Perceived Depth is Enhanced with Parallax Scanning
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Dennis Proffitt & Tom Banton
Department of Psychology
University of Virginia

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Background

1.1 It is well known that people, animals, and insects can recover relative depth by moving the head from side to side when viewing a scene[1-4]. The head movement creates different retinal image motions for objects at different depths (motion parallax). For example, in Fig. 1a an observer fixates point P. During head movement, an object that is *farther* than the point of fixation (A) will produce retinal image motion *to the left* of the image of the fixation point. An object that is *closer* than the point of fixation (B) will produce retinal image motion *to the right* of the fixation point image. An object at the fixation point (P) is imaged on the fovea, and therefore will not produce retinal motion during head movement. Thus, the direction of retinal image motion determines an object's depth relative to the fixation point. Additional depth information is gained from the magnitude of retinal image motion during head movement: As distance from the fixation point increases, image displacement also increases. Perceptually, objects more distant than the fixation point appear to move in the same direction as the head, while objects closer than fixation appear to move opposite the direction of head motion. The apparent movement increases as the distance of the object from fixation increases (Fig. 1b). In sum, both the relative direction and speed of retinal image motion provide depth information. Some aspects of the geometry of motion parallax have been specified mathematically[1].

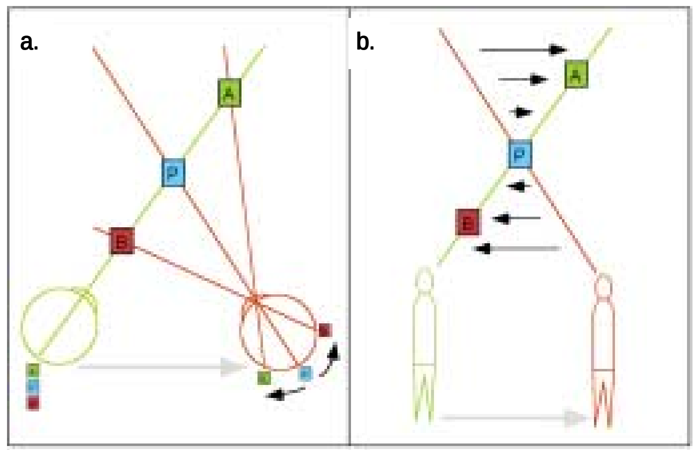


FIG 1. *Motion parallax. Gray arrows signify a rightward movement.* ***(a)*** *Black arrows show the retinal image motion created by the head movement.* ***(b)*** *Black arrows show the perceived object motion which results. The size of the arrow indicates the relative amount of motion perceived.*

1.2 The geometry of motion parallax (FIG 1a) and stereopsis is similar. Stereopsis is the perception of depth arising from the different viewpoints of the two eyes. Both motion parallax and stereopsis compare different viewpoints and extract the changes in object position to reconstruct depth. Even though these processes are related[5-6], they differ in that motion parallax is based on viewpoints that are gathered over time while stereopsis is based on simultaneously presented viewpoints. Thus, motion parallax is a monocular cue to depth while stereopsis is a purely binocular process.

1.3 The geometry that specifies depth from motion parallax can be applied to camera systems to enhance depth. Early systems produced motion parallax by alternating between views from two different cameras[7-9]. Unfortunately, this method was either accompanied by unstable rocking motion or required heroic efforts to maintain precise calibration of the two cameras[9]. Recent systems by Vision III Imaging produce motion parallax by using a single camera whose lens[10] or lens aperture[11] moves during continuous filming. The Vision III process is unique in two respects: (1) continuous filming allows motion parallax to be used in live action recordings, and (2) the rotational movement of the lens aperture (termed "parallax scanning") produces motion parallax in two dimensions (Fig. 2). Because motion parallax in the environment is usually one-dimensional, parallax scanning has the potential to enhance depth beyond that which occurs from parallax under natural viewing conditions. Furthermore, parallax scanning does not require paired cameras or viewing spectacles as in stereoscopic techniques. Therefore, parallax scanning systems are attractive candidates for enhancing depth in motion pictures.

