a function of the simulated speed of approach, shown on a *log*-scale. Data are fit to a 2-parameter sigmoid model (solid lines). Scale change required approximately two orders of magnitude greater speed for similar detection rates as the optic flow stimuli. Error bars are the standard error of the mean (s.e.m.) across subjects.

Experiment 1a: Heading discrimination

Performance on the heading task was measured for the optic flow, scale change and speed only conditions for two speed gradients (0.5 and 1.0 m/s, Figure 3). At the higher speed gradient, subjects successfully reported their direction of heading for all cue types, with highest performance for optic flow (OF, 92.4% correct), slightly lower performance for scale changes (SC, 88.4%), and worst performance for speed only (SP, 71.0%). In all three conditions performance was significantly above chance (chance=20%), demonstrating that for sufficiently high velocity gradients all three cues can support the detection of direction of self-motion. However, at the lower speed gradient (0.5 m/s), performance on the three tasks was very different, suggesting that there was a difference among the usefulness of each of the cues for carrying out the task (87.2% for optic flow, 66.1% for scale change, 25.7% for speed only).

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Although performance on heading from scale changes was significantly worse than for optic flow (two sample paired t-test for the 0.5 m/s speed gradient: t_{10}=–4.66, p<0.001), it was still well above chance (one sample t-test relative to a 20% correct baseline: t_{10}=44.8, p<0.001). Performance on the speed-only condition was significantly worse than for scale changes condition (two sample paired t-test for the 0.5 m/s speed gradient: t_{10}=17.7, p<0.001), indicating that subject performance cannot be explained by the use speed gradients present in the scale change stimuli. Instead, this result suggests that the detection of scale changes themselves underlies the performance on the heading task.

Experiment 1b: Pairwise comparison control experiment

However, the ability to determine the direction of heading does not alone necessarily imply the existence of mechanisms dedicated to extracting heading from a visual stimulus containing scale changes. It is possible that subjects used a cognitive strategy in which they determined the speed of each panel and cognitively select the slowest. To determine whether such a strategy could explain performance, we tested five subjects who participated in the main heading experiment on a two-panel velocity discrimination control task. We reasoned that if subjects were detecting heading direction by identifying the panel with the slowest speed through a series of velocity comparisons (rather than detecting their heading direction across the entirely display in a single computation), their overall performance should be predictable based on their ability to discriminate each pair of panels.

To test this, we presented subjects with two panels selected from neighboring locations in the heading display and asked them to determine which moved faster. We then used results from this task (the probability of a correct comparison, p) as the basis to quantitatively predict overall heading detection based on a strategy in which subjects had to make a series of similar comparisons. For a heading stimulus containing n possible heading directions *(5,* in our stimulus, Experiment 1), subjects would have to make at most n-*1* comparisons. However, the exact number of comparisons required (k) varied depending on the configuration of panels (e.g., for a configuration in which the heading direction on a far edge, a single comparison could be sufficient if subjects compared the pair of panels at that edge first). Since the target panel was defined with uniform probability among all panels, any comparison sequence had an equal chance of requiring subjects to make from 1 to n-*1* comparisons. Performance on the task ($P_{heading}$) therefore can be described as making k correct comparisons, each with probability p of being correct. This can be written as

$$P_{heading} = \frac{\sum_{k=1}^{n-1} p^k}{n-1}$$

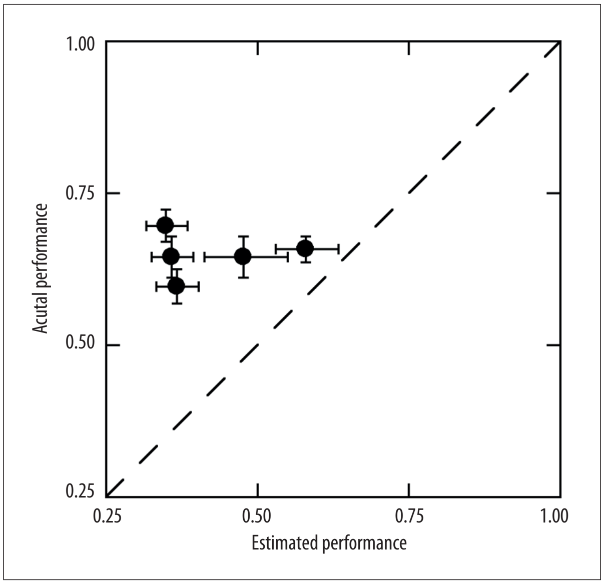

Figure 4. Comparison of scale change heading performance to the prediction of the pairwise comparison cognitive strategy. Performance for five subjects between the predicted performance based on the two-panel controsl experiment ("estimated" data, x-axis) and the scale change heading task ("actual" data, y-axis). The dashed line represents equality between the actual and predicted performances. Points above this line (as seen for all subjects) indicate that subjects outperformed the performance that would be expected if they were using the pairwise cognitive strategy.

