C en Bi l g , V l. 14, 247–251, Feb a 3, 2004, ©2004 El e ie Science L d. All igh e e ed. DOI 10.1016/j.c b.2004.01.031

Stabilized Structure from Motion without Disparity Induces Disparity Adaptation

Fang Fang and Sheng He*
De a men f P ch l g
Uni e i f Minne a
75 Ea Ri e R ad
Minnea li , Minne a 55455

Summary

3D structures can be perceived based on the patterns of 2D motion signals [1, 2]. With orthographic projection of a 3D stimulus onto a 2D plane, the kinetic information can give a vivid impression of depth, but the depth order is intrinsically ambiguous, resulting in bistable or even multistable interpretations [3]. For example, an orthographic projection of dots on the surface of a rotating cylinder is perceived as a rotating cylinder with ambiguous direction of rotation [4]. We show that the bistable rotation can be stabilized by adding information, not to the dots themselves, but to their spatial context. More interestingly, the stabilized bistable motion can generate consistent rotation aftereffects. The rotation aftereffect can only be observed when the adapting and test stimuli are presented at the same stereo depth and the same retinal location, and it is not due to attentional tracking. The observed rotation aftereffect is likely due to direction-contingent disparity adaptation, implying that stimuli with kinetic depth may have activated neurons sensitive to different disparities, even though the stimuli have zero relative disparity. Stereo depth and kinetic depth may be supported by a common neural mechanism at an early stage in the visual system.

Results and Discussion

Spatial Context Can Disambiguate the Ambiguous Rotating Cylinder

Ambig c e f mm i n gene a ed f m h g a hic jec i n f 3D m ing bjec can be di ambig a ed b inf ma i n (e.g., di a i eed, c n a , e c.) ha ecifie he de h de he m ing elemen [5–8]. M i le ambig im li end c a [9–11], gge ing he ibili ha he e ce i n f an ambig im l c ld be infl enced b i a ial c n e . Se en and Se en (1999) dem n a ed ha m i n f he 2D nd f an ambig l a ing im l can bia he i el m ing d be e cei ed a he f n face f a 3D kine ic he e a im l c ld alm c m le el abili e he ambig im li.

The im l ed in d i a ical a ing c linde gene a ed f m an h g a hic jec i n f d n a a ing 3D c linde and i imila im li ed in e i ch h ical [3, 7] and h i l gical [4, 15, 16] die . The ambig im l e cei ed a a a ing c linde i h i a i n di ec i n i ching e e fe ec nd , a e en ed nl ne e e, (Fig e 1A). (The e ce f c nca e c n e hee , m ing ac each he , a e al ible [3] b e e a el een b b e e ; hence, he a e n di c ed in hi a e and n de ic ed in fig e .) When di a i inf ma i n a added he end f hi bi able c linde (i.e., a h le c linde a e en ed ne e e, and nl end f he c linde e e en ed he he e e), he h le c linde a e cei ed a e in he di ec i n ecified b he di a i in he end , al h gh he middle ec i n c n ained n inf ma i n ecif he de h de (Fig e 1B). F he f b e e e ed, all e cei ed he c linde a a ing nambig l , 100% f he ime, e m i le 1 min e e i d . The a ial c n e al c e a e effec i e in di ambig a ing he ambig m i n.

O b e a i n diffe f m ea lie e f c n e al bia e n ambig a i n. The c n e al bia d e im le 2D m i n c n a im l enhance he i e di ec i n f m i n in he cen al egi n and h bia e d m ing in ch a di ec i n be e cei ed a being in f n [12]. In he ca e f linkage be een m i le bi able im li, he c ling end b eak d n be een nambig and ambig im li [11]. The ke ea n ha he ambig and nambig ec i n in im l emain ngl linked i ha m n c la e en a i n f he ambig ec i n f he im l ed ced he di a i c n a be een n n e ela i e di a i in he nambig ec i n and e ela i e di a i in he ambig ec i n. Addi i nall , nlike in ea lie die in hich he ambig and nambig im li a ea ed a e a a e and di inc bjec , e made he ambig and nambig ec i n f he im l a ea be a f he ame bjec and h enhanced he effec i ene f he di ambig a i n.