FIG 2. *Parallax scanning along a circular iris path.*

1.4 The purpose of the studies presented in this report was to determine if parallax scanning with a Vision III moving optical element (MOE) lens system enhances perceived depth. Three experiments confirmed this hypothesis. The first experiment showed that depth order was more accurately perceived in the presence of parallax scanning. The second and third experiments reduced extraneous cues to depth to show that the depth enhancement was based on motion parallax. Guidelines for selecting the optimum magnitude and frequency of parallax scanning are also provided.

Experiment 1

Part 1

Purpose: The first part of the experiment examined the accuracy with which subjects judged depth order during parallax scanning and with no parallax scanning.

Stimuli: Subjects viewed a video monitor displaying a scene containing a collection of objects that had misleading depth cues (Fig. 3a). For example, the playing card was oversized and brightly illuminated, suggesting that it should appear toward the front of the scene rather than in the back where it was actually positioned (Fig. 3b). The scene was captured in real time through a MOE Jr. lens system by Vision III Imaging.

FIG 3a. *Scene with misleading depth cues, as viewed by experimental subjects.*

FIG 3b. *Same scene as in Fig. 3a, viewed from higher up to reveal the actual depth order of the objects.*

Procedure: Six subjects were asked to rank the objects in the scene from closest to farthest from themselves. Each subject did this for parallax scanning magnitudes of 0, 16, and 23, where 0 is no scanning and 23 is the maximum scan magnitude used.

Results: In the absence of parallax scanning, observers were fooled by the misleading depth cues. The group perceived the card as being closer than the Coke can and the ferris wheel as being most distant (Table 1). Performance improved when parallax scanning was added. Only the Coke can and playing card were incorrectly ordered at a scanning level of 16. With a sufficient amount of parallax, subjects almost always perceived the depth order correctly: Just one error was made at a scanning level of 23.

		DEPTH ORDER				
	PARALLAX	butterfly	screen	ferris wheel	coke can	playing card
SUBJECT	(MOE level)	**1**	**2**	**3**	**4**	**5**
AR	0	1	2	4	5	3
ES	0	1	2	5	4	3
HH	0	1	2	5	4	3
KG	0	1	2	4	5	3
KS	0	2	3	5	4	1
WM	0	1	2	5	4	3
GROUP	0	1.17±0.17	2.17±0.17	4.67±0.52	4.33±0.21	2.67±0.33
AR	16	1	2	3	5	4
ES	16	1	2	4	3	5
HH	16	1	2	3	5	4
KG	16	1	2	3	5	4
KS	16	1	2	4	5	3
WM	16	1	2	3	4	5
GROUP	16	1.00±0	2.00±0	3.33±0.21	4.50±0.34	4.17±0.31
AR	23	1	2	3	4	5
ES	23	1	2	4	3	5
HH	23	1	2	3	4	5
KG	23	1	2	3	4	5
KS	23	1	2	3	4	5
WM	23	1	2	3	4	5
GROUP	23	1.00±0	2.00±0	3.17±0.17	3.83±0.17	5.00±0

Table 1. *Depth ordering of the scene by experimental subjects.*

Part 2

Purpose: Although parallax scanning clearly enhanced perceived depth in Part 1, some of the scenes contained enough motion to be disconcerting. There appears to be a trade-off between maximum depth enhancement and pleasantness of the image during parallax scanning. This part of the experiment measured subjects' criteria for maximizing depth and for producing the best image quality during parallax scanning.

Procedure: Parallax scanning can be controlled by adjusting the parallax magnitude (iris offset) and the scanning rate (frequency of iris rotation). Using the scene in Part 1, the same six subjects were asked to adjust the scanning rate to produce (1) the greatest sense of depth and (2) the best overall image quality. Each subject did this for parallax scanning magnitudes of 6, 10, and 16.