Note that this slightly overestimates expected performance, as the easiest condition (making a single comparison) is less likely than the other conditions, since it requires both a panel being on the far edge of the display, and a strategy which makes that comparison first. Thus, we consider this value an upper bound on the expected performance when subjects use a cognitive strategy based on a series of pairwise comparisons between neighboring panels (Figure 4).

Based on this, we computed the predicted performance for five subjects and compared them to their actual performance on the scale change heading condition for a gradient of 0.5 m/s. Figure 5 shows that for all subjects, the actual performance was significantly better than the upper-limit of performance predicted by the pairwise cognitive strategy (t_4=3.86, p=0.009), indicating that this strategy cannot fully account for subjects' ability to discriminate direction of heading from scale change cues. Instead, this data supports the direct use of scale changes in the detection of heading.

Experiment 2: Object trajectory discrimination

To determine whether scale changes support the perception and discrimination of object trajectories, we used a task in

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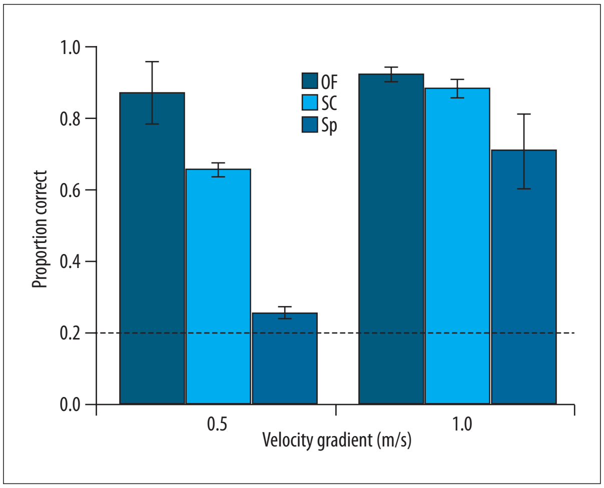

Figure 5. Heading detection performance for optic flow (OF), scale change (SC) and speed only (Sp) stimuli. The dashed line indicates chance performance on the 5AFC task (20%). The X axis indicates the velocity gradient (change in velocity across space) and the Y axis indicates the mean proportion correct across subjects (n=11), with error bars showing the standard error of the mean (s.e.m.)

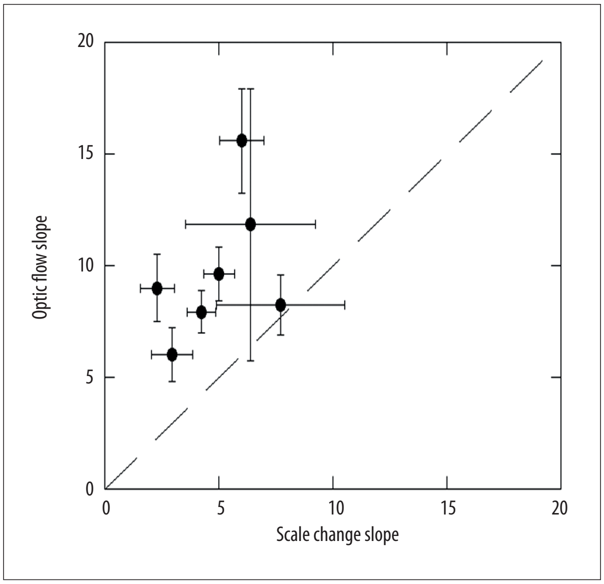

Figure 6. Comparison of sensitivity to 3D trajectory with optic flow and scale change as the depth-motion cue. X and Y axes indicate the slope parameter of a sigmoidal fit of the performance data for scale change and optic flow respectively. Slopes were computed from the performance (proportion correct) as a function of the distance between the observer and object trajectory. Higher slopes indicate the performance increased more rapidly as the distance increased and indicate a high degree of sensitivity. Slopes were significantly greater for optic flow than for scale changes (p=0.004), indicating greater sensitivity of responses to passage distance, and therefore better discrimination of the trajectory.