Occl i n in gene al i a ng c e de h ela i n hi . The ccl i n c e ha been h n be me ha effec i e in di ambig a ing ambig kine ic de h e ce i n [17, 18]. We al e ed if an ccl i n c e can di ambig a e he face a ignmen f he

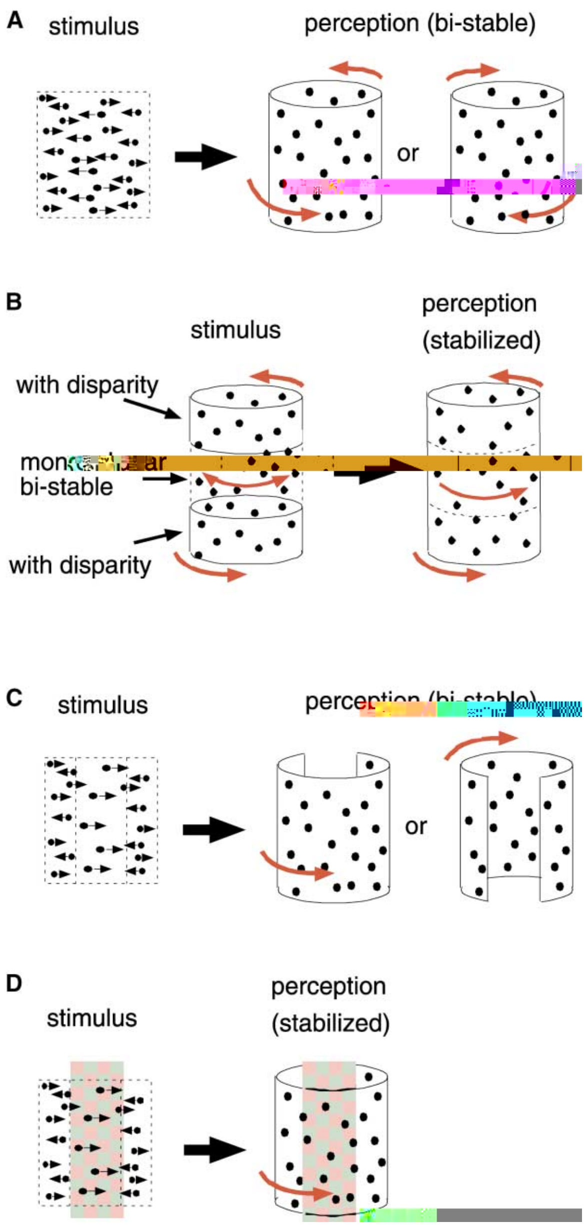

Fig e 1. Ambig S im li and Thei S abili a i n f m C n e - al C e

(A) Bi able a ing c linde . The 2D m i n ignal i c n i en i h ei he f he 3D in e e a i n .
(B) When he bi able c linde i laced be een nambig l a ing c linde (f m di a i), he h icall bi able middle ec i n i di ambig a ed b he end .
(C) A ec i n f d m ing in ne di ec i n i em ed, c ea ing a en ial bjec i e ccl de , b he e ce emain bi able.
(D) A i ible checke ed ccl de i laced behind he f n face, bl cking d f he back face. Pe ce i n i c m le el abili ed.

he back face. We hen gh enhance he ccl de b making i e lici . A checke ed ec angle a laced behind he f n face and bl cked a f he back face. Thi mani la i n a e effec i e in elimina ing he ambig i f face a ignmen (Fig e 1D). The e cei ed a i n became c m le el n-