Results: Perceived depth was greatest at moderate scanning rates, while overall picture quality was best at lower scanning rates (Fig. 4). The difference was significant [$F(1,27)=48.57$, $p < 0.05$], confirming a trade-off between maximum depth enhancement and pleasantness of the image during parallax scanning. It is important to note that the values reported here were optimized for a stationary scene where observers are least tolerant to excess motion. Greater parallax scanning can be applied during camera panning or subject motion to enhance depth further[10]. Finally, one observer reported that details in the scene appeared to be enhanced during parallax scanning. The effect of parallax scanning on texture appearance has not yet been investigated.

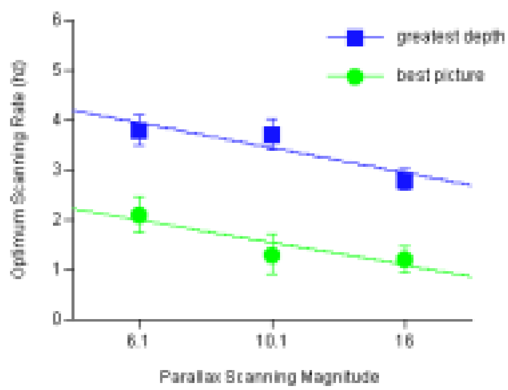


FIG 4. *Scanning frequencies maximizing perceived depth and best overall picture quality.*

Experiment 2

Purpose: The scene viewed in Experiment 1 contained numerous monocular cues to depth, as is the case in most real-world scenes. To determine if the depth enhancement found in Experiment 1 was indeed based on motion parallax, perceived depth was measured when extraneous cues to depth were minimized.

Stimuli: Computer generated objects were used in this experiment. Each object was composed entirely of small bright dots. This minimized depth cues from dot occlusion, dot aspect ratio, and dot shading. On side view, the objects had one of six aspect ratios (length/width) ranging from 1:2 to 16:1 (Fig 5). From the front, each object was identical in size and shape. Therefore, the aspect ratio could not be used as a cue to depth when the objects were stationary. Parallax scanning magnitudes of 0.05 and 0 arc degrees were simulated using a software plug-in developed by Vision III Imaging for Lightwave™.

Procedure: Five subjects were presented with front views of the stimuli on a computer monitor. They estimated the perceived depth of each object, and used the response scale to select the aspect ratio that most closely matched their depth estimate (Fig 6). Each subject completed 120 trials (10 estimates per stimulus). Trials were presented in random order. Viewing was monocular to reduce cues to screen flatness.

Results: In the absence of parallax scanning, subjects could not differentiate object depth [$F(5,20)=0.95$, n.s.]. Perceived depth was about 1:1 for all objects that were not scanned (Fig 7). With parallax scanning, object depth was clearly differentiated [$F(5,20)=40.06$, $p<0.05$] and perceived depth was enhanced [$F(1,44)=28.92$, $p<0.05$]. The amount of depth enhancement depended on the object's depth [$F(5,44)=37.04$, $p<0.05$], and was significant at the 0.05 level on post-hoc tests when object aspect ratio was 2:1 or more. Below 2:1, the effect broke down because the magnitude of parallax scanning became very small for nearly flat objects at the point of convergence. Overall, this experiment shows that perceived depth is enhanced by parallax scanning. The results suggest that the enhancement is based on motion parallax since extraneous sources of depth were minimized.