which the depth component of a 3D object motion stimulus was defined by either optic flow or scale changes. We asked subjects to judge the trajectory of an approaching object as either passing in front of them or behind based on the combination of translational motion (a shift in location across the display) and depth motion (from scale changes or optic flow). Performance was measured as the proportion of trials in which subjects indicated the object passed behind them, and were fit to 2-parameter (slope and point of subjective equality, PSE) sigmoidal psychometric functions. We used a bootstrapping curve-fitting procedure based on trial resampling with replacement for 500 repetitions to estimate the standard deviation of the PSE and slope parameters. Fits performed for each subject (n=7, Figure 6) showed that for all subjects, slopes were larger in the optic flow condition than for scale changes and that the effect was significant across the group (t=3.56, p=0.004).

The higher subjects' sensitivity seen in the OF condition indicates that performance increased faster as a function of passage distance (ΔZ) for OF than SC, suggesting that subjects were more sensitive to changes in object trajectory when depth-motion was conveyed via optic flow. The poorer sensitivity in the scale change condition could result from either reduced sensitivity to the depth motion component (since, as shown in PE1, subjects are less sensitive to scale changes than optic flow), or from the fact that scale changes do not provide useful information for the detection of object trajectories. The first alternative, that poor performance stems from poor sensitivity to scale changes, seems qualitatively unlikely because the depth-motion velocities used in the stimulus (2–3 m/s) were easily detectable by all subjects (performance in detecting approach/recede was >90% for all subjects, see PE1). To determine quantitatively which stimulus features governed object trajectory discrimination, we performed a statistical analysis on the trial-by-trial subjects' responses.

We reasoned that if subjects cannot directly use scale changes to perceive the trajectory of a moving object, they would base their responses on the frontoparallel and/or depth-motion components, without veridically integrating them into a 3D trajectory percept. Although the depth-motion and horizontal-motion velocities were chosen such that neither alone could be used to accurately perform the task, there was nonetheless a correlation between the individual motion velocities and the overall trajectory (slower horizontal motions tended to pass behind, while slower depth-motions tended to pass in front). Because of the correlation between the horizontal and depth motion components and the 3D trajectory, if subjects based their responses on either of them, they would still be likely to get some trials correct. To investigate this possibility, we used a 3-way ANOVA (continuous variables $\dot{x}$, $\dot{z}$, ΔZ)

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Table 1. Summary of a 3-way ANOVA with interactions used to explain responses for the optic flow (left) and scale change (right) conditions of the trajectory discrimination task (Exp 2). Trial-by-trial data was compared to the *x* and *z* velocities ($\dot{x}$, $\dot{z}$) and the distance of actual passage, ΔZ, as well as all interactions among them, to determine which of the stimulus variables were significant drivers of performance. In the OF condition, only ΔZ was related to performance, indicating that subjects could veridically infer trajectory from the motion components. In the SC condition, the interaction between translational motion and depth motion (from scale changes), but not the trajectory (ΔZ) itself, was a significant predictor of performance.

Motion cue	OF performance		SC performance	
	F	p>F	F	p>F
DZ	**8.76**	**0.003**	0.93	0.33
$\dot{x}$	1.42	0.23	0.02	0.89
$\dot{z}$	1.89	0.17	2.52	0.11
$\dot{x}$*DZ	1.56	0.21	0.74	0.39
$\dot{z}$*DZ	0.92	0.34	2.84	0.09
$\dot{x}$*$\dot{z}$	0.79	0.37	**3.91**	**0.048**

with interactions to determine whether subject performance could be accounted for by reliance on the individual motion components (i.e., translational motion with either optic flow or scale changes), rather than an estimate of the true 3D trajectory. Trial-by-trial subject data was combined for all subjects and separate ANOVAs were run for the optic flow and scale change conditions.

In the optic flow condition, neither the x- nor z-velocity components ($\dot{x}$, $\dot{z}$) were significantly related to task performance, nor was their interactions. Rather, the only significant predictor was ΔZ (p=0.003, see Table 1, OF Performance columns). This suggests that subjects used a veridical 3D trajectory estimate as the basis for their responses as to whether the trajectory would pass in front of or behind them, and did not rely on the individual *x* and *z* motion components to do the task.