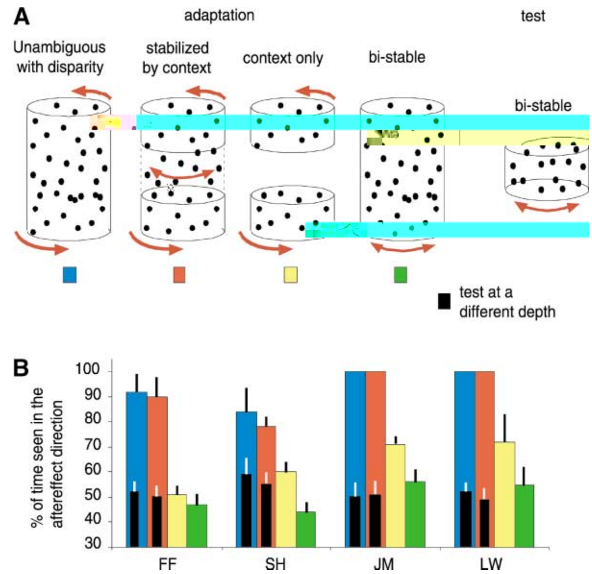

Fig e 2. Effec f Ada a i n he R a ing C linde , incl ding he C n e -S abili ed Ambig S im l

(A) F diffe en ada a i n im li e e ed. The e im l a an ambig c linde . F he fi ada a i n c ndi i n , he e im l a laced a he ame, a ell a a diffe en , e e de h f m he ada a i n im li.
(B) The ada a i n effec , a mea ed b he in f ime b e e e cei ed he a i n di ec i n i e he ada ed di ec i n. When he ada ing im l a ei he di ambig a ed i h f ll di a i c n e al di a i , he af e effec a ignifi-can l la ge han he c n l c ndi i n (< 0.01). The af e ef-fec al di a ea ed hen he e im l a laced a a diffe -en de h han he ada ing im li (black ba). E ba a e 1 anda d de ia i n. See he e f de ail .

ambig f h ee f he f b e e (ee E e i-men al P ced e) e m l i le 2 min e e i d and became alm c m le el nambig f he b e e S.H., h cca i nall (le han 10% f he ime) a he d a eling behind a emi an a en ccl de .

Disambiguated Motion Can Generate an Aftereffect

P l nged e e nambig a ing im li [7, 19], b n an ambig l a ing im l [20], can lead a i n af e effec . Can e b e e an af e effec f m a im l ha i e ce all abili ed b i c n e ? N e ha in he c en d he ada - ing e ie , di ec i n f a i n he e f d ha a e in f n , a e n ecified in he l cal ada ing im l b a e e ce all abili ed b c n e .

Immedia el af e 1 min f ada a i n ne f he f ada ing im li, b e e e e e en ed i h a bi able e c linde f 15 (Fig e 2A). A h n in Fig e 2B, c n i en i h ea lie die [7, 20], ada - ing he c linde ha a di ambig a ed b f ll di a - i e l ed in a e ng af e effec . H e e , ada - ing he c n e - abili ed ambig a ing c linde al e l ed in a e ng af e effec . All f b e - e e cei ed he e im l a ing in he di ec i n ie he ada ing di ec i n f m f he 15

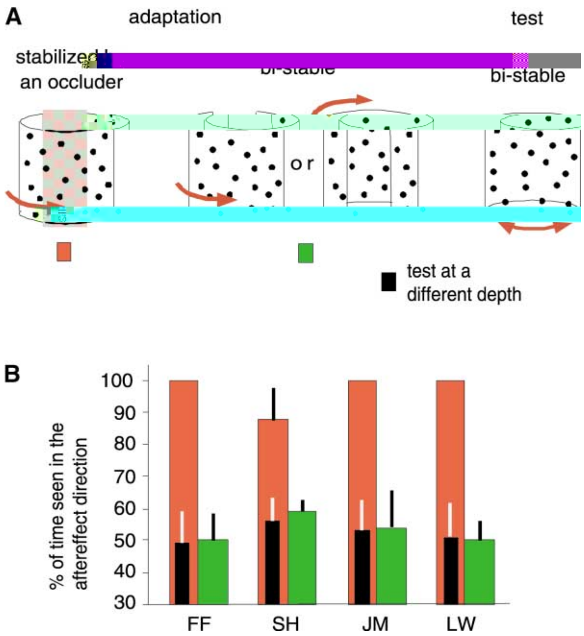

Fig e 3. Effec f Ada a i n he R a ing C linde S abili ed b he Occl i n C e

(A) The ada a i n im li had he ame 2D m i n ignal. The im l i h he e lici ccl de a abili ed, he ea he ne i h he im lici ccl de emained bi able, hich e ed a a nice c n l c ndi i n. F he abili ed ada a i n c ndi i n, he e im l a laced a he ame, a ell a a diffe en , e e de h f m he ada a i n im l .

