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S abili ed S o e f M i n i h Di a i In ce Di a i Ada a i n

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S a

3D o e can be e cei ed ba ed n he a e n f 2D i n ig nal [1, 2]. Wi h h g a hic jec i n f a 3D i n a 2D la ne, he ki ne ic i n f a i n can gi e a i id i e i n f de h, b he de h de i i n i n icall a big , e l i n g i n bi able e en l i able i n e e a i n [3]. F e a le, a n h g a hic jec i n f d n he face f a a i n g c li n de i e cei ed a a a i n g c li n de i h a big di ec i n f a i n [4]. We h ha he bi able a i n can be abili ed b addi n g i n f a i n, n he d he el e , b hei a ial c n e . M e i n e e i n gl , he abili ed i h ki n e ic de h a ha e ac i a ed n e n e n i i e diffe e n di a i ie , e e n h gh he i li ha e e ela i e di a i . S e e de h a n d ki n e ic de h a be ed b a c n n e al echa n i a a n ea l age i n he i al e .

Re l a n d Di i n

S a ial C n e Ca n Di a big a e he A big R a i n g C li n de

Ambiguous structure from motion generated from orthographic projection of 3D moving objects can be disambiguated by information (e.g., disparity, speed, contrast, etc.) that specifies the depth order to the moving elements [5–8]. Multiple ambiguous stimuli tend to covary [9–11], suggesting the possibility that the perception of of dots moving in one direction, our intention being to create a subjective occluder in the middle of the cylinder that blocks part of the back surface (Figure 1C). However, with this manipulation, the stimulus remained bistable. Observers perceived alternations between two percepts, as depicted in Figure 1C: two partial cylinders

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stimulus could almost completely stabilize the ambiguous stimuli.

The stimulus used in our study is a typical rotating cylinder generated from an orthographic projection of dots on a rotating 3D cylinder and is similar to stimuli used in previous psychophysical [3, 7] and physiological [4, 15, 16] studies. The ambiguous stimulus, perceived as a rotating cylinder with its rotation direction switching every few seconds, was presented to only one eye, (Figure 1A). (The percepts of two concave or convex sheets, moving across each other, are also possible [3] but were rarely seen by our observers; hence, they are not discussed in this paper and not depicted in figures.) When disparity information was added to the two ends of this bistable cylinder (i.e., a whole cylinder was presented to one eye, and only two ends of the cylinder were presented to the other eye), the whole cylinder was perceived to rotate in the direction specified by the disparity in the two ends, although the middle section contained no information to specify the depth order (Figure 1B). For the four observers tested, all perceived the cylinder as rotating unambiguously,opposite direction of motion in the c thus biases dots moving in such a direction to be perceived as being in front [12]. In the case of linkage between multiple bistable stimuli, the coupling tends to break down between unambiguous and ambiguous stimuli [11]. The key reason that the ambiguous and unambiguous sections in our stimulus remain strongly linked is that monocular presentation of the ambiguous section of the stimulus reduced the disparity contrast between nonzero relative disparity in the unambiguous sections and zero relative disparity in the ambiguous section. Additionally, unlike in earlier studies in which the ambiguous and unambiguous stimuli appeared as separate and distinct objects, we made the ambiguous and unambiguous sections of the stimulus appear to be parts of the same object and thus enhanced the effectiveness of the disambiguation.

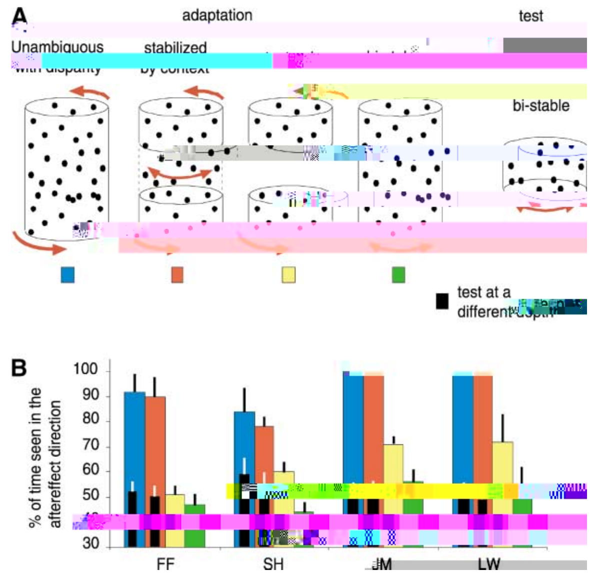

Figure 2. Effects of Adaptation to the Rotating Cylinders, including the Context-Stabilized Ambiguous Stimulus