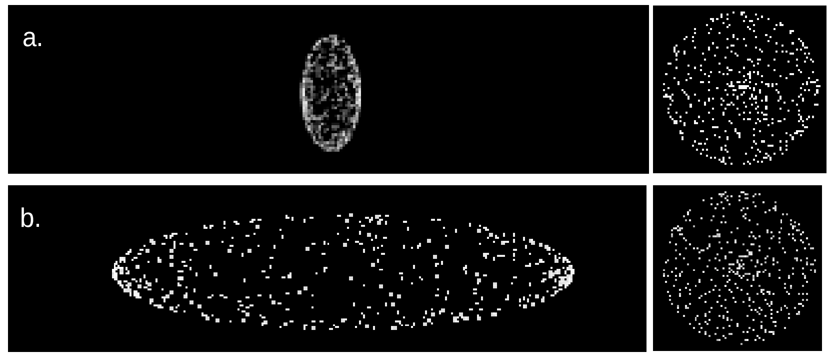


FIG 5. *Two experimental stimuli viewed from the side (left) and from the front (right). **(a)** The object depth is 1/2 its height. **(b)** The object depth is 4 times its height. Note that subjects only saw front views (right), from which the different object depths are not appreciated when stationary (right).*

FIG 6. *The experimental procedure. Subjects saw front views of the dotted objects (left). They estimated each object's depth and then used the response scale to select the side view that most closely matched their estimate (right).*

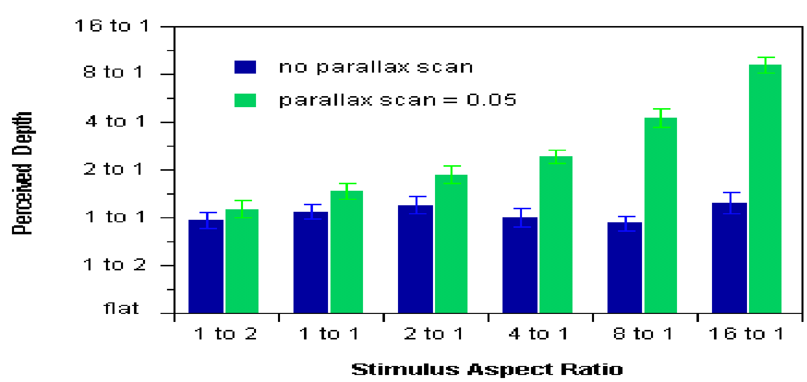


FIG 7. *Perceived object depth with and without parallax scanning. Parallax scanning enhances perceived depth, especially when the object depth is large.*

Experiment 3

Purpose: Dynamic occlusion is a powerful cue to depth that may be accentuated by parallax scanning: The changing viewpoint during iris rotation increases the chance that neighboring picture elements will occlude one another. In Experiment 2, occlusions occurred, but were ineffective in signaling depth because the dots were small and uniform: Either dot could be perceived as being closest under these conditions. In the third experiment, the effect of occlusion on perceived depth was investigated during parallax scanning. It was anticipated that the production of dynamic occlusion from parallax scanning would further enhance perceived depth.

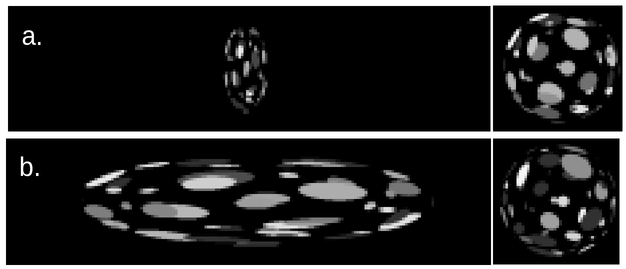
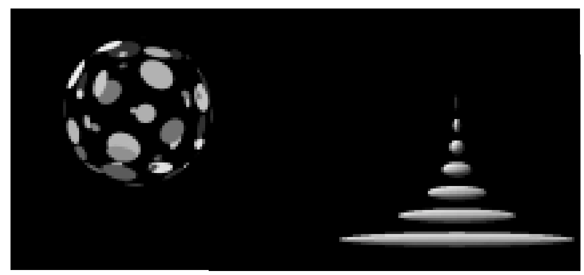


FIG 8. *Two experimental stimuli viewed from the side (left) and from the front (right). **(a)** The object depth is 1/2 its height. **(b)** The object depth is 4 times its height. Subjects only saw front views during the experiment (right). Occlusion and patch aspect ratio are potential depth cues in these stimuli.*

Stimuli: The six objects from Experiment 2 were used again, but this time they were formed by large patches rather than by dots (Fig 8). The front view of each object was similar, but not identical, since the aspect ratios of the patches and the occlusion produced by the patches differed slightly. The objects had a simulated parallax scanning magnitude of either 0.05 or 0 arc degrees.