(B) The af e effec in he h ical- ccl de c ndi i n i ignifican l la ge han ha in he c n l c ndi i n, in hich he 2D m i n a he ame b he 3D in e e a i n a bi able (< 0.01). The af e effec al e i ed ha he ada ing and e a e n be laced n he ame de h lane (black ba). E ba den e 1 anda d de ia i n.

e ing e i d. In addi i n he abili ed a i n im li incl ded a ada (f ll di a i nambig , c n e - abili ed, ambig), c n l c ndi i n e eal incl ded. In ne c n l (c n e nl), b e - e ada ed he end ni al ne, i h he middle ambig ec i n. Thi a e he he he af e effec c ld im l be a eading f ada a i n f m adjacen egi n a a e l f, f e am le, la ge ece i e field f he nde l ing ne n . An he c n- l c ndi i n (bi able) a im l he e ended bi a- ble c linde . Thi a e he he me el being e - ed a bi able a ing c linde f 1 min ld lead me abili a i n d ing he e ha e. Af e ada a i n in b h c n l c ndi i n , b e e e- cei ed he e ing c linde a a bi able ne, al e na- i el a ing in ei he di ec i n i h cl e 50% chance (Fig e 2B). When ada ed he end ni al ne, he nai e b e e (J.M. and L.W.) h ed a eak af e effec , likel d e le able fi a i n d ing ada a i n. H e e , he mall af e effec i m ch eake han ha gene a ed b he abili ed, ambig ada .

When he ambig c linde a abili ed i h an ccl de , he ada a i n effec a al e ng (Fig e 3). Th ee f he f b e e al a e cei ed he e im l be a ing in he di ec i n i e he ada ed di ec i n. Ob e e S.H. a he nl ne h a cca i nal e e al in a i n di ec i n d - ing ada a i n and, c n e en l , h ed a ligh l eake ada a i n effec (e im l a ing in he af e effec di ec i n 88% in ead f 100% f he ime). F a c n l c ndi i n, e k ad an age f he b e- a i n ha hen he ccl de a n e licil de- ic ed (bjec i e ccl de), e ce i n a n able, b al e na ed be een he in e e a a i n f de h (ee Fig e 1C). The 2D m i n in he c n l c ndi i n a he ame a m i n i h he e lici c- cl de . H e e , af e ada a i n he c n l im l f 2 min, n ne f he b e e h ed an e idence f an af e effec (Fig e 3B). N e ha , in b h he e and he c n l c ndi i n, he e a nl ne di ec i n f m i n ignal in he middle ec i n, hich c ld and did lead a im le 2D m i n af e effec . H e e , he im le 2D m i n af e effec c ld n infl ence he a ignmen f d he f n he back face f he ambig e c linde , a dem n a ed b he ab ence f a a i n af e effec in he c n l c ndi i n (Fig e 3).

The Aftereffect Is Retinotopic and Disparity Specific

The ada a i n effec f nd he e i e in ical e- ecific. I e ie ha he e a e n be e en ed a he ame e inal l ca i n a he ada ing a e n [21, 22]. Thi e in ic ecifici i e iden af e ada a i n a a ing c linde ha ha been di ambig a ed b di a i abili ed b c n e ccl de . F e am- le, in Fig e 2, he c n e - nl c ndi i n did n gene - a e he ada a i n effec . In f he e , he af e effec a n b e ed a l ng a he e a n a ial e la be een he ada ing and e ing im li. M e i- ingl , hi ada a i n effec al e ie ha he e a e n be laced a he ame e e de h lane a he ada ing a e n. The af e effec di a ea ed if he ada ing and e im li e e e en ed i h diffe en ab l e di a i ie (Fig e 4A). Unde ch c ndi i n , all b e e e cei ed ha he e a e n al e na ed di ec i n f a i n, i h each di ec i n being b e ed f nea l he ame am n f ime (black ba in Fig e 2 and 3). The e in ic and di a i ecifici f hi af e effec im lie ha hi ada a i n cc ela i el ea l in he i al em hen ne c n ide ha a- i n- en ii e ne n ha e i e la ge ece i e field [23]. I i in e e ing n e ha he abili a i n f a i n di ec i n, e in e mi en e en a i n [13, 14], eem be me ha e in ic ecific b n di a i ecific [24].