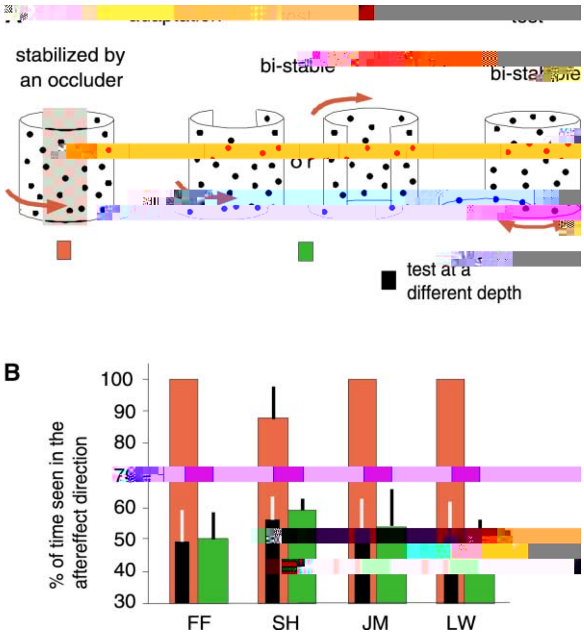

Figure 3. Effects of Adaptation to the Rotating Cylinder Stabilized by the Occlusion Cue

(A) The two adaptation stimuli had the same 2D motion signal. The stimulus with the explicit occluder was stabilized, whereas the one with the implicit occluder remained bistable, which served as a nice .6048 409n 465.M.9(plicit)-T5 dF6048 409n0ionc465.e2.hon back surk teback 3.5ous atnd here is Specific

the test stimulus to be rotating in the direction opposite the adapted direction. Observer S.H. was the only one who saw occasional reversals in rotation direction during adaptation and, consequently, showed a slightly weaker adaptation effect (test stimulus rotating in the aftereffect direction 88% instead of 100% of the time). For a control condition, we took advantage of the observation that when the occluder was not explicitly depicted (subjective occluder), perception was not stable, but alternated between the two interpretatations of depth (see Figure 1C). The 2D motion in the control condition was the same as motion with the explicit occluder. However, after adaptation to the control stimulus for 2 min, none of the observers showed any evidence of an aftereffect (Figure 3B). Note that, in both the test and the control condition, there was only one direction of motion signal in the middle section, which could and did lead to a simple 2D motion aftereffect. However, the simple 2D motion aftereffect could not influence the assignment of dots to the front or the back surface of the ambiguous test cylinder, as demonstrated by the absence of a rotation aftereffect in the control condition (Figure 3).

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The adaptation effect found here is retinotopically spe-

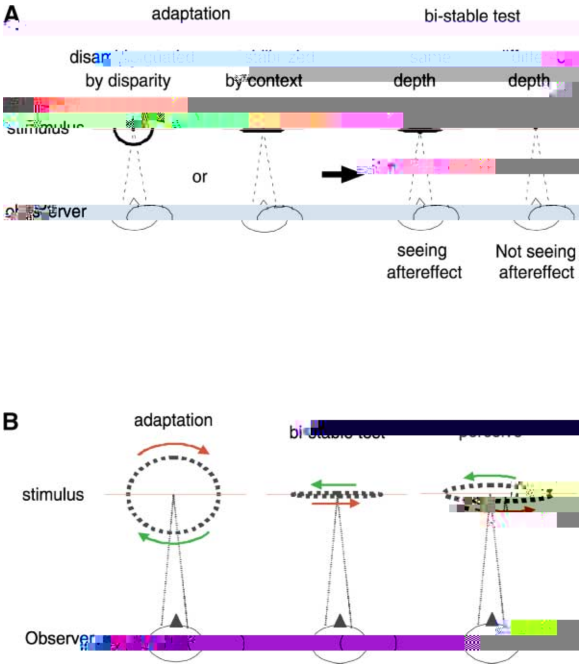

Figure 4. Adaptation Is Depth (Disparity) Specific

(A) The aftereffect was only observed when the test pattern was placed at the same depth plane as the adapting pattern. This was true for both the unambiguous adapting stimulus with disparity and the context-stabilized adapting stimulus.