FIG 9. *The experimental procedure. Subjects saw front views of the patch objects (left). They estimated each object's depth and then selected the side view that most closely matched their estimate (right).*



Procedure: Five subjects were presented with front views of the stimuli on a computer monitor. They estimated the perceived depth of each object, and used the response scale to select the aspect ratio that most closely matched their depth estimate (Fig 9). Each subject completed 120 trials (10 estimates per stimulus). Trials were presented in random order. Viewing was monocular to reduce cues to screen flatness.

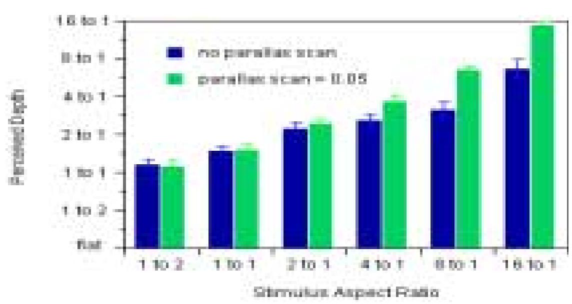
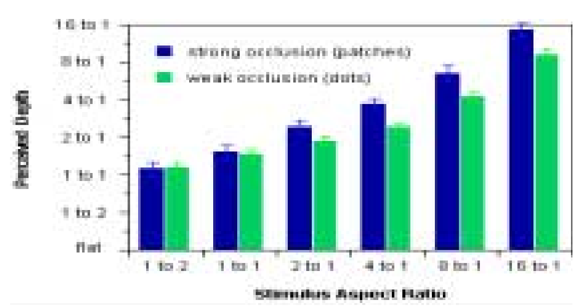


FIG 10. *Perceived object depth with and without parallax scanning. Parallax scanning enhances perceived depth primarily when the object depth is large.*

Results: In the absence of motion parallax, subjects perceived longer objects to have increasingly more depth [$F(5,20)=5.12$, $p<0.05$]. This is shown in Fig 10, and is presumably due to static depth cues from patch aspect ratio and occlusion. With parallax scanning, subjects also perceived longer objects to have more depth [$F(5,20)=33.67$, $p<0.05$]. Post-hoc analyses showed that perceived depth with scanning was greater than that with static cues for objects having 8:1 or 16:1 aspect ratios. Therefore, parallax scanning can enhance depth, even in the presence of additional cues to depth. With respect to the dotted objects used in Experiment 2, Fig 11 shows that parallax scanning with patches produced a small improvement in depth judgements that was significant at aspect ratios of 4:1 and above on post-hoc testing. This small effect could be the result of occlusion or the patch aspect ratio.

FIG 11. *Perceived depth with parallax scanning for dotted objects (Exp. 2) and patch objects (Exp. 3).*



Conclusions

1. Parallax scanning enhances perceived depth. Scanning disambiguated depth order in Experiment 1 and increased the magnitude of perceived depth in Experiments 2 and 3. Depth enhancement was strongest when the parallax scanning magnitude was high and the scanning frequency was near 3 to 4 hz. However, the best image quality was obtained with slightly lower scanning magnitudes and frequencies. Users of parallax scanning technology will want to use values that strike a balance between these perceptions. The values reported here should be considered as minimum values, since the data were collected using a stationary scene where observers are least tolerant to excess motion. In practice, greater parallax scanning can be used during filming due to masking by subject motion or by camera panning[10].

2. Motion parallax is the basis for depth enhancement during parallax scanning. Computer-generated scenes relying on motion parallax as the cue to depth produced strong perceived depth (Experiment 2). Dynamic occlusion and changes in the aspect ratio of an object's texture also contributed to depth enhancement from parallax scanning (Experiment 3).

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