The af e effec c ld igina e in mechani m enc d- ing de h ge he i h an la i nal m i n. Al e na- i el , he af e effec c ld be a a i n af e effec [19]. In he la e ca e, beca e he af e effec a b e ed nl hen he e im li and ada ing im li e e e en ed a he ame di a i and l ca i n, da a gge ha , a he ame e inal l ca i n, he e a e e a- a e a i n- en ii e ne n f diffe en di a i ie . Thi e i emen make he a i n ada a i n m del le a im ni , al h gh he e icall ible. H -

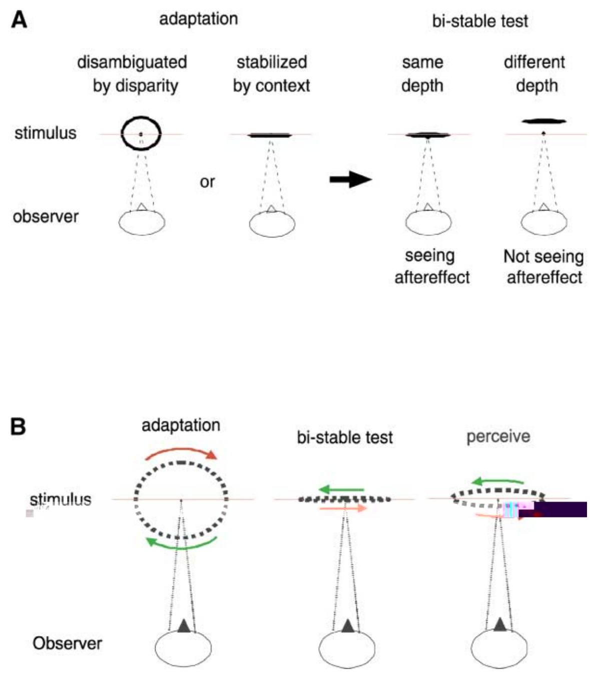

Fig e 4. Ada a i n I De h (Di a i) S ecific

(A) The af e effec a nl b e ed hen he e a e n a laced a he ame de h lane a he ada ing a e n. Thi a e f b h he nambig ada ing im l i h di a i and he c n e - abili ed ada ing im l .

(B) Ill a i n f m i n di ec i n c n ingen di a i af e effec . D ing ada a i n a c linde ha i a ing cl ck i e, he d m ing he lef and he igh ha e diffe en di a i ie (nea and fa , c ed and nc ed). When e incl de m ing d i h e ela i e di a i (bi able), he lef a d-m ing d a e hed a a f m he b e e (g een a), he ea he igh a d-m ing d a e hed cl e he b e e (ed a). A a e l , he e a e n i een a a ing c n e cl ck- i e. N e ha hi af e effec de end n he e i ence f diffe en di a i ie a cia ed i h he m i n di ec i n d ing ada - a i n.

e e, addi i nal c n ide a i n a g e again hi m del. Fi , an nen mechani m ned a i n ld edic ha af l nged ada a i n an nambig - a i n, ne ld e cei e a a ic c linde a e in he i e di ec i n. H e e , hi i n he ca e [7]. We failed b e e a a i n af e effec i h a a ic e a e n. Sec nd, ne n n ible f c m le m i n e ce i n h a la ge deg ee f i- i n and cale in a iance [23, 25], b , he e, he af e ef- fec b e ed a i e ecific in l ca i n and i e. Thi d, he af e effec i n ied he c e f he ada ing [21, 22] e ing im l . We b e ed ha , af e ada a i n he abili ed a ing c linde , fla hee f i el m ing d i h e ela i e di a i h ed a de h de c n i en i h he e- dic i n f he di a i ada a i n c n ingen n m i n di ec i n.