(B) Illustration of motion direction contingent disparity aftereffect. During adaptation to a cylinder that is rotating clockwise, the dots moving to the left and to the right have different disparities (near and far, or crossed and uncrossed). When tests include moving dots with zero relative disparity (bistable), the leftward-moving dots are pushed away from the observer (green arrows), whereas the rightward-moving dots are pushed closer to the observer (red arrows). As a result, the test pattern is seen as rotating counterclockwise. Note that this aftereffect depends on the existence of different

Blake found nonzero relative disparity between the two sets of dots moving in opposite directions, whereas in our experiment the two sets of dots had zero relative disparity. In other words, we believe that the kinetic depth adapted disparity-sensitive neurons as if they had nonzero relative disparities. This interpretation implies that, within certain limits, kinetic depth indeed is equivalent to the disparity depth in the sense that the disparity-tuned neurons are selectively responsive to depth signals defined by motion. Nawrot and Blake (1993) showed that disparity and kinetic depth could be perceptually metameric [22]. Here, our experiments suggest that the two mechanisms can cross-adapt, which is a stronger indication that the two have shared neural mechanisms.

In 2D motion, attentional tracking can induce a motion aftereffect when tested with a dynamic or flicker stimulus [26]. Attention was also shown to modulate the adaptation to 3D rotation [27]. Can attentional tracking account for our observation? We tested this possibility by reducing the number of dots in the disparity-defined, unambiguous rotating cylinder while preserving the perception of a rotating cylinder. The logic is that the attention system tracks the direction of rotation, whether there are 600 or 30 dots, but a system that depends on the energy of the motion and disparity signal would be much less stimulated by the 30 dots than the 600 dots. If the aftereffect were due to attentional tracking, then we would expect that tracking 30 dots should also generate an aftereffect. However, we failed to observe an aftereffect when we reduced the number of dots, suggesting that the aftereffect was not due to attentional tracking.

C ol. i

Contextual and pictorial information can disambiguate and stabilize an ambiguous kinetic stimulus. The stabi-
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edge to $+0.1$ (or -0.1) degree of arc disparity at the center. The cylinder rotated at 0.231 revolutions/s.

In the first adaptation experiment (Figure 2), four kinds of adapting stimuli were used. They were (1) a rotating cylinder with complete, unambiguous disparity information; (2) a rotating cylinder with unambiguous disparity information at its two ends (i.e., the middle section of one eye's stimulus was removed from condition 1 to generate condition 2. The two ends were each 1.5° tall, and the middle section was 2° tall); (3) the two ends of a rotating cylinder with unambiguous disparity information (i.e., the middle sections of both eyes' stimuli were removed from condition 1 to generate condition 3; (4) a bistable rotating cylinder. The two eyes' stimuli were identical in this condition. The test stimulus was a bistable, rotating cylinder extending only 2° vertically; thus, the test stimulus was only presented in the location of the middle section of the adapting stimuli. Under conditions 1 and 2, the bistable test stimulus was also placed either at the same or different depth plane (0.2 deg disparity for all dots) as the adapting stimuli.

In the second adaptation experiment (Figure 3), there were two kinds of adapting stimuli. (1) A rotating cylinder (its parameters were the same as that in the first experiment) with a checkered red/green rectangle placed behind the front surface and blocking a vertical section of the back surface. The rectangle subtended 6.2° vertically and 2.8 degrees horizontally. Possible afterimages were avoided by the checker colors switching every 6 s. (2) A vertical section of the

6. Longuet-Higgins, H.C., and Prazdny, K. (1980). The interpretation of a moving retinal image. Proc. R. Soc. Lond. B. Biol. Sci. *208*, 385–397.
7. Nawrot, M., and Blake, R. (1989). Neural integration of information specifying structure from stereopsis and motion. Science *244*, 716–718.
8. Schwartz, B., and Sperling, G. (1983). Luminance controls the perceived 3-D structure of dynamic 2-D displays. Bull Psychon Soc *21*, 456–458.
9. Eby, D.W., Loomis, J.M., and Solomon, E.M. (1989). Perceptual linkage of multiple objects rotating in depth. Perception *18*, 427–444.
10. Gillam, B. (1976). Grouping of multiple ambiguous contours: towards an understanding of surface perception. Perception *5*, 203–209.
11. Grossmann, J.K., and Dobbins, A. (2003). Differential ambiguity reduces grouping of metastable objects. Vision Res. *43*, 359–369.
12. Sereno, M.E., and Sereno, M.I. (1999). 2-D center-surround effects on 3-D structure-from-motion. J. Exp. Psychol. Hum. Percept. Perform. *25*, 1834–1854.
13. Leopold, D.A., Wilke, M., Maier, A., and Logothetis, N.K. (2002). Stable perception of visually ambiguous patterns. Nat. Neurosci. *5*, 605–609.
14. Maier, A., Wilke, M., Logothetis, N.K., and Leopold, D.A. (2003).