The results for the scale change condition showed a different pattern (Table 1, SC Performance columns). Neither the x- nor z-velocities alone were significant, suggesting that subjects were not basing their responses on either the translation motion of scale change velocity alone. Unlike in the optic flow condition, however, here ΔZ was not a significant predictor of responses (F=0.93, *p*=0.33), indicating that subjects did not rely on a veridical estimate of trajectory. Instead, the interaction analysis revealed that the only significant predictor of responses was the x-z velocity interaction. This suggests that in the scale change condition, subjects did combine the translational (x) and depth (z) motion components into an accurate estimate of 3D trajectory, but instead estimated the x- and z-velocities independently, and used a combination of them to estimate the object's path. This implies that subjects, while sensitive to both the translation and SC motion, do not integrate these cues into a veridical 3D motion percept when estimating the trajectory of a moving object.

Discussion

We investigated the ability of observers to use scale changes – changes in the spatial frequency content of a stimulus over time – to detect motion in depth in tasks of heading and object trajectory discrimination. In the heading task (Exp 1), we found that subjects could determine their direction of heading on the basis of scale changes alone, and that performance could not be explained by either the use of differences in the distribution of local speeds, nor by the use of a cognitive strategy based on a comparison of speeds across the display. Instead, performance was consistent with the use of an integration of scale changes over the entire display similar to FOE detection mechanisms that have been described for the detection of heading from optic flow. In the trajectory discrimination task (Exp 2), the performance data showed that when depth motion was conveyed by scale changes, observers did not effectively integrate them with the translational motion indicated by a position shift across the display (although they did when depth motion was conveyed by optic flow). Although performance did vary with the speed of the SC stimulus (which was expected since subjects could detect motion in depth from SC alone), statistical analysis of performance data showed that the SC and translational motion components were not combined into an accurate representation of the object's true 3D direction of motion. The results of these two experiments indicate a role for scale changes in the detection of self-motion (heading), but not object motion (trajectory discrimination).

This functional specialization can be interpreted in terms of the spatial frequency content typically associated with each task. Self-motion (e.g., heading) computation depends on the detection of scene-static items, such as background landscapes and buildings, rather than smaller objects that are likely to move independently without providing useful information about the

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observer's self-motion. As such, the features that should be most useful in detecting heading are likely to be large, and therefore contain a wide range of spatial frequencies (and especially, low spatial frequencies). Contrary to this, object trajectory discrimination is likely to be computed over comparatively small spatial extents. Since the sizes of the relevant items here are generally smaller, the spectrum of their spatial frequencies content is more limited, with low spatial frequencies less likely to be present. Therefore, if the detection of depth motion from scale changes is facilitated by having a wide band of spatial frequencies available (including low frequencies), we would expect that they would be more useful in tasks of self-motion than object-motion, consistent with our results. While this may explain the functional roles for motion and scale changes, it is important to point out that it does not directly explain the data we have reported, since an identical range of spatial frequencies was used in each task.

The task specificity we have reported also suggests the possibility that perception of scale changes may be useful in the separation of self- and object-motion when both are present. Recent studies have suggested that optic flow can be used to estimate and remove perceived motion that arises due to self-motion [21–26], allowing the isolation and perception of world-centric object motion. Since scale changes are shown to be useful for detecting self-motion, and not object-motion, we suggest that they may provide valuable information in this separation: changes in the low-frequency content in the scene would be produced by background rather than objects, thus providing an estimate of self-motion that is relatively unaffected by the presence of moving objects.

Overall, our results point to a role for scale change detection in the perception of self-motion, and in particular in the detection of heading direction (Experiment 1). It is well established that subjects can use optic flow to determine how they are moving [1–3] but other visual information such as landmarks [10–13,27] and stereoscopic cues [9] have also been association with this computation.

Conclusions

This work suggests that scale changes provide yet another alternative means for the computation of heading. We have suggested [18] that scale changes are a type of second order (nonluminance based) motion [28], and the results reported here support previous studies showing that in certain conditions, these cues can support the detection of self-motion [29–32] and heading [33]. These results suggest the intriguing possibility that scale changes may provide a useful strategy for motion-impaired observers, when motion information is noisy or unavailable, and in situations in which self- and object-motion are confounded, questions which deserve further investigation.

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