We fa he in e a i n ha he af e effec i a m i n di ec i n-c n ingen di a i af e effec , imila ha ed b Na and Blake [7] (ee Fig e 4B). H e e , he ke diffe ence be een e l and he e l f Na and Blake i ha Na and Blake f nd n n e ela i e di a i be een he e f d m ing in i e di ec i n , he ea in e imen he e f d had e ela i e di a i . In he d , e belie e ha he kine ic de h ada ed di a i - en i i e ne n a if he had n n e ela i e di a i ie . Thi in e e a i n im lie ha , i hin ce ain limi , kine ic de h indeed i e i a- len he di a i de h in he en e ha he di a i - ned ne n a e elec i el e n i e de h ig- nal defined b m i n. Na and Blake (1993) h ed ha di a i and kine ic de h c ld be e ce all me ame ic [22]. He e, e imen gge ha he mechani m can c -ada , hich i a nge indica i n ha he ha e ha ed ne al mechani m .

In 2D m i n, a en i nal acking can ind ce a m i n af e effec hen e ed i h a d namic flicke im - l [26]. A en i n a al h n m d la e he ada - a i n 3D a i n [27]. Can a en i nal acking ac- c n f b e a i n? We e ed hi ibili b ed cing he n mbe f d in he di a i -defined, nambig a ing c linde hile e e ing he e- ce i n f a a ing c linde . The l gic i ha he a en- i n em ack he di ec i n f a i n, he he he e a e 600 30 d , b a em ha de end n he ene g f he m i n and di a i ignal ld be m ch le im la ed b he 30 d han he 600 d . If he af e effec e e d e a en i nal acking, hen e ld e ec ha acking 30 d h ld al gen- e a e an af e effec . H e e , e failed b e e an af e effec hen e ed ced he n mbe f d , g- ge ing ha he af e effec a n d e a en i nal acking.

Conclusions

C n e al and ic ial inf ma i n can di ambig a e and abili e an ambig kine ic im l . The abi- li ed ambig m i n can gene a e a c n i en af e- effec . The af e effec b e ed i likel be a m i n di ec i n-c n ingen di a i af e effec , igina ed f m he ne nal e i alence be een di a i and m i n a alla .

Experimental Procedures

Observers

T e ienced b e e (F.F. and S.H.) and na e b e e (W.L. and J.M.), i h n mal c ec ed- -n mal i i n, a ici- a ed in he e e imen . N f mal ee i i n e e gi en he b e e , b all b e e c ld e cei e and m d e- e g am .

Apparatus and Stimuli

The im li e e en ed e e c icall i h li id-c al (LCD) h e ed gla e (S e e G a hic C a i n, San Rafael, CA). The m ing d e e gene a ed n a PC and e en ed n a SONY T ini n M l i can G420 19 inch m ni , i h a ial e l i n f 1280 × 1024 i el and a ef e h a e f 100 H . D ing he e imen , b e e e he LCD gla e i h he ie ing di ance e a 57 cm. The ba ic im l ed in he e imen a a a ing c linde defined i h 600 mall, and ml aced d (0.08° × 0.08°). The eed f each d f ll ed a ine a e f nc i n. The 2D jec i n f he c linde b ended 5 deg ee e icall and 4 deg ee h i n all . The d e e hi e (82.1 cm/m[2]) again a black backg nd. F c ndi i n in hich he c linde m i n a di ambig a ed b he di a i , di a i a ied m hl (i hin he limi f i el i e) f m e di a i a he edge +0.1 (−0.1) deg ee f a c di a i a he cen e . The c linde a ed a 0.231 e l i n / .

In he fi ada a i n e imen (Fig e 2), f kind f ada ing im li e e ed. The e e (1) a a ing c linde i h c m le e, nambig di a i inf ma i n; (2) a a ing c linde i h n-ambig di a i inf ma i n a i end (i.e., he middle ec i n f ne e e' im l a em ed f m c ndi i n 1 gene a e c ndi i n 2. The end e e each 1.5° all, and he middle ec i n a 2° all); (3) he end f a a ing c linde i h nambig di a i inf ma i n (i.e., he middle ec i n f b h e e ' im li e e em ed f m c ndi i n 1 gene a e c ndi i n 3; (4) a bi able a ing c linde . The e e ' im li e e iden ical in hi c ndi i n. The e im l a a bi able, a ing c linde e ending nl 2° e icall ; h , he e im l a nl e en ed in he l ca i n f he middle ec i n f he ada ing im li. Unde c ndi i n 1 and 2, he bi able e im l a al laced ei he a he ame diffe en de h lane (0.2 deg di a i f all d) a he ada ing im li.

In he ec nd ada a i n e imen (Fig e 3), he e e kind f ada ing im li. (1) A a ing c linde (i a ame e e he ame a ha in he fi e imen) i h a checke ed ed/g een ec angle laced behind he f n face and bl cking a e ical ec i n f he back face. The ec angle b ended 6.2° e icall and 2.8 deg ee h i n all . P ible af e image e e a ided b he checke c l i ching e e 6 . (2) A e ical ec i n f he d m ing in ne di ec i n a em ed (i.e., he ec angle in c ndi i n 1 e e changed he backg nd c l). The e im-l a a bi able c linde e ending 5° e icall . Unde c ndi i n 1, he e im l a e en ed in ei he he ame de h lane a he ada ing im l a a diffe en de h lane (0.2° di a i f all d).

D ing he ada a i n and e e i d, a fi a i n in a laced in b h he cen e f he ada ing im l and he cen e f he e ing im l , b h a he cen e f he m ni .

6. L ng e -Higgin , H.C., and P a dn , K. (1980). The in e e a-i n f a m ing e inal image. P c. R. S c. L nd. B. Bi l. Sci. *208*, 385–397.
7. Na , M., and Blake, R. (1989). Ne al in eg a i n f inf ma-i n ecif ing c e f m e e i and m i n. Science *244*, 716–718.
8. Sch a , B., and S e ling, G. (1983). L minance c n l he e cei ed 3-D c e f d namic 2-D di la . B ll P ch n S c *21*, 456–458.
9. Eb , D.W., L mi , J.M., and S l m n, E.M. (1989). Pe ce al linkage f m l i le bjec a ing in de h. Pe ce i n *18*, 427–444.
10. Gillam, B. (1976). G ing f m l i le ambig c n : a d an nde anding f face e ce i n. Pe ce i n *5*, 203–209.
11. G mann, J.K., and D bbin , A. (2003). Diffe en ial ambig i ed ce g ing f me a able bjec . Vi i n Re . *43*, 359–369.
12. Se en , M.E., and Se en , M.I. (1999). 2-D cen e - nd ef-fec n 3-D c e-f m-m i n. J. E . P ch l. H m. Pe - ce . Pe f m. *25*, 1834–1854.
13. Le ld, D.A., Wilke, M., Maie , A., and L g he i , N.K. (2002). S able e ce i n f i all ambig a e n . Na . Ne - ci. *5*, 605–609.
14. Maie , A., Wilke, M., L g he i , N.K., and Le ld, D.A. (2003). Pe ce i n f em all in e lea ed ambig a e n . C . Bi l. *13*, 1076–1085.
15. B adle , D., Chang, G., and Ande en, R. (1998). Enc ding f h ee-dimen i nal c e-f m-m i n b ima e a ea MT ne n . Na e *392*, 714–717.
16. D dd, J., K g, K., C mming, B., and Pa ke , A. (2001). Pe ce - all bi able h ee-dimen i nal fig e e ke high ch ice babili ie in c ical a ea MT. J. Ne ci. *21*, 4809–4821.
17. P ffi , D.R., Be en hal, B.I., and R be , R.J., J . (1984). The le f ccl i n in ed cing m l i abili in m ing in -ligh